

Design and Optimisation of a low cost Cognitive Mesh Network



Thesis submitted in fulfillment of the academic requirements

for the degree of

**Doctor of Philosophy in Computer Science** In the Faculty of Science

University of CapeTown

Supervised by

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# Dedication

This piece of work is dedicated to family which comprises a grouping of people who have been a pillar of strength both before the inception of the study, during and will also continue beyond. These are my wife Nancy, daughter Rachel, son Richard, my mother Nelly, all my nine siblings and finally my late friend and father Joseph who would have been the happiest to see this day

# Declaration

I declare that this dissertation is my own work. Where collaboration with other people has taken place, or material generated by other researchers is included, the parties and/or materials are indicated in the acknowledgements or are explicitly stated with references as appropriate.

This work is being submitted for the Doctor of Philosophy in Computer Science at the University of Cape Town. It has not been submitted to any other university for any other degree or examination.

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Date \_\_\_\_\_

# Certification

As the candidate's Supervisor(s) , I have approved this dissertation for submission.

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# Abstract

Wireless Mesh Networks (WMNs) have been touted as the most promising wireless technology in providing high-bandwidth Internet access to rural, remote and under-served areas, with relatively lower investment cost as compared to traditional access networks. WMNs structurally comprise of mesh routers and mesh clients. Furthermore, WMNs have an envisaged ability to provide a heterogeneous network system that integrates wireless technologies such as IEEE 802.22 WRAN, IEEE 802.16 WiMAX, IEEE 802.11 Wi-Fi, Blue-tooth etc. The recent proliferation of new devices on the market such as smart phones and, tablets, and the growing number of resource hungry applications has placed a serious strain on spectrum availability which gives rise to the spectrum scarcity problem. The spectrum scarcity problem essentially results in increased spectrum prices that hamper the growth and efficient performance of WMNs as well as subsequent transformation of WMN into the envisaged next generation networks. Recent developments in TV white space communications technology and the emergence of Cognitive radio devices that facilitate Dynamic Spectrum Access (DSA) have provided an opportunity to mitigate the spectrum scarcity problem. To solve the scarcity problem, this thesis reconsiders the classical Network Engineering (NE) and Traffic Engineering (TE) problems to objectively design a low cost Cognitive Mesh network that promotes efficient resources utilization and thereby achieve better Quality of Service (QoS) levels. Our low cost Cognitive mesh network design, provides solutions to two fundamental research questions.

Firstly from a NE perspective, the two designs proposed in this thesis give a solution to the question on network node cognition i.e., whether next generation mesh networks can be designed to include Cognitive nodes that may learn from their environment and broadcast that information in order to allow the mesh network to optimize its routing performance based on informed decision. There are two approaches to the design: centralized and de-centralized. The centralized cognitive mesh network is based on the IEEE 802.22 Wireless Regional Area (WRAN) standard and, has nodes that behave cooperatively with complete information from the environment and are coordinated by a central entity that has a global view of the network. The decentralized architecture has no central authority with only localized information that is incomplete. To this end, the network engineering problem is cast as a resource allocation problem, i.e., a White Space spectrum sharing problem wherein we employ game theory and subsequently develop a cooperative and non-cooperative optimization framework for TV White Space sharing. In the cooperative framework, the resource allocation is formulated as a cooperative Stackelberg game wherein individual nodes/networks are able to cooperate with each other by forming coalitions. Specifically, the Cognitive mesh network comprises a TVWS Base Station (BS) and Wi-Fi Access Points (APs) belonging to different operators which may be entrepreneurs engaged in TV White Space trading. The interaction of the BS and APs is considered to as a pricing problem wherein a BS strives to maximize its profit by selling secondary spectrum and Wi-Fi APs strive to satisfy customer demand by acquiring as much secondary spectrum as possible. The pricing problem is subsequently translated to a leader-follower Stackelberg game in an oligopolistic market setting. The BS station is considered to be the leader and the APs followers. The cooperative framework comprises three analytic models based on delay, throughput, and composite (delay+throughput) QoS metrics. The non-cooperative framework for TV White Space sharing is developed for anal-

ysis of a competitive scenario. In the competitive case, we consider a suitable next generation network in the form of a low cost Cognitive wireless mesh network comprising of Licensed users (PUs) that compete to offer services to a group of unlicensed Secondary users (SUs) in the form of mesh routers belonging to different entrepreneurial network providers engaged in TV White Space trading. The non-cooperative interactive engagement of PUs is viewed as a pricing problem wherein each PU strives to maximize its pay-off/profit. Subsequently the problem is reformulated into a Bertrand game in an oligopolistic market with the PUs and SUs as the players involved. In this oligopolistic market, PUs are players that are responsible for selling TV White Space Spectrum while the SUs are the buyers. The PUs strategy is by way of price adjustment, with a general trend that SUs tend to naturally favour the lowest prices when buying. Thus the non-cooperative framework, like the cooperative framework, comprises three tractable analytic models based on delay, throughput and composite (Combination of delay and throughput). Performance evaluation based on numerical simulation of the cooperative framework points to the throughput based model as faring better than the delay and composite models on the basis of the profit obtained as well as the direct dependence between throughput and price. As for the non-cooperative framework, the throughput model delivers the same channel quality at a decreased price as compared to the other two models, making it a more desirable model.

Our second research question concerns traffic engineering and hinges on QoS routing strategy in a network. Three QoS routing strategies, namely CSPF, MIX and IOPT are considered and the fundamental question is, what will be the best and appropriate QoS strategy among Traffic and Networking Engineering approaches for next generation Cognitive mesh networks. The solution to this question is our second major contribution and is obtained through adaptive routing model wherein we leverage on the both the cooperative and non-cooperative frameworks in the resource allocation problem. The routing model designed to traffic engineer the network, is based on a time dependent usage and pricing policy wherein the user is charged on the basis of how much bandwidth has been used and which time of day is it consumed. Numerical analysis for day time routing and night time routing reveals that it is possible to reserve more white space during the night time owing to the lower prices carefully designed to encourage secondary users to shift to use of the network at night. Using the Lagrangian and genetic algorithm optimisation approaches, the CSPF is proven to be the best QoS routing strategy compared to the MIX and IOPT routing strategies by virtue of a lower link cost. Moreover, the CSPF strategy has a high bandwidth reservation at a given price than the MIX and IOPT routing strategies when deployed in both cooperative and non-cooperative TVWS sharing frameworks. Furthermore by leveraging on MPLS technology to design an adaptive traffic engineering framework based on a Time of Day (ToD) theoretical routing model and a TVWS occupancy measurement campaign. An experimental analysis of the best routing strategy is carried-out using a discrete event simulator integrated with practically measured white space occupancy measurements, wherein using acceptance ratio, utilisation, delay and interference performance parameters, a Standard Traffic Engineered (Std TE) OSPF network is compared with a Time of Day Traffic Engineered (ToD TE) OSPF network. The simulation experiment is carried on three networks of different sizes and results indicate a ToD TE performs better than Std TE. The designed low cost Cognitive mesh network is best suited for rural and remote areas where smaller populations exist. The Implications of our findings for both highly populated rural and urban areas is the enablement of Internet of Things (IoT), Machine-to-Machine (M2M) communications as well as the smart city applications.

# Acknowledgements

I would like to begin by expressing my deep gratitude to my supervisory team comprising of Prof Antoine Bagula and Dr Maria Keet for guiding me through the PhD research process during which i acquired knowledge and skills that I will proudly use in future in my career as an academic. Indeed I am now at a different level with regards to the skills acquired. To the National University of Science and Technology 's Staff development committee, the faculty of applied science and the department of Computer science I do acknowledge your support and encouragement. Furthermore I will also want to acknowledge Prof Ermanno, Dr Marco Zennaro, Dr David Johnson, Dr Mishra Amit Kumar, Prof Tim Brown, Hope Mauwa as well as other colleagues in the ISAT lab and the entire computer science department at UCT. Finally to my wife Nancy and children (Rachel and Richard(2Rs))as well as the entire Mahube family thank you for your patience, understanding and outstanding support during the PhD process.

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# List of Acronyms

AAA	Authentication, Authorization and Accounting
ANN	Artificial Neural Networks
AP	Access point
BS	Base Station
BER	Bit Error Rate
CCC	Common Control Channel
CDN	Content Delivery Network

CSCC	Common Spectrum Control Channel
CR	Cognitive Radio
CWMN	Cognitive Wireless Mesh Network
CSPF	Constraint Shortest Path First
DOS	Denial of Service
DSA	Dynamic Spectrum Access
DSL	Digital Subscriber Line
FC	Fusion Centre
FCC	Federal Communications Committee
GA	Genetic Algorithm
GDB	Geolocation Database
GPRS	General Packet Radio Service
GT	Game Theory
IGW	Internet Gateway
IoT	Internet of Things
IOPT	Interference Optimisation Routing
ITU	International Telecommunications Union
LTE	Long Term Evolution
MAC	Media Access
MC	Mesh Client
M2M	Machine to Machine
MPLS	Multi Protocol Label Switching
MPMP	Multi-Point to Multi-Point
MR	Mesh Router
N.E	Nash Equilibrium
NE	Network Engineering
NLOS	Non Line of Sight
PHY	Physical Layer
PTMP	Point-to-Multi-Point
PTP	Point-to-Point
PU	Primary User
QoS	Quality of Service
SABC	South African Broadcasting Corporation
SB	Spectrum Broker
SU	Secondary User
TDMA	Time Division Multiple Access
TE	Traffic Engineering
ToD	Time of Day
TVBD	Television Band Device
TVWS	Television White Space
UHF	Ultra High Frequency
UMTS	Universal Mobile Telecommunications System
VHF	Very High Frequency
WLAN	Wireless Local Area Network
WPANS	Wireless Personal Area Networks

WiFi	Wireless Fidelity
WiMAX	Worldwide Inteoperability for Microwave Access
WMAN	Wireless Metropolitan Network
WMN	Wireless Mesh Network
WRAN	Wireless Regional Area Network
WS	White Space
WSN	Wireless Sensor Network

# 1. Overview

Recently multi-hop wireless communications networks have been attracting great interest within the research community. Wireless Mesh Networks (WMN), which are a form of multi-hop network, have demonstrated a huge potential to fulfil the requirements of Next Generation Networks (NGN). Wireless Mesh Networks (WMNs) are envisaged to be a key technology that allows ubiquitous connectivity to the end user. A typical WMN consists of Mesh Routers (MRs) forming the backbone of the network, interconnected in an ad-hoc fashion. Each MR can be considered as an access point serving a number of users or Mesh Clients (MCs). The MCs could be mobile users, stationary workstations or laptops that exchange data over the Internet. They direct their traffic to their respective MRs, which then forwards it over the backbone, in a multi-hop manner, to reach the gateway that links to the Internet. Therefore, WMNs promise community wide network access at affordable monetary and infrastructure costs [60]. Although WMN enhance performance with flexible network architectures, easy deployment and configuration, and fault tolerance, the high density of nodes may lower the network capacity. The high densities of nodes in close geographic proximity generate severe mutual interference among each other and thus devastating network performance [248]. Furthermore, most of the current wireless mesh networks have adopted the unlicensed Industrial Scientific and Medical (ISM) bands for backbone communications. As a consequence, the recent surge in wireless technologies such as smart phones, tablet, Personal Computers, Vehicular Networks, Tactical networks, and Machine-to-Machine /Internet of things (M2M/ IoT) as well as resource-hungry applications has led to overcrowding in the ISM band thus further depleting network capacity. However, the limited spectrum within the ISM can no longer sustain the ever evolving network applications and this is synonymous with spectrum scarcity. Furthermore, a series of empirical spectrum occupancy studies has revealed a gross under-utilisation of allocated spectrum [289], called White Space (WS). To this end, as a way of mitigating the impending spectrum scarcity problem, tangible efforts have been made to deregulate wireless spectrum and promote Dynamic Spectrum Access (DSA). The regulatory aspects have evidently been the recent steps by the Federal Communications Commission (FCC) in opening up the Television Spectrum band subsequently allowing unlicensed devices to opportunistically access it for as long as the unlicensed users do not interfere with legacy systems. This regulatory reform has largely been inspired firstly by the results of the empirical studies that we previously alluded to based on a gross under-utilisation of licensed spectra. Secondly, the analogue to digital television transition has also made available large chunks of spectrum called TV White Space (TVWS). To this end, the urge to exploit white spaces is irresistible as they have the potential to significantly enhance the performance of WMNs and other related technologies. Pursuant to the cause of harvesting and harnessing White Spaces, Cognitive Radio (CR), a device with the ability to sense the environment as well as automatically adjust the configuration parameters, has been proposed as a viable candidate solution for the frequency reuse problem. A clearly attractive application of CR is that of DSA, a technique which makes it possible for CR to operate in the best available channel. Specifically, the technique is such that at any instance when the Primary User (PU), i.e., licensed user of the spectrum, is not using the Primary band, the Secondary User (SU) equipped with CR device will utilise the White Space. Consequently the Secondary User will owing to the abilities of CR:

- Determine which portions of the spectrum is available and detects the presence of licensed users when a user operates in a licensed band.
- Select the best available channel or available spectrum (Spectrum management).
- Coordinate access to this channel with other users (Spectrum Sharing).
- Vacate the channel when a licensed user is detected (Spectrum mobility).

Practically, embracing the DSA technique has far-reaching implications as wireless networks are set to experience a significant change in the Quality of Service (QoS) levels, such as a dramatic increase in the throughput and reduction in delay. Moreover, WMN may potentially easily be extended to the rural and remote areas where these were previously deemed not economically viable by operators. Service providers often claim, dispersed populations, cost of roll-out as well as lack of power infrastructure as the main hindrance to their efforts [173]. However, with the advent of DSA, wireless technologies will create an enabling environment for rural Internet service providers to access lower-frequency spectrum thereby significantly reducing the cost of network deployment and operation. Potentially, the lower cost of network deployment and operation may translate to service providers, for the first time being able to implement profitable business models in which consumers and businesses are provisioned with affordable and sustainable services [215]. According to Song [252], a joint decrease in cost and increasing of pervasiveness of access will have a positive social and economic impact in rural and remote areas. Ultimately DSA translates to increased spectrum availability and combined with suitable business models may potentially lower barriers for new players or entrepreneurs into the market and thus promote healthier markets through competition.

In this thesis, we revisit the classical networking problems with a view to designing a novel solution that incorporates and builds upon recent advances in software and hardware technologies for networking over the recently opened TV white space spectrum. Specifically, the classical network and traffic engineering problems are revisited for the purposes of objectively designing a low cost Cognitive mesh network which promotes efficient resources utilisation and hence achieving better Quality of Service (QoS) levels.

## 1.1 What is being investigated

The research revisits traffic engineering and network planning methods to assert their implementation in the emerging multi-radio multi-channel mesh networks with a specific focus on cognition both at the level of network nodes but also the routing process. The main challenge consists of implementation and performance evaluation of QoS routing mechanisms and network resource control strategies when deployed in low cost multi-channel multi radio Cognitive Mesh Networks.

## 1.2 Spectrum Sharing in Cognitive Wireless Mesh Networks

Cognitive radio has emerged as a new design paradigm for next-generation wireless networks that aims to increase utilization of the scarce radio spectrum (both licensed and unlicensed) [188]. However the challenge of spectrum access takes an entirely different dimension more complex than legacy radios. This emanates from a realization that legacy radios have fewer operating states compared to the states achievable in CR radio. In the process of interacting with the environment, CR radios engage in significantly more and complex interactions between and among radios. Subsequently this phenomenon complicates the analysis of the spectrum access process. To this end, when designing new techniques for spectrum access that allow sharing of spectrum, the fundamental issues of efficiency and fairness must be addressed [165]. In the first instance, a spectrum sharing mechanism must assure that the spectrum is being used efficiently, which is a drawback of the current spectrum access mechanism. Secondly, the spectrum sharing mechanism must assure fair access to all radios.

## 1.3 Opportunistic Routing in Cognitive Wireless Mesh Networks

Traffic engineering is a network management technique that involves adapting the routing of traffic to the network conditions, with the joint goals of good user performance and efficient use of network resources. However, the routing of traffic in wireless mesh networks is constrained by the following challenges [52]:

- **Spectrum Awareness:** There is a paradigm shift in terms of the requirements for efficient routing solutions for next generation networks such as Cognitive mesh networks. The new design metaphor requires a tight coupling between the routing module and the spectrum management functionalities such that the routing module can be continuously aware of the surrounding physical environment to take more informed decisions. Spectrum awareness can be achieved in three ways:
  1. Information on the spectrum occupancy is provided to the routing engine by external entities (e.g., SUs may have access to a data-base of TVWS towers [64]).
  2. Information on spectrum occupancy is to be gathered locally by each SU through local and distributed sensing mechanisms.
  3. A mixture of the previous two.
- A second challenge involves the set up of quality routes in dynamic variable environments. The dynamic variable environment is a direct consequence of primary user behaviour. Unlike in the classical case, routing in Cognitive mesh networks will certainly not involve end to end resource reservation owing to the dynamic nature of White Spaces which are in-turn

influenced by the random behaviour of primary users. Reservations will most probably be available on a link by link basis. Subsequently resources for secondary traffic will have to be sought and reserved at node level.

- Route maintenance: the sudden appearance of a PU in a given location may render a given channel unusable in a given area, thus resulting in unpredictable route failures, which may require frequent path re-routing either in terms of nodes or used channels. In this scenario, effective signalling procedures are required to restore “broken” paths with minimal effect on the perceived quality.

## 1.4 Research Questions

**Question 1 :** (“**Cognitive nodes:**”) *Can next generation mesh networks be designed to include Cognitive nodes that can learn from their environment and broadcast that information in order to allow the mesh network to optimize its routing performance based on informed decision? can free spectrum be shared economically over spectrum sharing games.*

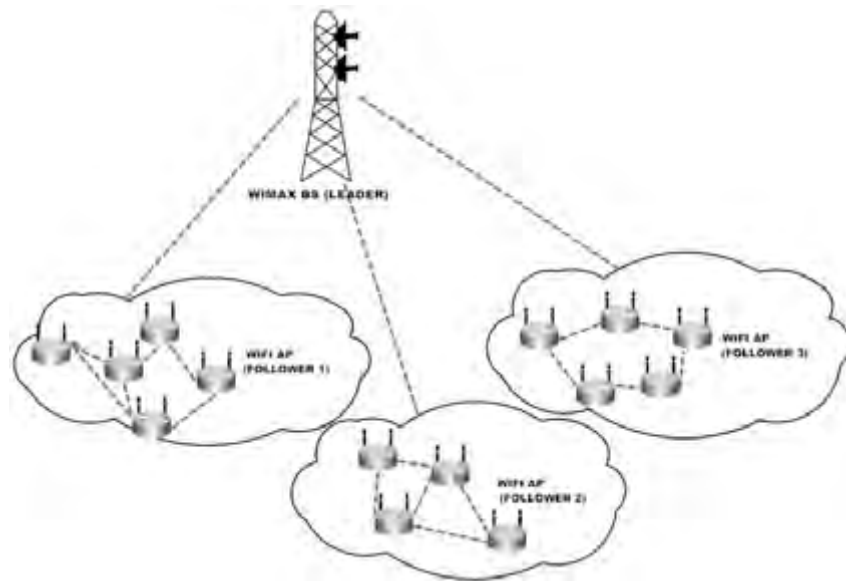
Unlike classical network nodes, routing in Cognitive nodes is constrained by factors such as (i) Different nodes operate on different frequency bands and should be closely attained by spectrum assignment in order to find next hope nodes and determine frequency band selection (ii) White Space of nodes may vary with time thereby changing the topology of the network with respect to time. Thus a white space exchanging and synchronization mechanism is required to find a route with communication potential. Clearly efficiently sharing information learned from the environment among next generation nodes in the dynamic spectrum still remains a challenging task.

**Question 2.:** (“**QoS Strategy:**”) *Looking at QoS routing strategies, what will be the best strategy among Traffic and Networking Engineering approaches for next generation Cognitive mesh networks?*

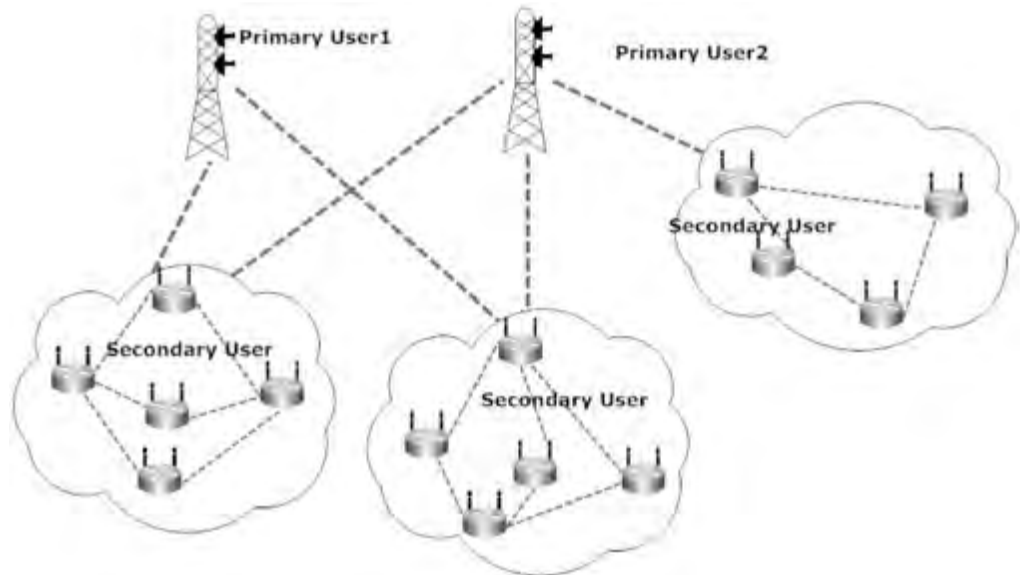
Although next generation networks have attracted great attention, research on Cognitive mesh networks is still immature. One of the researches hot-pot is the Quality of Service (QoS) routing decision strategy. QoS routing in next-generation wireless mesh networks involves route selection, spectrum allocation and scheduling. End-to-end QoS performance is the most important criterion to evaluate the effectiveness of routing decision strategy.

## 1.5 Contribution to Knowledge

Our efforts culminate in a contribution to knowledge in the research area of DSA and adaptive routing with regards to the IEEE 802.11 based Cognitive Wireless Mesh Network (CWMN). The contributions are viewed from both a network and traffic engineering perspective and answer the two research questions. For convenience, we present the centralized in Figure 1.1a and decentralized in Figure 1.1b designs upon which our contributions are based.



(a) Centralized Cooperative Approach



(b) Decentralized Non-cooperative Approach

Figure 1.1: Spectrum Sharing

1. Network Engineering: Spectrum sharing-Research Question 1

The first research question is based on network engineering and our research efforts have culminated in two partial responses where we have developed both a centralized cooperative and a de-centralized non-cooperative TVWS spectrum sharing frameworks. In the cooperative framework the Cognitive radio nodes (Wi-Fi (SUs)) in the radio environment cooperate based on some binding agreements so as to detect and attain services from the PU. This cooperation enables the multiple SUs to concurrently improve their individual performance as well as the overall spectrum utilisation. Suffices to say that the cooperative TVWS sharing framework comprises Cognitive radio nodes that exchange information within the

radio environment so as to optimize both their individual performance and that of the overall network. Non-cooperative Cognitive radio nodes do optimize their performance on an individual basis. Prior to enumerating our contributions, it suffices to confine our scope to a scenario where one primary wireless communication system owns the license rights to the spectrum band of interest. Our band will be either in TV band (UHF or VHF) for TVWS or WiMAX range for WS. Next we detail our contributions, starting firstly with the cooperative TVWS sharing framework, followed by the non-cooperative TVWS spectrum sharing framework as follows:

- Cooperative TV White Space (TVWS) sharing framework: A cooperative TVWS framework is designed in Figure 1.1a objectively for the sole purpose of allocating resources in a heterogeneous network using a cooperative Stackelberg game. Formulating the problem as a cooperative game is motivated by the need for network nodes to cooperate by forming coalitions. Concretely, a Cognitive mesh network was designed to represent a heterogeneous network comprising a WiMAX Base Station (BS) and Wi-Fi Access points (APs) that belong to different operators engaged in the trading of TVWS. The interaction of the BS and APs was subsequently generalized to a pricing problem wherein the BS strives to maximize its profit by selling secondary spectrum and the Wi-Fi APs strive to satisfy client's demands by acquiring as much spectrum as possible to meet the demand. The pricing problem is ultimately generalized into a Stackelberg game in an oligopolistic market setting where the BS attains a leader role and the APs attain a follower role, engage in a game with Nash Equilibrium as the solution. Our cooperative spectrum sharing framework comprises three analytic models premised on different inter-operator QoS agreements as follows:
  - (a) Delay QoS-based model which analytically attempts to characterize how spectrum can be dynamically shared to simultaneously satisfy QoS of the SU traffic that carries different classes of traffic while protecting the PU.
  - (b) Throughput QoS-based model which strives to characterize a scenario of maximizing overall network throughput for SU in the heterogeneous network while protecting the QoS of the PU.
  - (c) Composite Metric QoS-based model, this model is formulated from a combination of the throughput and delay QoS parameters.
- Non-Cooperative TVWS sharing Framework: The second part of the network engineering problem is the formulation of a competitive TVWS spectrum sharing framework for heterogeneous networks in Figure 1.1b. The problem is also approached from a game theoretic perspective in which the interaction between different competing technologies viewed as a non-cooperative game with Nash Equilibrium as the solution. The non-cooperative game is a competitive game in which PU strives to maximize profits and SUs strive to maximize the amount of bandwidth. Subsequently the game is generalized into a Bertrand game in an oligopolistic market with the PUs and SUs as the game players with different strategies. The PU owns the spectrum and thus performs the role of selling the spectrum and the SUs perform the role of buying spectrum. The PUs strategy is by way of price adjustment, with a general trend that SUs tend to favour the lowest prices when buying. Three tractable analytic models

are used in the framework based on QoS inter-operator agreements as follows:

- (a) Delay based model
  - (b) Throughput based model
  - (c) Combination of delay and throughput metrics model.
2. Traffic Engineering: (Routing-Research Question 2): A revisiting of this problem subsequently led to the leveraging on MPLS technology to design an adaptive traffic engineering framework based on a Time of Day (ToD) theoretical routing model and a TVWS occupancy measurement campaign.
- Theoretical Time of Day routing model: The model leveraged on the cooperative and non-cooperative frameworks for TVWS sharing and objectively strives to optimize network cost. Furthermore the model contextualizes a Cognitive mesh network wherein three routing strategies, namely the Constraint Shortest Path First (CSPF), Interference Optimisation routing (IOPT) and a combination of CSPF and IOPT routing (MIX) are deployed for the routing of traffic flows from source to destination. The deployment of these routing strategies allow for the performance evaluation of the framework based on such parameters as link cost, demand, reserved bandwidth and price. The CSPF is found to be a better strategy in terms of link cost compared to the IOPT and MIX strategies.
  - Adaptive Traffic Engineering: Spectrum occupancy: We Leveraged on our results from the theoretical model as well as MPLS capabilities to build an adaptive sub- framework based on the daily occupancy measurements for a two week period. Three different networks with nodes ranging from 20 nodes, 50 nodes and 90 nodes are configured and the CSPF strategy deployed in both a standard network and ToD TE network. Simulation results indicate a higher acceptance rate, lowered delay and utilisation for the ToD TE Cognitive mesh network as compared to the Std TE network.

## 1.6 Research Methodology

1. **Literature:** In the initial phase, an extensive literature survey of past and currently ongoing research with special emphasis on DSA and routing within the context of both cooperative and non-cooperative approaches was carried out. During this phase the technological developments in CR, WMN, TVWS, new standard initiatives and protocols were outlined. Furthermore relevant concepts in Game Theory (GT) were also explored.
2. **Theory:** The next phase involved game theoretical modelling of both cooperative and non cooperative dynamic spectrum access among coexisting wireless network technologies within the context of wireless Mesh networks. The game theoretical modelling was then extended to the scenario of a joint dynamic spectrum access and routing.
3. **Experiments:** Within the context of this thesis, the experiments are as follows:

- (a) A TVWS spectrum occupancy measurement within the UHF band. The occupancy characterises the TVWS occupancy on a Time of Day (ToD) basis.
- (b) A simulation experiment wherein the the occupancy measurement results are fed into a discrete event simulator. The discrete event simulator is developed using C++ and is employed to characterize traffic engineering based on Time of Day (ToD).

## 1.7 Thesis Structure

Figure 1.2 depicts the thesis structure in relation to the two main research questions centred on Network Engineering (NE) and Traffic Engineering (TE). Chapters 2, 3 and 4 constitute the groundwork information necessary for answering both research Questions 1 and 2. Furthermore it is shown that Research Question 1 which pertains to NE is answered in chapters 5 and 6. Chapter 7 answers Research Question 2 which pertains to the TE of the network. More specifically, in chapter 2, we review the related work regarding the domain of our research, specifically a comprehensive analysis of WMN technology with regards to such issues as characteristics, applications as well as challenges impeding the progress and deployment of WMN is presented. Furthermore, the concepts of TVWS and Cognitive radio are introduced with a subsequent characterization of TVWS and Cognitive Radio as an enabler of DSA. TVWS standards and standard initiatives as well as the deployment and research challenges are also discussed.

Our methodology in chapter 3 describes the set of methods and procedures used in the design and optimization of our envisioned Cognitive Radio mesh network. Specifically, three important theoretic bases for this thesis in the form of optimisation techniques namely, game theory, Lagrange Multiplier, and Genetic algorithms are discussed. Thus our work relies heavily on analytic modelling. Furthermore an approach to how practical white Space (WS) occupancy measurements are carried out, is outlined. To this end, our initial efforts are presented in chapter 4 wherein two fundamental system design architectures in the form of centralized and decentralized architectures are presented. These architectures will be used in the other chapters when carrying-out analytic modelling. On the basis of a centralized architecture, chapter 5, provides the first part of the answer to the first research question wherein we present cooperative TV White space Spectrum Sharing Framework, from a game theoretic perspective, three tractable models based on different QoS inter-operator agreements where WiMAX (PU) and WiFi(SU) coexist, are developed. Furthermore based on a decentralized architecture, a second part of the answer to the first research question in the form of a Non-cooperative TV White space Framework for spectrum sharing is our focus in chapter 6. Using three tractable analytic models inspired by a Bertrand oligopoly in which the service providers (primary users) compete to offer services to the secondary users, we model the interaction and the impact of channel quality on the service provider's utility.

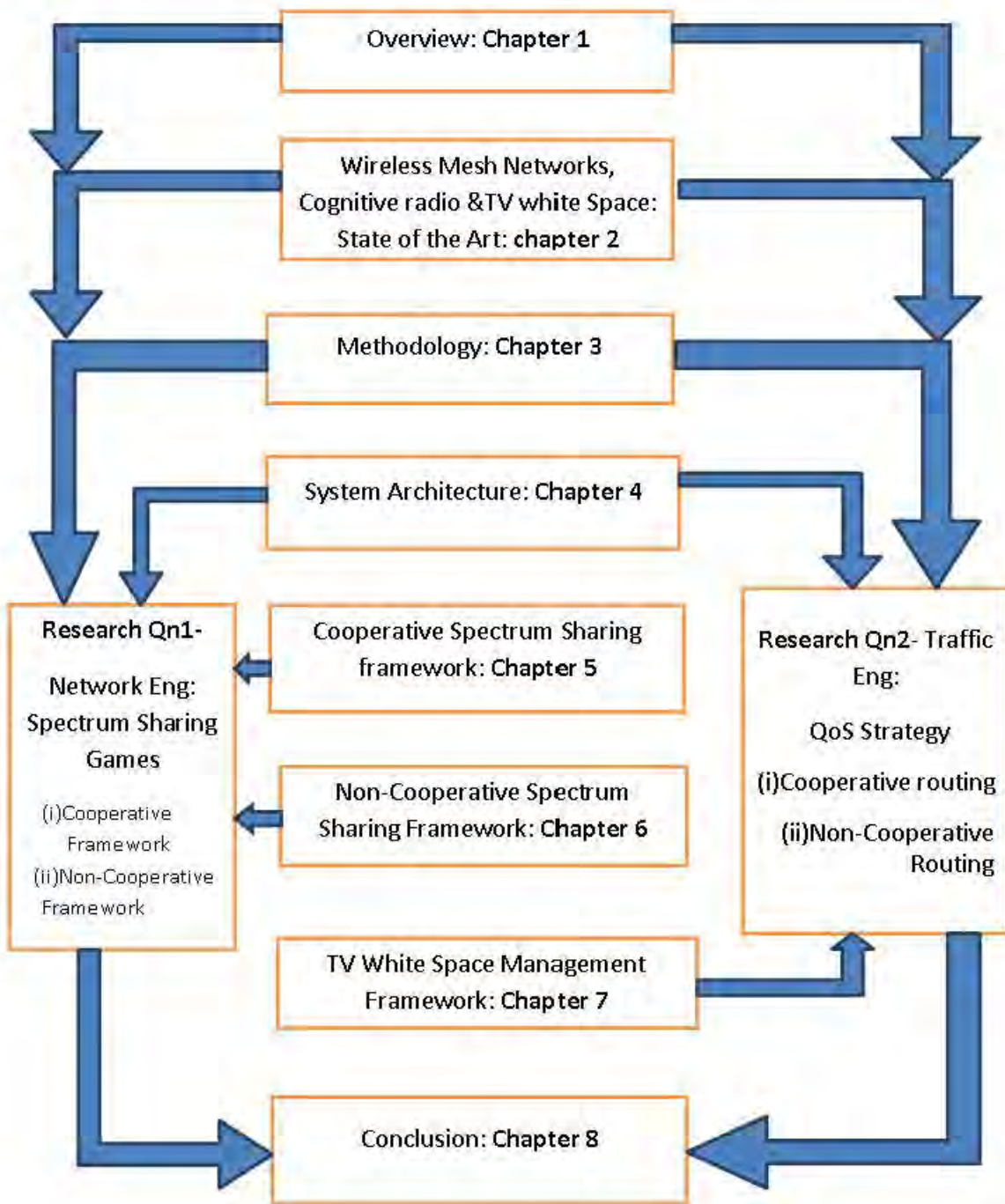


Figure 1.2: Overview of thesis structure

The first model analyses the impact of delay, second throughput and the third a combination of the delay and throughput. Chapter 7 addresses the issue of efficient TVWS management in multi-hop Cognitive mesh networks from an adaptive Traffic Engineering (TE) perspective. Specifically the inter-dependence between route selection and spectrum management is investigated wherein a TVWS management framework is designed. The TVWS framework is based on a Time of Day (ToD) routing model coupled with the cooperative and non-cooperative spectrum framework. A conclusion and recommended further-work concludes the research in chapter 8.

# 2. Wireless Mesh Networks, Cognitive Radio and TV White Spaces: State of the Art

## 2.1 Introduction

Wireless Mesh Networks have demonstrated a huge potential to fulfil the requirements of Next Generation Networks (NGN). The International Telecommunication Union (ITU) defines a NGN as a packet based network able to provide telecommunication services to users and able to make use of multiple broadband, Quality of Service (QoS) enabled transport technologies and in which service related functions are independent of the underlying transport related technologies. It enables unfettered access for users to networks and to competing service providers and services of their choice. Furthermore it supports generalized mobility which is consistent with a ubiquitous provision of services to users [123]. The IEEE 802.11-based backbone mesh networks constituted by static wireless mesh routers are able to create a wireless multi-hop backbone to provide high speed last-mile wireless Internet access to both rural and remote communities. To this end, this huge potential has subsequently positioned them as a candidate technology for the last mile connectivity. The multi-hop nature of mesh networks increases the probability of collision, packet corruption and other problems such as hidden and exposed terminal problems [25]. Furthermore, the progression of this candidate technology has been mainly marred by capacity constraints leading to the so called Spectrum scarcity problem [253, 69]. The implication of the spectrum scarcity problem is that radio spectrum relevant to wireless communications is densely allocated by regulators, making it unlikely that the bandwidth requirements of emerging technologies can be met [94]. The perception of spectrum scarcity is further reinforced by a look at the Federal Communications Commission (FCC) Frequency charts [47], which is a United states regulatory authority. The Frequency charts in [47] show multiple allocations over all of the frequency bands which is a situation essentially also assumed true worldwide. This has resulted in fierce competition for use of spectra, especially in the bands below  $3GHz$ . On the other hand, some of the licensed bands, which are normally shielded through regulation, have revealed an inefficient frequency usage contrasting with the over-crowding and over usage of the Industrial Scientific and Medical (ISM) band. A case in point is that of frequencies reserved for TV broadcasting which usually show an overbooking of under-utilized frequencies. This discrepancy between frequency usage and allocation has raised the need for a redesign of the frequency regulation by taking advantage of the recent technological innovations. Certainly an implication of this view is that new unique business models need to be explored. Intuitively, two parallel developments have taken place, the first being a transition from analogue to digital Television releasing appreciably huge chunks of spectrum. The spectrum released from this process has been referred to as Television White Space (TVWS). The second development is that of cognitive radio which does not only deal with the spectrum scarcity problem, but also promotes the desired any-time anywhere connectivity. A consequence of these developments has been the subsequent equipping of wireless mesh nodes with Cognitive radio interfaces to form Cognitive Radio mesh networks. Cognitive radio (CR)

is a new paradigm that utilizes the available spectrum band. A key characteristic of CR is its capacity to sense spectrum environment so as to adapt its operation and dynamically vary its radio operating characteristics. The technique of dynamically harnessing the unused spectrum band is known as Dynamic Spectrum Access (DSA) [93]. Ultimately the advent of CR and DSA has the potential to change how networks are formed, owned and operated [259]. Intuitively, DSA has the potential to transform the multi-billion telecommunication market by making it possible for new entrants into the market and encouraging further innovations.

Practically, license owners called Primary users (PUs) can now lease their spectrum to unlicensed spectrum users called Secondary users (SU). The Cognitive radio interface can harness the white spaces spectrum, thereby mitigating the capacity constraints. In view of these technological developments, innovations, regulatory frameworks and subsequent evolution of the Internet in different domains, including the Internet of services, Internet of Things (IoT) and the network of the future, this chapter explores background information relevant to the design of Cognitive mesh networks. To do so, the structure of this chapter will be as follows. In section 2.2 a comprehensive analysis of wireless mesh network technology is carried out to include such issues as characteristics, applications, and challenges impeding the progress of this technology. The concept of TV White Spaces is introduced in section 2.3 wherein TV Whites Spaces are mainly characterized. In section 2.4 a broad analysis of Cognitive radio is presented to encompass important concepts such as spectrum sensing, spectrum mobility, spectrum decision and spectrum analysis. An overview of TV white space standards is presented in section 2.6. Practical deployment scenarios of TV white space based networks from a global perspective are presented in section 2.7 and research challenges conclude the chapter in section 2.8.

## 2.2 Wireless Mesh Networks

Tangible advancements in wireless technologies coupled with the explosive growth of wireless Internet networks especially Wireless Mesh Networks (WMN) are the main drivers behind a fundamental evolution towards next generation networks. The WMN structurally comprise of nodes in the form of mesh routers and mesh clients. Each individual node functionally operates not only as a host but also as a mesh router, forwarding packets on behalf of other nodes that may not be within direct wireless transmission range of their destinations. Moreover WMN are endowed with the ability to dynamically self-organize as well as self-configure, with the network nodes automatically establishing and maintaining mesh connectivity among themselves (creating, in effect, an ad hoc network). Special features such as low up-front cost, easy network maintenance, robustness, and reliable service coverage have given WMN an edge over other types of network. In real life scenarios, network nodes equipped with wireless radio interface cards are able to connect directly to mesh routers, while those not equipped can connect by way of ethernet. Additional gateway/bridge functionalities in mesh routers facilitate the integration of WMNs with various existing wireless networks such as cellular, wireless sensor, wireless-fidelity (Wi-Fi), worldwide interoperability for microwave access (WiMAX), WiMedia networks [33, 4]. Consequently, through an integrated WMN, the users of existing networks can be provided with access to otherwise impossible services from these networks. To this end, WMN have emerged

as a candidate solution for the design of next generation networks and has practical applications in numerous life facets.

**2.2.1 Classification of WMNs.** Wireless networks can be categorized on the basis of their nature of connectivity to numerous network elements ranging from Point to Point (PTP), Point to Multi-point (PTM) and Multi-Point to Multi-Point (MPM) as shown in Figure 2.1.

1. Point to Point: This class of networks represents the very basic form of the network [20, 276]. A drawback of this approach is that the network is not scalable and exhibits a low level of adaptability.
2. Point to Multi-Point: Point-to Multi-Point networks [100, 132, 164] are moderately scalable compared to PTP networks. This type of network has been known to have low adaptability as well as reliability.
3. Multi-Point to Multi-Point: Compared to PTP and PTM, MPM networks [55, 287] exhibit a rather high degree of reliability, adaptability as well as a better scalability which accommodates increased users. As the number of nodes in the network increases, the transmission power needed for each node will be reduced. Consequently, MTM wireless networks leverage on current wireless standards such as IEEE 802.11 and these special type of networks are called Mesh Networks [234].

**2.2.2 Characteristics of WMN.** Wireless mesh networks generally comprise of numerous wireless technologies, exhibiting the characteristics of each component (ad hoc, cellular and sensor networks). Wireless mesh networks are characterized by the authors in [7] as follows:

1. Multihop wireless network: A fundamental basis for the adoption of WMN is their ability to extend current coverage range without altering channel capacity. Furthermore WMN have the ability to provide non-line-of-sight (NLOS) connectivity to users without direct line of sight (LOS) links. To this end, mesh multihopping is crucial as it facilitates higher throughput without sacrificing effective radio range via shorter link distances, minimized interference between and among nodes, and more effective frequency reuse.
2. Low installation costs: Current and more recent efforts aimed at providing wireless connection services to end users have been achieved by utilizing 802.11 based Wi-Fi Access Points (APs). Attempts to achieve large area coverage have translated to deployment of a large number of APs to mitigate the problem of limited range transmission. A disadvantage of this approach is that it is highly expensive given that a cabled connection is imperative for each AP. To this end, WMN have arisen as a promising cost effective solution capable of providing high network coverage and low infrastructural cost [82]. This is owing to the fact that WMN require only a few points of connection to the wired network. Consequently, WMN can facilitate rapid implementation and possible modifications of the network at reasonably lower costs, which is extremely important in today's competitive market-place.
3. Support for ad hoc networking, and capability of self healing, and self organization: One of the most useful characteristics of WMN is its support for ad hoc networking. Ad hoc

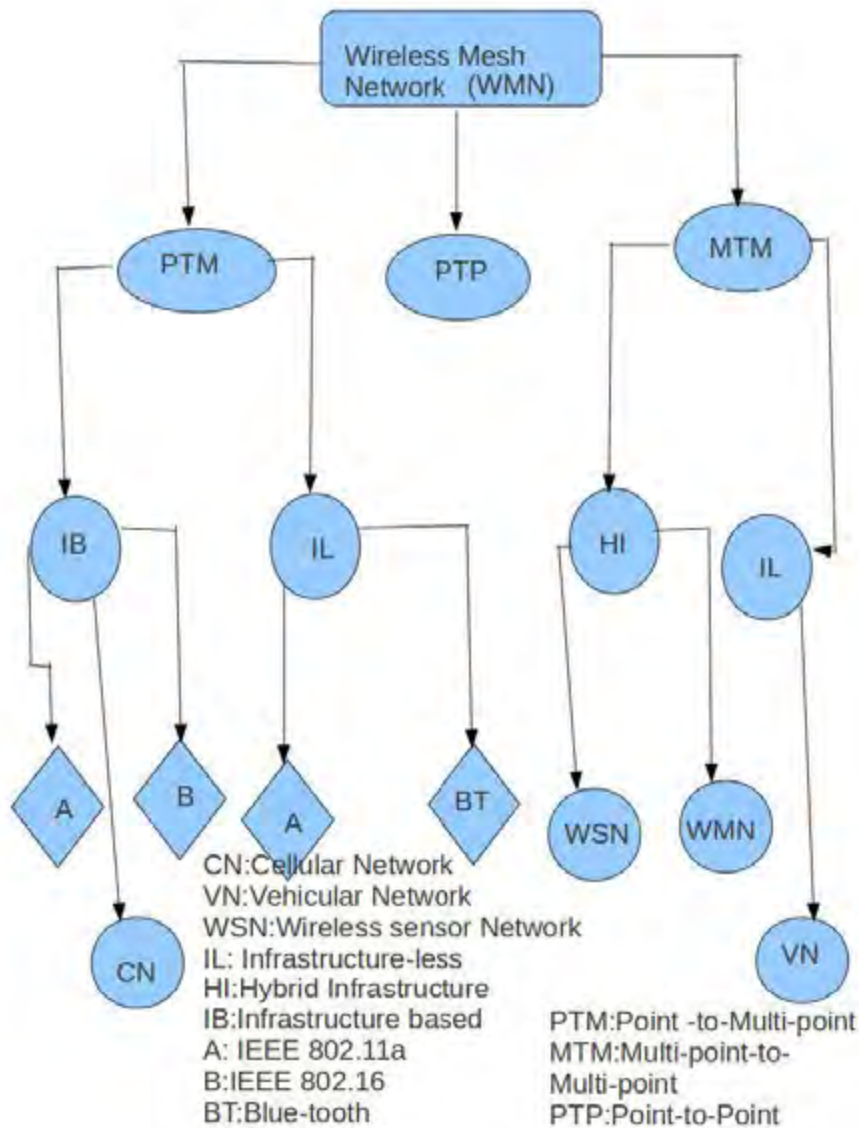


Figure 2.1: Classification of Mesh Networks

networking enhances performance of network as it allows for flexible network architecture, easy deployment and configuration, fault tolerance, and mesh connectivity, i.e. multipoint-to-multipoint communications. These characteristic features make it feasible for WMN to have low upfront investment requirements and also facilitate network growth.

4. Multiple types of network access: WMN technology supports both back-haul access to the Internet and peer-to-peer communications. The ability to support multiple types of network access enables the WMN to integrate together different wireless networks to provide different services to a diverse range of clients.
5. Dependence of power consumption constraints on the type of mesh nodes: WMNs routers as major components have no stringent constraints on power consumption and this subsequently translates to a major advantage. However this does not hold true for WMN

clients as they seek power efficient protocols. This characteristic is similar to wireless sensor networks [246, 168, 291, 108].

6. **Compatibility and interoperability with existing wireless technologies:** The ability to conform to other wireless technologies such as the IEEE 802.11 family standard is a plus for WMNs. With regards to interoperability, WMN should be interoperable with other mesh networks such as WiMAX, ZigBee and cellular systems.

**2.2.3 Applications of WMNs.** Wireless Mesh Networks have been and are still being actively researched and developed as one of the most promising and enabling network technologies to support various multimedia services and applications in Wireless personal area networks (WPANs), wireless local area networks (WLAN), wireless metropolitan area networks (WMANs) as well as cellular multihop networks and other networking technologies. Potential applications of WMNs include broadband home networking, community and neighbourhood networking, enterprise networking, building automation, health and medical systems, public safety and security systems, intelligent transportation, emergency or disaster networking, metropolitan broadband Internet access [279]. The applications are briefly described as follows:

1. **Broadband Wireless Access:** The modern information economy is highly dependent on broadband access due to its transformative power as an enabler for economic and social growth making it an essential tool for empowering people, creating an environment that nurtures the technological and service innovation, and triggering positive change in business processes as well as society as a whole [138]. A majority number of services for real-time applications ranging from video, telephone, on-line gaming, video on demand are only possible in a connected environment [89] enabled by broadband access. However it has been the trend that in urban and suburban areas that are largely densely populated wired access (via DSL and cable) is the first available choice. This is in sharp contrast to rural and remote areas where wireless technologies such as satellite [81, 181] and cellular technologies have been deployed and proved unaffordable for the inhabitants [207]. For example, apart from being expensive satellite technology, also has a high latency. However, cellular networks have proved to be similarly expensive in terms of installation and operational costs. To this end, WMN has become a candidate choice for broadband provision in such areas [90].
2. **Industrial Automation:** A popular application in this regard is that of building automation [74, 137, 103, 172, 86] in which numerous devices need to be monitored such as power, light, air conditioner, elevator etc. WiFi technology offers an affordable option for the achievement of such operations by way of WMN technology, which makes it less costly.
3. **Healthcare:** Healthcare is a critical business be it in a doctor's office or large hospital , there are always a number of factors that interplay and there must be a balance between urgency, privacy, regulations and technology. The implication is that the ability to connect to a network is of crucial importance in healthcare [15, 50]. For example in most hospitals broadband is usually useful as there are huge amounts of data that must be transmitted, for example high resolution medical images and periodic monitoring information [73, 57].

4. **Transportation:** WMN technology makes it feasible to extend Internet services to lorries, buses, ferries and other public transport systems [96]. This implies that passengers are able to enjoy the benefits of using the Internet while on board. Furthermore mesh networks also facilitate systems for communication among people with disabilities [265]. Finally remote monitoring in vehicles [76, 302], drivers communications is also possible [228].
5. **Hospitality:** The tourism and hospitality sector is also a beneficiary of WMNs technology as hotels [264], restaurants and other resort centres are provided with high speed Internet connectivity at minimal or no cost. Often this does not involve disrupting nor disturbing the existing infrastructure for both indoor and outdoor activities.
6. **Warehouses:** Wireless networks have been deployed to provide connectivity in modern warehouses [268, 226] and other logistical operations with minimal costs. In the warehouses stocks are monitored by way of scanners.
7. **Temporary venues:** Temporary benefits of mesh networks are associated with construction sites wherein a service is easily setup and removed after use. This means engineers, architects and other interested parties are connected for the purposes of communication and monitoring progress at the site. Certainly other applications can benefit from this capability such as live shows, fairs, political rallies or even after a disaster [125, 95, 212, 53, 88, 51].

**2.2.4 System and Network Architectures for Wireless Mesh Networks.** From a design perspective, wireless mesh architecture design is an initial step towards the provision of broadband Internet access over a particular coverage area. Basically, WMN comprise of Mesh clients (MCs) and Wireless Mesh routers (WMRs) which interact by way of relaying each other's packets in a multi-hop manner. The routers have minimal capacity for mobility and certainly form the backbone of the wireless Mesh network. From an architectural perspective, WMN are able to cater for long distances by breaking the distances into a series of shorter hops to boost the signal by intermediate nodes. Subsequently, the intermediate nodes assist the entire transmission process by not only sustaining signal strength, but also forwarding packages on behalf of fellow nodes about their knowledge of the network status. As a consequence, WMN system architecture facilitates continuous connection and reconfiguration around broken or blocked paths by making forwarding decisions from node to node until the destination is reached. Furthermore, broadband Internet access is provided at a low cost. The infrastructure that sustains a WMN comprise of a wireless mesh router network or backbone wireless mesh Network. It is from the backbone wireless mesh network that mesh clients are able to access broadband Internet services provided in a multi-hop manner. Additional backbone wireless mesh networks have Internet Gateways (IGWs) that play the role of bridging the backbone network and the Internet.

### **2.2.5 Design Challenges of WMNs.**

1. **Dynamic Mesh Connectivity and Self-Configuration:** WMNs are mainly inspired by mesh connectivity, meaning a reliable mesh connectivity is a requisite. This means that it is imperative to eliminate single point failures and potential bottleneck links, the wireless backbone needs to provide redundant paths between the sender and the receiver, i.e., mesh connectivity [102]. This requirement thus calls for network self-organization as well as

topology algorithms to be in place. Once the topology aware MAC and routing protocols are realized then a notable network improvement should be possible.

2. **Heterogeneous Quality of Service (QoS) Requirements:** Unlike classical networks, the nature of applications in WMNs are broadband services with variable QoS requirements and are exemplified by file transfer as well as real-time multimedia such as live video streaming [56]. This demands the consideration of other metrics apart from end-to-end transmission delay and fairness such as delay jitter, aggregate, and per node throughput, as well as packet ratios to be factored into protocols.
3. **Security:** Current security in mesh networks is still void of efficient and scalable solutions. This observation stems in part from the fact that the Internet architecture lacks built-in security mechanisms. Needless to say, WMN inherit the security properties and limitations of the Internet and are subsequently prone to flooding, Denial of Service (DDos) attacks and other malicious operations [220]. Moreover, other attacks leverage on the Media access control layer features. A case in point is that of jamming attacks that inhibit data transmission from any wireless network node within the vicinity. It is also inferred that the approaches known from wired networks such as adding AAA ( i.e. authentication, authorization, and accounting), are not appropriate for mesh networks given that there is no centralized authority to distribute a public key in WMN architecture. Ultimately, the authors in [102] assert the need for new security schemes ranging from efficient encryption and authentication mechanisms to secure key distributions, and intrusion detection mechanisms.
4. **Mobility Support:** Features such as mobility support or elaborated PHY mechanisms such as concurrent usage of multiple wireless channels and directed antennas [180] add to design complexity of WMN. It is thus imperative to design advanced layer and networking techniques, which can adapt to the fast fading conditions commonly associated with the mobile users. On top of these advanced features, low latency handover and location management algorithms are highly sought for the enhancement of QoS during mobility [102].
5. **Compatibility and Inter-operability:** Existing networking technologies have limited capabilities of integrating different wireless networks [102]. Intuitively, all the vital components of a WMN must not only be compatible but must also be interoperable with other network components from different wireless networks that may be rolled out in future. To this end, it is imperative for WMNs to be backward compatible with conventional client nodes if widespread deployment of WMNs is to be a success. Integration of WMNs with other wireless networks requires certain mesh routers to have the capability of interoperation among heterogeneous wireless networks.
6. **Network Management Tools:** Next generation networks will be required to have the capacity to overall monitor the network performance. Additionally, maintaining network operation as well as flexible and scalable network management capability is imperative for WMNs. The management capability for WMNs, include (but are not limited to):
  - bandwidth provisioning
  - installing security and quality of service policies

- supporting service level agreements
- addition and removal of network entities
- change of network functions
- accounting and billing

However, with these design challenges, current technological developments and regulatory reforms can be leveraged to improve network design. For example, the emerging radio technologies such as reconfigurable radios and cognitive radio [293] are set to transform the design approach in higher layer protocols, particularly in MAC and routing. In the context of classical wireless mesh networks constrained by spectrum scarcity needing to meet the high speed requirements of current existing wireless applications, emerging radio technologies are imperative. Emerging radio technologies such as Cognitive radio facilitate opportunistic spectrum access so as to alleviate the spectrum scarcity problem of mesh networks by enabling the mesh nodes to dynamically explore any available spectral opportunities [143]. The combination of white spaces and Cognitive radio technology are set to have a strong influence on mesh networks design and therefore we give an overview of white spaces in section 2.3 and Cognitive radio in section 2.4.

## 2.3 TV White Space

The term White Space is interpreted to mean portions of the licensed radio spectrum that licensees do not use all the time or in all geographical locations. These white spaces are usually found in the Very High Frequency (VHF) and Ultra High Frequency (UHF) bands for digital TV broadcasting services and are thus commonly termed TV White Spaces (TVWS). As for the TV broadcast network, it comprises high rise TV towers with high power transmitters. As a way of minimizing interference, TV programs are delivered over different frequency bands from each TV tower or frequency network. The combination of large coverage area coupled with static frequency allocation makes it opportune for secondary access in TV bands given that primary usage is relatively easy to detect by implementing Geolocation Databases (GDB). TVWS also have the added advantage of wider area coverage for both indoor and outdoor environments as compared to spectrum bands used in mobile communications exemplified by Universal Mobile Telecommunication System (UMTS) as well as the Industrial Scientific and Medical bands (ISM). For the record in 2004 the United States of America (USA) 's spectrum regulatory body the Federal Communications Commission (FCC) opened TV bands for Secondary access for the first time. This was followed in 2010 by a revision of the ruling with additional technical specifications. Motivated by the potential for secondary access, the United Kingdom (UK)'s regulatory body Ofcom joined the bandwagon for TVWS exploitation [256]. To date efforts to exploit TVWS have not only spread, but have intensified as manifested among other things by standards being developed and testbeds as well as trials by industry and academia, (we defer the discussion on trials and deployments to section 2.7).

**2.3.1 Characterization of TVWS.** Bahl et.al in [32] characterize TVWS in the UHF band in three ways relative to the spectrum in the ISM band. The characterization is centred on spatial variation, fragmentation and temporary variation.

1. **Spatial variation:** The UHF band is generally associated with television stations as primary users. Accordingly, the set of occupied channels in any locality is a function of the location of TV transmitters as well as the number of stations or incumbents. Spatial variations, although on a small scale, are a consequence of obstructions and construction materials. For example microphones which are used in small lecture rooms and live musical shows have a range of a few hundred metres.
2. **Spectrum Fragmentation:** In the UHF band spectrum fragmentation means white spaces are fragmented as a result of the incumbent's presence. The size of spectrum fragments ranges from a single channel to several channels sometimes aggregated together. The amount and size of fragments is a function of the number of incumbents as well as the population density. As a consequence, rural, remote and suburban areas are more likely to have larger fragment chunks. An implication of fragmentation is that radios have to tune the spectrum that they occupy so as to fit within the available fragments. This, however, leads to radios to use variable channel widths or channel bonding. Variable channel width presents two problems, the first being that it makes channel allocation a challenging task. Secondly, it makes discovering access points by nodes in a WiFi network a bit lengthy. This emanates from a lack of techniques that can achieve variable channel widths on cards. Radios can generally decode packets sent on a common or same channel width as well as same centre frequency.
3. **Temporal Variation:** Temporal variations in the UHF white spaces is a consequence of the intermittent operation of wireless microphones and demands as a pre-requisite a protocol capable of signalling the presence of wireless microphones to the network without interfering with the microphone.

**2.3.2 Benefits of Using TVWS.** TVWS have great potential [83, 185] and are thus expected to deliver tangible benefits in the near future. An immediate impact of TVWS is expected to be in the area of broadband i.e., according to [63], broadband can transform poor communities by bringing the benefits of education and health care closer to rural and remote populations, and delivers social and economic benefits to all. Furthermore broadband builds bridges between individuals, communities, and nations. By harnessing broadband power brought about by TVWS, Millennium Development Goals (MDGs) and other future sustainable development goals can easily be attained. Another expected benefit of TV white space is the lower communication costs to be experienced by business. This is because the low cost of TVWS is best suited for rural areas where the deployment of broadband connectivity can be realized using TVWSes. However, despite their unlicensed nature and existence, TVWS need to be controlled. Furthermore, TVWS are expected to spearhead entrepreneurship following regulatory reforms. The increased and often competitive demand for licensed spectrum has raised the bar for market entry so high that none but the wealthiest of investors get involved [211]. With the advent of TVWS technology rural broadband service delivery will be availed to an entire generation of entrepreneurs interested in providing local, competitive broadband services. If TVWS technology lives up to its promise, it will not only provide opportunities to small entrepreneurs but also introduce competition which will possibly lower prices. Subsequently, rural communities will gain easier access to information on health, agriculture, security, distance education services, disaster warning, access to job information, and closer contact with distant family members.

Exploitation of TVWS is ongoing and several efforts are currently underway worldwide. Numerous challenges exist, although not everyone has been open about it. Mwangoka et.al [183] reports the following as the challenges encountered when exploiting white spaces for the provision of broadband Internet services. The challenges are identified as:

- Harmonization: This is because of different national interests as well as historical reasons. Harmonization is imperative in cross-border interference, standardization of cognitive technology as well as white spaces technology, certification and compliance requirements of devices, etc.
- Region lags behind: The European region lags behind other regions, specifically the USA in respect of the exploitation of TVWS. Feasible approaches need to be investigated with regards to regulatory policies, market potential as well as technology to accelerate the process.
- Business models: An absence of business models to attract investment in TVWS is a major challenge [131]. There are proposals for a bicameral geolocation database to support both commons and spectrum trading. The model strives to facilitate the introduction of different wireless business models in the areas of spectrum trading, wireless service provisioning and other value added services such as sensor networks, mobility management, coexistence etc.

Despite the benefits attributed to TVWS there are still sentiments within the research community that these benefits may potential be increased if the definitions of WS are expanded beyond the three dimensions of the spectrum space, namely time, frequency, and geographic region [6].

## 2.4 Cognitive Radio

According to the FCC, software defined radio (SDR) encompasses any “radio that includes a transmitter in which operating parameters such as frequency range, modulation type or maximum output power can be altered by software without making any changes to hardware components that affect the radio frequency emission” [67]. In his doctoral thesis [176] mitola extended the definition of SDR further by envisioning a radio that could make decisions as to the network, modulation, and or coding parameters based on its surroundings, and called such a “smart” radio a cognitive radio [67]. Cognitive radio is a paradigm for wireless networks where an entire network or individual network nodes adjust their transmission or reception parameters for effective communication so as to avoid interference with either licensed or unlicensed users. Although the cognitive radio term is generally attributed to J. Mitola, it first appeared in the year 1999 [177] in an article co-authored by G.Q. Maguire which was later followed by his doctoral thesis [176]. Specifically, unlike conventional radio devices, Cognitive radio endows the user with cognitive capability as well as reconfigurability. In this regard, varied forms of Cognitive radio inspired paradigms [122] such as underlay [107], overlay paradigms [146] as well as Interweave [231] which are pointing towards the successful use of Cognitive radio.

**2.4.1 Relevance of Cognitive radio to Wireless Mesh networks.** Cognitive radio is a new approach to intelligent managing of wireless resources. From a WMN perspective, CR represents a way to improve overall utilization of available spectrum and an extension of available spectrum to individual networks [44]. The CR has the ability to use any spectrum that is not being used thus is able to provide additional bandwidth and subsequently enhance WMN performance [122]. This is to say CR can be deployed in WMN to make effective use of available wireless channels e.g. in IEEE 802.11b/g. In the event that access and transit links use the same technology, then the transit network will have a far lower throughput as compared to an individual access link [122]. CR deployment also translates to a use of multiple user technologies within the same network. This implies there is coexistence of CR equipped devices together with legacy systems.

**2.4.2 Key Characteristics of Cognitive Radio.** The deployment of Cognitive radio device should make it possible for a technological ecosystem in which both new and old technologies coexist. The CR is characterised as follows:

1. **Interoperability:** Cognitive radio is widely regarded as a feasible solution to the interoperability problems that plague communication networks [167]. Interoperability in the context of this thesis refers to the ability of one or more systems to provide services to and accept services from one or more other systems and to use these to enable the different systems to operate effectively together. Interoperability has increasing relevance in a world where many different wireless communications-based systems and devices exist but many of these systems cannot communicate with each other [227, 194]. Interoperability thus translates to a CR being able to quickly and automatically reconfigure itself to communicate between two or more incompatible radios. This characteristic is very welcome as interoperability is a hot issue challenging the Internet of Things (IoT) and high demand for inter-networking heterogeneous systems.
2. **Cognitive Capability:** The device has the ability to sense as well as gather information from the surrounding environment which may encompass issues as transmission frequency, bandwidth, power, amplitude etc. Subsequently, upon gathering the information mentioned above, the device is in a position to give secondary users the capacity to pinpoint the best available spectrum [110].
3. **Frequency Agility:** CR devices are expected to be highly flexible in the way they send and receive data. Specifically, the agility gives them the capacity to adapt spectrum usage on the fly thereby tremendously improving the performance of wireless networks [48]
4. **Awareness:** The capability to know and understand the transmissions enhances the Cognitive radio's ability to salvage information from the environment. Specifically, its ability to sense and possibly ascertain channel conditions throughout the spectrum band and subsequently store and retain memory of its environment. Awareness should also include that the level of hardware, applications, user characteristics and specifically its goals.
5. **Reconfigurability:** Cognitive radio can be configured to transmit and receive on a variety of frequencies and using various access technologies supported by its hardware design. Several parameters ranging from operating frequency, transmission power, modulation etc

can be incorporated into cognitive radio. These parameters can be configured such that the CR is switched to a different spectrum band, the transmitter and receiver parameters are reconfigured and the reconfigured and the appropriate communication protocol parameters and modulation schemes are used [105]. The main tasks of cognitive or Cognitive radio are as depicted in Figure 2.3 and can be summarized as follows:

- **Spectrum sensing:** Continuously and persistently forages for unused spectrum. The unused spectrum is called spectrum hole or white space.
- **Spectrum management:** Upon the finding of spectrum holes, a decision is made as to which is the most suitable spectrum hole.
- **Spectrum sharing:** For as long as the primary user is not using its spectrum, Cognitive radio allocates it to the SU. The spectrum is however relinquished whenever the PU needs it. This is termed spectrum sharing. The diagram in Figure 2.2 shows a typical architecture for a Cognitive radio network where PU and SUs coexist and share the spectrum.

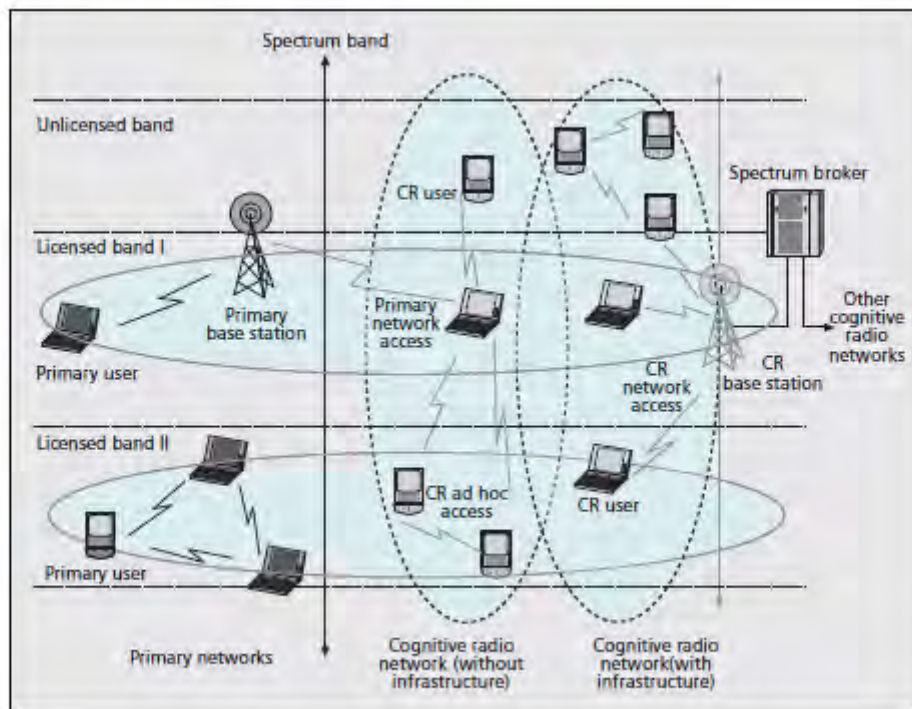


Figure 2.2: Cognitive Radio Network ( Source: [10] )

- **Spectrum mobility:** Upon detection of primary user, the secondary user must vacate the spectrum band or channel and relinquish it back to the PU. This is called Spectrum mobility.

In the subsections that follow, we present an analysis of each of the Cognitive radio tasks as well as their roles in the basic cognition cycle.

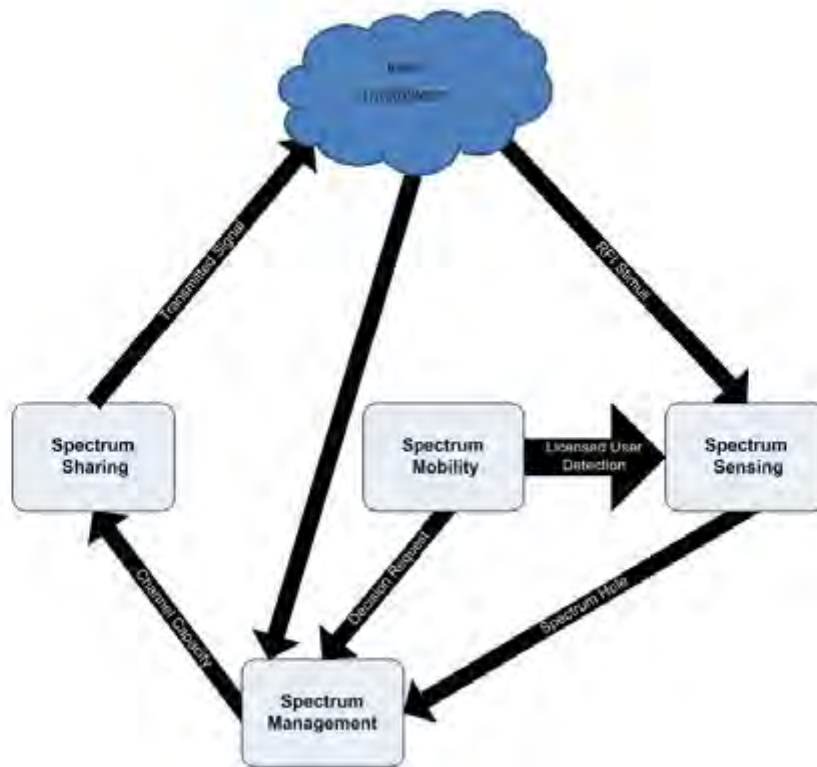


Figure 2.3: *Basic Cognition Cycle (Source: [169])*

**2.4.3 Sensing Algorithms.** Alemdar and Ersoy [16] define spectrum sensing as an act of measuring the RF environment in order to detect certain features of a signal for instance its energy. [202] asserts that success of CR completely depends on the spectrum sensing efficiency. Spectrum sensing basically complements the geolocation database to assist the network operator in finding the most noise-free channels to use. Sharan and Wankhede [111] provide a detailed analysis of the spectrum sensing task as encompassing; detection of spectrum holes, spectral resolution of each spectrum hole, estimation of the spatial directions of incoming interferences and signal classification. The spectrum sensing act brings understanding of spectrum occupancy from a multidimensional perspective i.e. time, frequency, space and geographical location. Thus the sensing algorithm is able to provide such intelligence as to what time a particular frequency spectrum is occupied or not occupied. To this end, signal detection is achievable via an optimum detection avenue or alternatively through a sub-optimum detection avenue. The current development efforts in spectrum sensing algorithms are still in the early stages [233]. Certainly the spectrum sensing algorithms developed so far are widely scattered in literature. However, attempts have been made to put these together such as [233] and [286]. A creative analysis of these works reveals some deficiencies, for example Seshukumar et.al [233] reports on two types of spectrum sensing algorithms namely transmitter detection and cooperative detection. The former is based on the detection of a weak signal from PU transmitter, algorithms in this category include matched filter, cyclostationary, energy detection and Eigen-value based. The latter is based on sensing information from other users and includes algorithms such as cluster based, distributed and centralized. These authors have not looked at Interference based spectrum sensing algo-

rithms. The efforts of Yucek and Arslan [286] though a bit more than those of [233] also fall short of interference based spectrum algorithms. The interference based spectrum sensing strives to regulate interference at the receivers. Intuitively, in Figure 2.4 a comprehensive classification mechanism for these algorithms is provided. The algorithms broadly fall into three categories, namely, transmitter detection algorithms, interference algorithms, and cooperative algorithms. In the next subsections we provide a summary of the algorithms, unless specified otherwise the mathematical analysis is borrowed from [286].

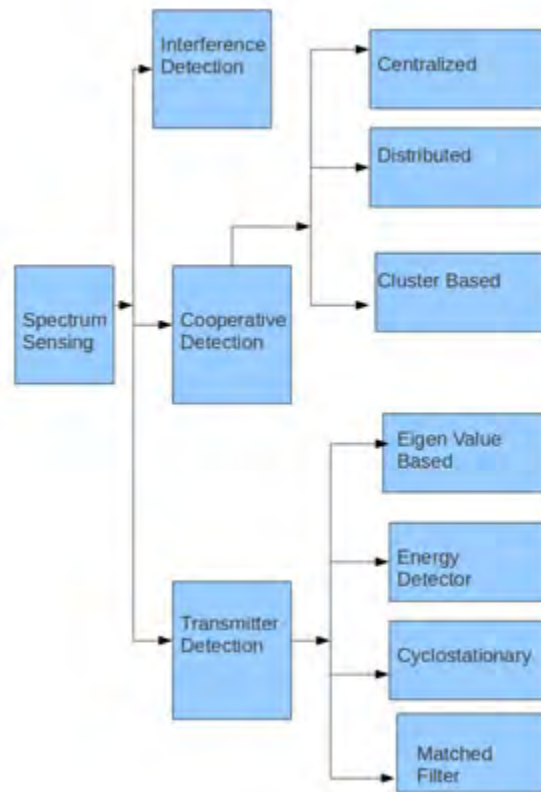


Figure 2.4: *Classification of Spectrum Sensing Algorithms*

1. Energy Detection. Energy detection is arguably one of the more popular spectrum sensing algorithms [80, 208, 250, 239]. This is because of its low implementation complexity as compared to other methods that we shall shortly present in this section. Furthermore another desirable feature of this method is its low implementation cost. The algorithm involves among other steps the selection of a threshold value of the power levels. Intuitively the fundamental idea behind this algorithm is shown in Figure 2.5 wherein a received signal is allowed through some pre-filtering circuit which removes the noise from the received signal.

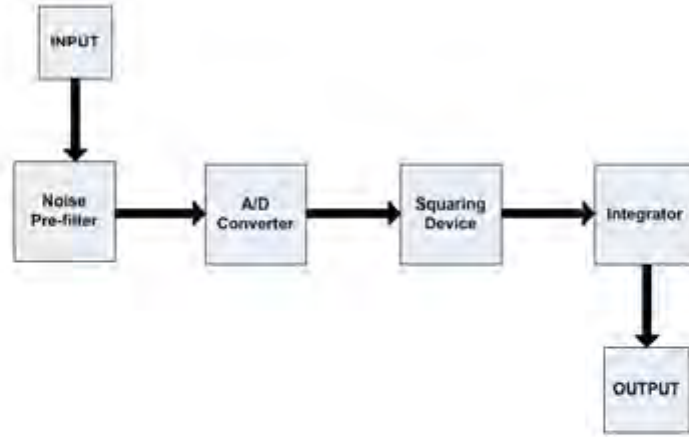


Figure 2.5: *Energy Detection*

The signal is further passed onto an analogue to digital converter. The square law device squares the now digital signal to calculate power within the specified window. In the integrator the received signal is compared to the threshold and a decision made as the output. Assuming the sensed signal to be of the form

$$x(n) = s(n) + w(n) \quad (2.1)$$

with the metric to the threshold being

$$M = \sum_{n=0}^N |x(n)|^2 \quad (2.2)$$

A decision making process for this algorithm involves two states as follows:

$$H_0 : x(n) = w(n) \quad H_1 : x(n) = s(n) + w(n) \quad (2.3)$$

The parameter  $w(n)$  denotes sample noise and  $s(n)$  represents the sample of the target signal. A major challenge of this method is the choice of a threshold. This threshold is usually dependent on the noise variance. The estimation of the noise variance is a tricky encounter in that any slight inaccuracies may degrade performance. The noise variance estimation is based on the autocorrelation of the received signal. In realistic scenarios fading and shadowing must be taken into consideration. Other limitations of this algorithm have been identified in [48] as follows:

- The energy detection algorithm does not distinguish between primary user signals, noise and interference. This renders the algorithm subsequently less useful in preventing interference.
- An Energy detector algorithmic approach is not a good choice for direct sequencing, frequency hopping signals as well as spread spectrum signals.
- When there are high oscillations of the signal power, it becomes difficult to differentiate the desired signal.

- Compared to other algorithms such as matched filter, this method takes longer to achieve the desired performance level.
2. Matched Filter. This is yet another transmitter-based spectrum sensing algorithm. The rationale in this approach is to correlate a known signal with an unknown signal so as to detect the presence of the known signal in the unknown signal [136]. The implementation block is shown in Figure 2.6, from a signal processing perspective, the primary signal is convolved with a time shifted version of the prior signal. Matched filter is thus considered to be a candidate choice if CR has knowledge of primary user waveform. From a signal processing perspective, the operation of a matched filter is described by [141] as:

$$Y[n] = \sum_{k=-\infty} h[n-k]x[k] \quad (2.4)$$

An evaluation of this algorithm reveals the following positives:

- It requires less computational time as a result of high processing gain.
- Matched filter requires short time to achieve a certain probability of false alarm or probability of missed detection. Notable limitations from the same analysis are:
  - Prior intelligence about every PU signal is needed.
  - CR needs a dedicated receiver for every type of primary user.
  - High implementation complexity translating to cognitive radio needing a receiver for every signal type.
  - Matched filtering consumes large power as various receiver algorithms are needed for detection.

However, undesirable results are certain in the event of the primary user waveform being unknown. This method is known to consume less computational time and resources [303].

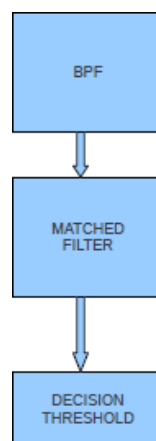


Figure 2.6: Matched Filter Sensing

3. Cyclostationary Spectrum Sensing Algorithm. This algorithmic approach to spectrum sensing takes advantage of the cyclostationarity properties of a received signal so as to detect the primary signal as shown in Figure 2.7. For concreteness, assuming a signal  $x(t)$  exists, then such a signal has cyclostationary properties if its statistics, mean, and autocorrelation are periodic with some period  $T_0$ .

$$R_x(t, \tau) = R_x(t + T_0\tau) \quad (2.5)$$

Equation 2.5 shows the autocorrelation's periodicity, this function can then be depicted in the form of a Fourier series.

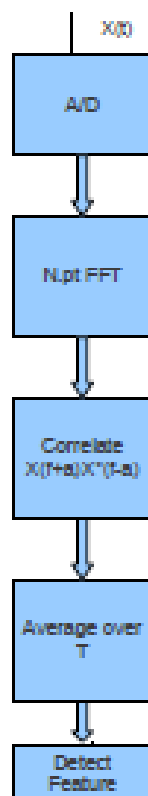


Figure 2.7: Cyclostationary Detection

Cyclostationary Feature Detection (CFD) has the following notable benefits:

- The algorithm performs better than energy detection at low SNR vicinities.
- Cyclostationary feature detection is not affected by noise uncertainties. It is essentially robust to noise.
- Frequency and noise synchronization of signal is not required.

The cyclostationary algorithm has its own flaws, such as:

- CFD is associated with long observation time, high sampling rate and high computational complexity.
  - CFD also requires requisite knowledge of the PU signal.
  - The probability of error sampling is high.
4. **Waveform-Based Sensing.** This algorithm utilizes known patterns in a wireless system to assist synchronization or other purposes. The class of patterns comprises preambles, mid-ambles, regularly transmitted pilot patterns, spreading sequences etc. A preamble is regarded as a known sequence transmitted before each burst, while a mid-amble is transmitted in the middle of a burst or slot. In the presence of such a pattern, the received signal can be correlated with it for sensing. To this end, the decision metric is as follows:

$$M = \Re\left[\sum_{n=1}^N y(n)s_*(n)\right] \quad (2.6)$$

The \* depicts a conjugation operation. In the absence of the incumbent, the metric attains the value:

$$M = \Re\left[\sum_{n=1}^N w(n)s_*(n)\right] \quad (2.7)$$

In the presence of the incumbent signal, the metric attains a value:

$$M = \sum_{n=1}^N |s(n)|^2 + \Re\left[\sum_{n=1}^N y(n)s_*(n)\right] \quad (2.8)$$

Ultimately, the decision on the presence of the incumbent or primary signal is made by comparing this metric with the threshold  $\lambda_0$ . This sensing algorithm out performs energy detector based sensing with regards to issues such as reliability and convergence time. Thus the main benefit of this method is that it requires a relatively short measurement time. On the limitation side the algorithm is susceptible to synchronization errors [26].

5. **Radio Identification-based Sensing.** In Radio Identification-based sensing, several features are duly extracted from the received signal and are subsequently utilized in the selection of the most probable incumbent technology by using various means.
6. **Cooperative Sensing.** The cooperative approach to sensing is considered as a way to mitigate problems that arise in spectrum sensing due to noise uncertainty, fading, and shadowing. The approach has always been known to reduce the probabilities of mis-detection and false alarm considerably. Furthermore cooperative sensing can solve the hidden user problem and can subsequently decrease sensing time. The approach is, however, considered complex in that there is need to utilize a user control channel to share spectrum sensing results. The collaborative spectrum sensing is most effective when collaborating cognitive radios observe independent fading or shadowing [9]. From an implementation perspective, cooperative sensing can be achieved in two ways namely centralized and decentralized.

- Centralized Spectrum Sensing: The configuration is such that a central unit collects all the information from CRs, identifies and broadcasts opportunity information. In the event of the number of users being large, hard decisions are adopted so as not to waste bandwidth with opportunity information. An alternative threshold can be employed to test the reliability of the data and censor some of the users.
  - Decentralized Spectrum Sensing: This approach involves CR nodes sharing information through local communities so as to make their own decisions as to which part or portion of the spectrum is usable. This approach is less costly given that it does not require any backbone infrastructure. To this end, unlike the other approach decentralized spectrum sensing requires no dedicated Access Points (AP) to gather all the information. A fundamental challenge facing this approach is that of coordination among users to the extent that it is preferable sharing the final decision instead of sensing information.
7. Interference Based Sensing. The interference temperature model is a brain-child of the Federal Communications Council (FCC). The model strives to regulate interference at the receivers. The algorithm achieves its function by setting an upper limit in interference power for a given frequency band in specific geographic location such that CR users are not allowed to create harmful interference while using the specific band in a specific locality [274, 273, 34, 124]. Certainly in practical terms this translates to CR having to measure the interference temperature in a manner that avoids them raising the interference temperature above the stipulated limit. Consequently secondary users can coexist with primary users so long as they do not exceed the marked interference temperature limit. A major benefit of this algorithm is that it can avoid the hidden terminal problem. On the flip side, the same algorithm has limitations as follows:
- (a) Measuring the interference temperature is a challenging task.
  - (b) In the course of detection, CR has no ability to distinguish between the actual signals from the primary users from the noise or interference [280].

In this subsection we have given an overview of common spectrum sensing algorithms as well as the merits and demerits of the algorithms. In table 2.1 a summary of the energy detection, feature detection, matched filtering and coherent detection, cooperative detection, and interference based detection algorithms is presented.

Table 2.1: Summary of Sensing Algorithms

<b>Algorithm</b>	<b>Test Statistics</b>	<b>Merits</b>	<b>Limitation</b>
Energy Detection	Energy of received Signal samples.	-Easy to implement.  - No need for prior information about PU signal.	-Huge false alarm due to noise uncertainty.  -Unreliable in low SNR. -Fails to distinguish PU signal from other sources.
Feature detection	Cyclic spectrum density function Personal Area Networks (LR-WPAN).	- Increased robustness and better detection in low SNR compared energy detection -Can distinguish between numerous types of transmissions and PU systems Control.	Cyclostationary features must be associated with PU signals.  -Special features may need to be introduced e.g. OFDM based communications.
Matched filtering and Coherent detection	Cyclic spectrum density function.	More robust to noise uncertainty and better detection in low SNR Interference management Coordination of wireless technologies Few signal samples.	Accurate information about PU wave forms a prerequisite.  -High complexity.
Cooperative detection	Energy of received signal.	Lower detection sensitivity. Reduced detection time.	- Increased overhead of CRN WiMAX. - CR are low cost and may lack dedicated hardware for cooperation. -Cooperation detection needs control channel.
Interference based detection	Interference temperature .	Ability to circumvent hidden node problem.	Challenging to measure interference temperature.  Hard to distinguish PU signal from noise or interference.

**2.4.4 Spectrum Decision.** . The sensing process identifies the spectra. Once the available spectra have been identified, the task before the CR user is that of selecting available bands according to QoS parameters. A decision model is required for spectrum access. Akyildiz et.al [11] decision model involves jointly undertaking spectrum selection and route formation. Furthermore the main functionalities required for spectrum decision are:

- **Spectrum characterization.** The cognitive radio user, will through observation of spectra, then characterize, the available spectra by considering such parameters as signal strength, interference, and number of users currently resident in that spectrum.
- **Spectrum selection.** The tendency by CR users is to allocate the best possible spectrum to satisfy the QoS requirements. In a communication session there exists multiple hops with heterogeneous spectrum availability, thus spectrum allocation is intertwined with routing protocols in determining the best combination of route and spectrum. A joint spectrum and routing decision method is imperative in the context of cognitive radio networks.
- **Routing Protocol.** The present scenario with on-demand routing protocols is that in which a common control channel is employed for the setup phase as well the shortest route metric, in a changed scenario involving multichannel and CR environment. Clearly sweeping changes such as radically new metrics are needed as well as optimization functions that collectively characterize spectrum opportunity are needed. In the route setup, the main decision is that of choosing between allowing the path to circumvent the affected PU activity region, or alternatively changing the spectrum so as to sustain the same direction towards the destination.
- **Reconfiguration.** Spectrum decision is not only limited to route and spectrum selection, but also extends to reconfiguration of CR users. Consequently CR users do reconfigure the communication protocol as well as communication hardware together with RF front-end in accordance with the radio environment and user QoS requirements [22]. To this end, suitably adaptive protocols have been formulated to determine the transmission power as well as the best combination of modulation and error correction code for a new spectrum band by considering variations in propagation loss.

**2.4.5 Spectrum Mobility.** The process by which a Cognitive radio user is allowed to change its operating frequency is referred to as spectrum mobility. Cognitive radio networks strive to use the dynamically changing spectrum by allowing radio terminals to operate in the best available frequency band, so as to sustain transparent communication as they migrate to an alternative frequency. Objectively, spectrum mobility in Cognitive radio networks strives to perform seamless channel switch-over while sustaining performance of ongoing SU communication [61]. Moreover, it is inferred from [175], that despite its importance, mobility is still largely an unexplored in the context of dynamic spectrum access. In this section, we present techniques that are presented in the literature as enhancing the process of spectrum mobility.

**2.4.6 Spectrum sharing.** Spectrum sharing encompasses several techniques such as administrative, technical and market based. A multi-dimensional spectrum sharing is feasible across time,

space and geography. The multi-dimensional spectrum sharing is made feasible via diverse approaches such as in-band sharing, leasing and spectrum trading, and use of unlicensed spectrum commons combined with the use of low power radios or advanced radio technologies including ultra-wide-band and multi-modal radios. Any framework at international, national and regional level will employ the spectrum management mechanisms ranging from:

- Common and control
- Market based
- Flexible Spectrum management
- Spectrum Sharing (overlay and underlay)
- Spectrum commons

The following subsections attempt to explain the different spectrum management approaches [77].

1. **Market-based:** This approach makes use of markets to improve access. It is generally envisaged that economically efficient use of spectrum translates to the maximization of the value of outputs produced from available spectrum, including the valuation of public outputs provided by the government or other public authorities. Consequently, spectrum should be allocated in such a way so as to benefit the overall economy. Thus economists believe that market-based approaches such as auctions [116, 117, 62, 260] and spectrum trading [62, 49] are superior to classical (administered) methods with regard to achieving economic efficiency. Market-based approaches make use of auctions or alternatively spectrum rights which are sold or bought over the lifespan of a license. Thus in circumstances of spectrum scarcity, effective and efficient assignments can be determined by market prices. Assuming rationality among the actors within the auction mechanism, a well-designed auction will normally ensure that spectrum goes to those who value it the most. It is thus assumed that the winner is probably the most efficient user of the spectrum. Moreover the winner makes a choice of which service to offer as well as technologies to deploy. Also from a Spectrum trading perspective, economically efficient utilization of spectrum is guaranteed on the premise that trade is feasible only when the spectrum is worthy more to the new user than it was to the old user. Ultimately spectrum trading greatly contributes to economic efficiency on the assumption that the players make good judgments, are rational in terms of behaviour, and that external effects are not adverse.
2. **Spectrum Commons:** Spectrum Commons depicts a spectrum band in which there is non-exclusive utilization of spectrum [155, 121, 46]. This is to say there is certainly no central authority to dictate who can or who cannot operate on the band. Apparently anyone can transmit without a license thereby justifying the commonly referred to name license exempt or unlicensed spectrum. Perceptions on the commonality of bands tend to differ, for example the Industrial Scientific and Medical (ISM) band is a spectrum common which imposes power restrictions on individual users. In Europe the perception is that of further

control in which devices transmitting must conform to technology standards. The commons notion has helped nurture tremendous innovations such as Wi-Fi by calling on proponents to call for more unlicensed bands [297]. In summary, Lehr and Crowcroft [155] assert that spectrum commons renders feasible:

- Shared -multiple devices with heterogeneous technologies and applications share spectrum access-multiplicity of power levels, bandwidth requirements, and duration which is
  - non exclusive use
  - commons
  - unlicensed
  - free
3. **Spectrum Sharing:** In the general case, efficient spectrum utilization translates to the fullest possible spectrum use of the available spectrum. Currently two yardstick measures are utilized in measuring technical spectrum efficiency
- Occupancy: This measure is exemplified by using time in determining technical efficiency in the sense of how constant or how heavy the usage is over a period of time.
  - Data rate: Signified by how much can be transmitted using a given amount of spectrum capacity

In the quest for more spectrum access and in the name of efficient spectrum use, the spectrum can be optimized in few but significantly meaningful, ways being:

- **Underlay Technology:** In this spectrum sharing scenario, technologies with low spectral density are permitted to coexist as secondary users, with incumbent (primary) users of the frequency band. Incumbent users deploy systems with high power density levels and are as a result not perturbed by the low power density underlay systems.
- **Overlay Technology:** The Overlay sharing approach is feasible in two ways namely the passive and active way. The former entails an Amateur service which has shared spectrum with various entities say in government and requires the users to look for radio channel that is free. The latter are increasingly becoming a realistic scenario.
- **Dynamic Spectrum access:** This approach involves unitizing spectrum in terms of time slots or geographical location. This enables users to have access to a particular spectrum block for a defined time period or in a specific area. In essence the number of potential users of a particular frequency are multiplied by factors of time and geographical space. Practically, DSA involves:
  - Monitoring to detect unused frequencies
  - Communicating and agreeing with other devices on which frequencies should be used
  - Monitoring frequency use by others

- Changing Frequency bands and adjusting power as needed

To effectively harvest maximal spectrum, this technique must contend with challenges such as interference, the quality of service level agreements as well as regulatory frameworks. However, new spectrum sharing models are constantly being developed and in the next subsection we present some of the more recent approaches.

## 2.5 Optimisation Techniques

- **Artificial Neural Network:** Owing to their capacity to dynamically adapt and be trained at any time, Artificial Neural Networks (ANN) are able to learn patterns, features, and attributes of the system they describe. With respect to the learning capability, the neurons stored in computer memory can have their outputs systematically adjusted to give a new result which correlates with the new situation. Neural networks have long been utilized in the characterization of functions, processes, or classes that are otherwise difficult to analytically formulate. Consequently the ANN can be employed in the classification or recognition of received stimuli as well as to assist with adaptation process [112]. Furthermore, ANN has been adapted for spectrum sensing, classification, radio parameter adaptation and transmission classification.
- **Fuzzy logic:** A fuzzy-based approach is able to get a solution in a context characterized by uncertain, incomplete and heterogeneous information. Fuzzy logic is a mathematical tool particularly appropriate to make decisions in situations where the available inputs are in general uncertain and imprecise or qualitatively interpreted [98]. Furthermore Guipponi and Perez-Neira [98] fuzzy logic is proposed for the generic knowledge and control implementation base for the cross layer optimization in cognitive radios. This is realized by describing the parameter values of the systems on different layers as linguistic variables. Link layer information is then obtained by way of measurements with the upper layers having to interpret cross-layer information. Cross-layer optimization is also applied to a scenario for channel selection [12],[237] wherein the most appropriate SU to access the spectrum by virtue of efficiency and its proximity from PU. Further efforts are recorded in [134] wherein a fuzzy logic-based algorithm is applied in channel selection in Wireless Regional Area Network. Elsewhere the Lala et al [154] considered eighteen parameters that influence Quality of Service (QoS). In pursuit of a better understanding of QOS the parameters are narrowed down to three namely throughput, delay and mobility and are analyzed using fuzzy based logic.
- **Genetic algorithms:** Genetic Algorithms (GAs) belong to the category of evolutionary computing which is a rapidly emerging area of Artificial Intelligence. A genetic algorithm is a biological inspired heuristic search technique that mimics the process of natural evolution. It's regarded as an adapted solution for optimization problems. In the context of, GAs are deployed in the cognitive engine to solve multi-objective optimization problem and to configure parameters when the environment changes. Rieser [219] emphasizes the importance of GAs in CR problems as they offer a range

of options and flexibility as the CR encounters a dynamic environments as well as situations that also include radio upgrades. This assertion is realized in [210] when a GA is utilized for CR wherein a proposal made for a resource manager to select an appropriate algorithm from a toolbox to solve problems.

#### 4. Spectrum Access through Auctions

Auctions are premised on the concept of buying and selling of goods and services. Intuitively the objective of employing auctions in CR is to provide a motivation for SUs to maximize their spectrum usage. The dynamic spectrum allocation based on auctions has become a topical issue for both academic research and industrial community. The practice renders feasible the leasing of unused PU bands to unlicensed SUs. Intuitively, in an SU market, a PU leases its idle spectrum chunks (channels) to SUs through auctions. Subsequently SUs submit bids for channels, and pay the PU a price to access a channel if their bids are successful. Spectrum auction design has the following properties:

- **Efficiency:** this involves maximizing social welfare, the aggregation, 'happiness' of everyone in the system. When an auction is efficient it tends to allocate the spectrum (channels) to SUs who value them the most.
- **Truthfulness:** Truthfulness is an imperative if market manipulations are to be resisted and this subsequently ensures auction fairness as well as efficiency. In untruthful auctions selfish bidders can manipulate their bids to game the system and obtain outcomes that favour themselves while hurting others [300]. Ultimately, when auctions are truthful, the dominant strategy is for bidders to bid truthfully, thereby eliminating the fear for market manipulation and the overhead of strategizing over others [301].
- **Individual Rationality:** each participant in the auction can expect a non-negative profit [277].
- **Time Complexity:** This tends to be a widely ignored property in most works[182]. The time complexity of an (auction) algorithm quantifies the amount of it takes to run a function of size of the input to the problem. Subsequently an algorithm that exhibits low time complexity is considered computationally tractable.

From both a practical and theoretical perspective there exist a number of forms of auction, which can be classified on the basis of market structure as:

- One-seller-Multiple buyer Cognitive radio
- One buyer-multiple sellers
- Multiple buyers-multiple sellers
- Ascending bid auction
- Descending bid auction
- Sealed bid auction
- **English Auction:** This kind of auction falls into the category of open ascending-bid auctions. The auction involves a beginning at a low price. The bidders raise their bids

until no-body is willing to bid higher [36]. From a mathematical perspective, when the commodity is sold, the hammer price  $p$  should satisfy the condition  $f_0(w) \leq p \leq \max_{b_i \in B} G(b_i)$  where  $f_0(w)$  is the seller's valuation of the auction commodity  $w$ . This is the lowest price at which the seller can accept to sell it,  $B$  is the set of bidders, and  $G(b_i)$  is buyer  $b_i$ 's budget. Hence, the hammer price may not necessarily equal the winning buyer  $b_i$ 's valuation  $f_i(w)$ . The price is thus a function of the level of competition in the auction. The optimal strategy in an English auction is to bid up to one one's value, staying in the auction until the bids exceeds one's value.

- **Dutch Auction:** This form of auction derives its name from its use in flower markets in Holland. The auctioneer usually commences with the highest value which he/she gradually reduces with time. The very first bidder to accept the offered price wins.
- **Double Auction:** This type of auction is a hybrid of some sort wherein participants are buyers and sellers in the same time and trade on the same product as in [283, 290, 71, 266]. Compared to other auctions this is a more practical form of auction widely deployed in real world markets, e.g., stock markets. In terms of functionality, the auction is conducted as follows. The auctioneer being the authority figure, collects asks and bids from buyers and sellers. The next step is to match the asks and bids by allocating auction commodities from sellers and buyers as well as payments from the buyers to the sellers accordingly [294]. This matching process is known as a market clearing process. A number of algorithms such as the ones in [162, 282, 281] are available for the market clearing process.
- **First Sealed Bid auction:** This form of auction does not give buyers the opportunity to call out prices. Instead, bids are privately submitted without the knowledge of other buyer's bidding strategies. Two categories of this auction form exist as first and second sealed bid respectively. The former has a scenario in which one should bid one's value an amount that depends on how many bidders there are. The more bidders, the closer to one's value that one should bid [294]. Subsequently there is a trade-off between profit and the frequency.
- **Second sealed-bid auction (Vickrey):** The winner pays the highest losing bid. It suffices to bid one's value in this form of auction.
- **Combinatorial auction:** Combinatorial auctions are best suited for scenarios in which buyers have an interest in buying a basket or a structured combination of heterogeneous commodities [3, 153]. Buyers kick-start the process by requesting a set of multiple auction commodities. The reality is that commodities may be partly allocated or in some instances fully allocated. Hence each buyer is comfortable with some of the requested commodities received. Other buyers may require nothing less than the full set. An algorithm is then invoked to achieve optimal commodity allocation [203, 65, 224, 225, 91, 298, 66].

## 5. Spectrum access: Game theoretical perspective

The mismatch between the increasing demands of wireless spectra and limited radio resources poses an imminent challenge in efficient spectrum sharing. In the quest towards achieving efficient dynamic spectrum access, numerous hurdles such as, the unreliable and

broadcast nature of wireless channels, user mobility and topology, various network infrastructures, and most important network users behaviours must be overcome. Consequently the intelligent behaviours and interactions must be analysed [251] and game theory is a candidate tool for such a task. Game theory can be defined as a mathematical framework which consists of models and techniques that are used to analyze the iterative decisions behaviour of individuals concerned about their own specific benefit. The benefits of a game theoretical approach to dynamic spectrum access are manifold.

- By modelling dynamic spectrum sharing among network users (PU and SUs) as games, the network user's behaviours and actions can be analyzed in a formalized game structure, by which the theoretical achievements in game theory can be fully utilized.
- Game theory equips us with various optimality criteria for the spectrum sharing problem.
- Non-cooperative game theory is one of the most important game theories, makes it feasible for us to derive efficient distributed approaches for dynamic spectrum sharing using only local information.

In the game theory approach to spectrum access, two game categories are known to exist, cooperative and non-cooperative. In the former, all players are concerned about the overall benefits and they are not very worried about their own personal benefits. The latter has players that are only concerned about their own personal payoff and therefore all the decisions are made competitively and moreover selfishly [19]. Associated with all game categories are some fundamental evaluation concepts which are enumerated as follows:

- **Nash Equilibrium** : Nash Equilibrium (N.E) is arguably the most popular and widely used concept in game theoretic analysis. Attainment of this property (if it exists in a game), means each player is assumed to be aware of the equivalent strategies of other players, and none of the players stands to gain by changing its own strategy.
- **Parento Optimal**: This particular property is named after Vilfred Parento. From a practical perspective, a situation is said to be parento efficient if there is no way to re-arrange things to make at least one player better off without making any other player worse off [129, 119].

In summary a comparison of the merits and demerits of these optimisation techniques is presented in table 2.2 The urgent need to access more of the precious spectrum has inspired efforts within academia, industrial as well as research and development institutions to explore from a game theoretic perspective how additional spectrum can be harvested by way of Dynamic spectrum access techniques. Previous [110], recent [186, 126, 38] as well as current efforts [128, 288, 178] certainly attest to this claim. In all instances different scenarios are being explored, for instance in [110] a scenario is premised on the PUs being aware of both their environment and SUs existing within the vicinity. The game plan is that of PUs taking the role of leader and subsequently selecting a subset of SUs and granting them spectrum access. An alternative set up is considered [190] wherein a PU shares with multiple SUs. The formulation is within the context of an oligopoly market and utilizes non cooperative game to satisfy SU demand requirements. There are however, a number of

opportunities to explore this oligopoly scenario using different formulations such as Cournot, Bertrand, Repeated game, Stackelberg [97] and other game forms.

## 6. Recent Spectrum Sharing models

Research efforts in organizations around the globe have yielded new models especially in Europe and America [170].

- **EC Sharing models:** In Europe, the European Commission has identified two approaches namely:
  - **Licensed Shared Access (LSA):** A regulatory approach which strives to facilitate the introduction of radio communication systems operated by a limited number of licenses under an individual licensing regime in a frequency band already assigned or expected to be assigned to one or more incumbent users. Under the licensed shared Access (LSA) approach, the additional users are authorized to use the spectrum in accordance with sharing rules in their rights of use of spectrum, thereby allowing all authorized users, including incumbents, to provide a certain Quality of Service (QoS).
  - **Collective Use of Spectrum (CUS):** The approach is a modality which allows an unlimited number of independent users and/or devices to access spectrum in the same range of designated CUS frequencies at the same time and in particular geographic area under a well defined set of conditions.

In respect of LSA, its practical implication translates to a primary user being able to share its assigned spectrum with new or several other users as long its acting within the confines of the stipulated rules. The stated conditions are a product of the negotiation between the primary and secondary user. Both parties PU and SU are protected from harmful interference as well as predictable QoS. In contrast, CUS is a kind of free for all given that it is based on general authorization and does not limit the number of users. Practically, any suitable device can utilize the spectrum and this can certainly be a chaotic setup. In light of this seemingly chaotic potential situation, It is absolutely essential to have a reliable coordination mechanism. This coordination mechanism will require the design and formulation of suitably reliable algorithms to handle spectrum sharing. Such algorithms are currently not available. Furthermore the implication of this model is that it cannot be relied upon to handle real-time traffic.

- **United States of America Sharing models:** The approach is articulated in a document authored by the President's council of advisors on Science and Technology (PCAST). In the document, a proposal is made for the use of a Geolocation database to enable reservation based dynamic sharing. The system is called the Federal Spectrum Access System (SAS) will support a three level spectrum usage, comprising the PU, SU and Tertiary User (TU). The three level approach is designed to ensure maximum utilisation of the spectrum independent of who is formally licensed to use the spectrum in the first two tiers.

Table 2.2: Comparison of Optimisation Techniques

<b>Technique</b>	<b>Merits</b>	<b>Demerits</b>
Neural Networks	<ul style="list-style-type: none"> <li>-less memory needed</li> <li>-Quick</li> <li>-Easily scalable</li> <li>-excellent for classification</li> </ul>	<ul style="list-style-type: none"> <li>-Complex</li> <li>-Requires training</li> </ul>
Fuzzy Logic	<ul style="list-style-type: none"> <li>-Applicable to systems that are difficult to model.</li> <li>-Simple implementation and interpretation</li> <li>-Good for device control with unclear quality boundaries</li> </ul>	<ul style="list-style-type: none"> <li>-Stability, accuracy and optimality of system are not guaranteed.</li> <li>-Performance is measured a posteriori</li> <li>-Settings are made by trials or errors</li> </ul>
Genetic Algorithms	<ul style="list-style-type: none"> <li>-Parallel processing</li> <li>-Simple calculation because they just use function to be optimised</li> </ul>	<ul style="list-style-type: none"> <li>-Slow</li> </ul>
Auction Theory	<ul style="list-style-type: none"> <li>-Simplicity equitables and transparent</li> </ul>	<ul style="list-style-type: none"> <li>-Licence fees high.</li> </ul>
Game Theory	<ul style="list-style-type: none"> <li>-Easy reading of the outcomes strategies.</li> <li>-Model agent's behaviour in saturation of choice.</li> </ul>	<ul style="list-style-type: none"> <li>-High cost</li> <li>-Does not make rational choice</li> </ul>
Markov Models	<ul style="list-style-type: none"> <li>-Modelling complicated processes</li> <li>-Prediction from experience</li> <li>-Well for classification</li> </ul>	<ul style="list-style-type: none"> <li>-Does not take into account the hidden states</li> <li>-cannot deal with large number of states</li> </ul>
Multi agent systems	<ul style="list-style-type: none"> <li>-Modularity</li> <li>-Quick</li> <li>-Reliability and flexibility</li> </ul>	<ul style="list-style-type: none"> <li>-High cost</li> <li>-Lack of software support</li> <li>-Lack of methods</li> </ul>

## 2.6 Overview of White Space Standards

The IEEE 802 is an assortment of communication standards concerned with local as well as metropolitan networks. In line with the vision and promotion of the TVWS networking paradigm, standardization efforts have seen the genesis of unique standards specific to TVWS networking. To this end, the results of these current standardization efforts include (but are not limited to) the following standards

- IEEE 802.22 for long range Wireless Regional Area Networks (WRAN).
- IEEE 802.11af is a white space version of Wi-Fi.
- IEEE 802.19 for co-existence among multiple TV white space networks.
- ECMA 392 is aimed at personal and portable wireless devices.
- Weightless mainly focused on Machine-to-Machine (M2M) interactions
- IETF PAWS covering the specification of the mechanism for discovering white spaces and a method for its access.

In the following subsections we present a brief overview and discussion of some of the wireless standards in TV White Spaces shown in Figure 2.8 such as IEEE 802.22, IEEE 802.19, ECMA 392 as well as Weightless. We conclude this section with a summary of more TVWS standards in Table 2.4 where we focus mainly on the brief description, target applications, strengths, and limitations [256].

**2.6.1 IEEE 802.22.** IEEE 802.22 is the first worldwide effort to define a standardized air interface based on CR techniques for the opportunistic use of TV bands on a non-interfering basis. The primary goal of IEEE 802.22 is to use cognitive radio techniques to enable the sharing of geographically unused spectrum allocated to TV broadcast services to build Wireless Regional Area Networks (WRAN), to deliver broadband wireless access in rural and remote areas. Other crucial markets for this standard include single family residential, multi-dwelling units, Small Office/Home Office (SOHO), small businesses, multi-tenant buildings as well as public and private campus. In terms of service coverage the standard is capable of facilitating access ranging from a minimum of 10 km to a maximum of 100 km. The standard also specifies a topology-based on a point to multi-point wireless interface. The point corresponds to a Base station (BS) and the multi-points are Consumer Premise Equipments (CPEs). The BS can serve up to about 255 fixed CPE units with outdoor directional antennas at nominally 10 m above ground level [255]. The target service capacity is to deliver a minimum throughput of about 1.5 Mb/s in the downstream direction to a CPE at the edge of the coverage and 354 kb/s in the upstream direction, comparable to Digital Subscriber Line (DSL) services. IEEE 802.22 requires two separate antennas at each CPE: one directional and one omni-directional. The directional antenna is pointed towards the base station and is used for communication purposes while the omni-directional antenna is required for sensing purposes. Ongoing efforts [217, 214] have updated the IEEE 802.22 standard. This standard is a welcome development in that it complements the fibre optic network as well as

## Wireless Standards

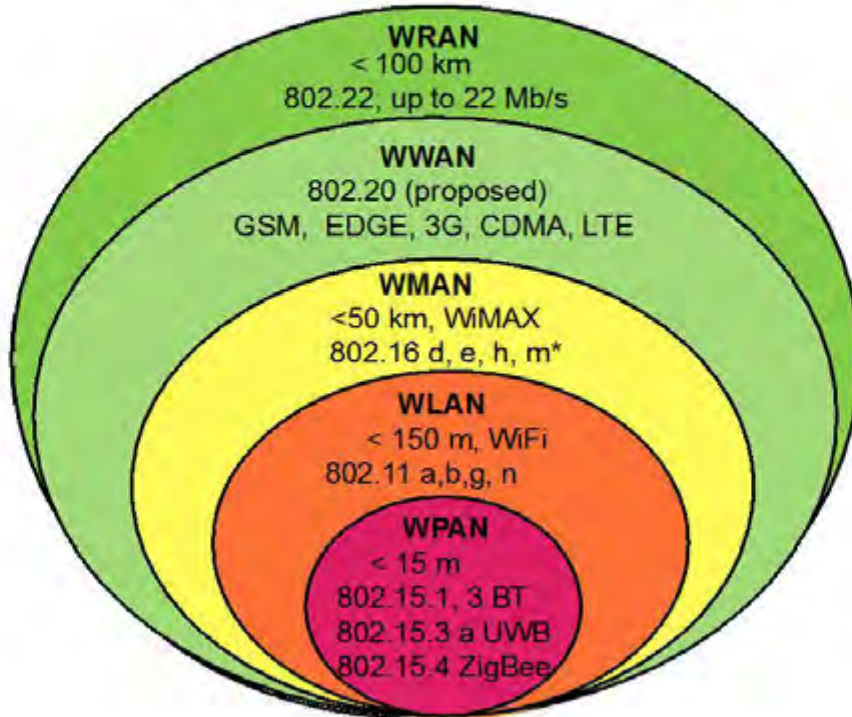


Figure 2.8: Geographical range for some TV White Space wireless standards (Source: [211]). [Wireless regional Area Network (WRAN) Wireless Personal Area Network (WPAN), Wireless Local Area Network (WLAN), Wireless Metropolitan Area Network(WMAN), Wireless Wide Area Network(WWAN)]

IEEE 802.16 efforts especially in the developing world where according to [199] some 341 million people in sub-Saharan Africa lived beyond a 50 km range of a terrestrial fibre optic network. To this end, a range of 100km is more than welcome and is set to reduce the digital divide. Furthermore this will most likely catalyse a bandwidth price decrease and consequently increase broadband uptake. IEEE 802.22 does not specify implicit support for multi-hop networks, but it can be useful cases of mesh networking aiming to establish regional networks. The adoption of this standard alone cannot be regarded as a sole solution to the broadband challenge, for example the question arises as to what happens if multiple telecommunication players decide to all setup their own WRAN. Already deployment efforts aimed at implementing WRANS have revealed self-co-existence and the hidden incumbent problems as being the two major challenges facing wireless regional area networks. The IEEE 802.19 standard in the next subsection is formulated to address the self-co-existence problem.

**2.6.2 IEEE 802.19.** When multiple TVWS networks are brought together, the implication is that of multiple TVWS standards coexisting together and this creates a challenge. The IEEE 802.19 is thus formulated to handle the so-called self-coexistence problem which is associated with challenges posed by similar TVWS based systems in the same geographical area. To this

end, the standard specifies a radio technology that allows co-existence among dissimilar or independently operated TV Band Device (TVBD) networks and dissimilar TVBDs [35, 135]. The IEEE 802.19 standard architecture comprises of the logical entities shown in Figure 2.9. IEEE 802.19 coexistence mechanisms exist to enable the co-existence of multiple TVBD networks in TV white spaces and minimize (and control) interference. Interference prevention is the major concern with the use of TVWS. Two independent co-existence mechanisms exist to support information exchange relevant to the co-existence of TVBD networks in TVWS, one distributed and one centralized [263]. The former implements beacon transmission via a wireless broadcast channel and has a plug and play feature. The latter uses a centralized database which acts as a repository to the aforementioned information and is handled by a co-existence provider. The beacon approach has not been endorsed by FCC or OFCOM both of which have chosen the database approach as the only acceptable method.

The IEEE 802.19 standard points to the high possibility of integrating new TVWS networks with the back-haul networks that are already in existence and also to a mechanism for mitigating interference. On the other hand, this simplifies the task and cost of infrastructure development especially when both under and overlay networks are deployed. Moreover, over coexistence is desirable for short range transmissions. Intuitively, multiple coexistence scenarios will if well planned and implemented present business opportunities as this amounts to a market like environment. The flip-side to this standard is that there may be undesirable overhead when network devices are burdened with coexistence support mechanisms. An interesting scenario may also be that the market may have the leeway to decide on which mechanism is best suited to the clientele. Ultimately as a way of refining and improving this standard, more research still needs to be carried out to comprehend usage scenarios from a TVWS perspective in both the technical and business contexts.

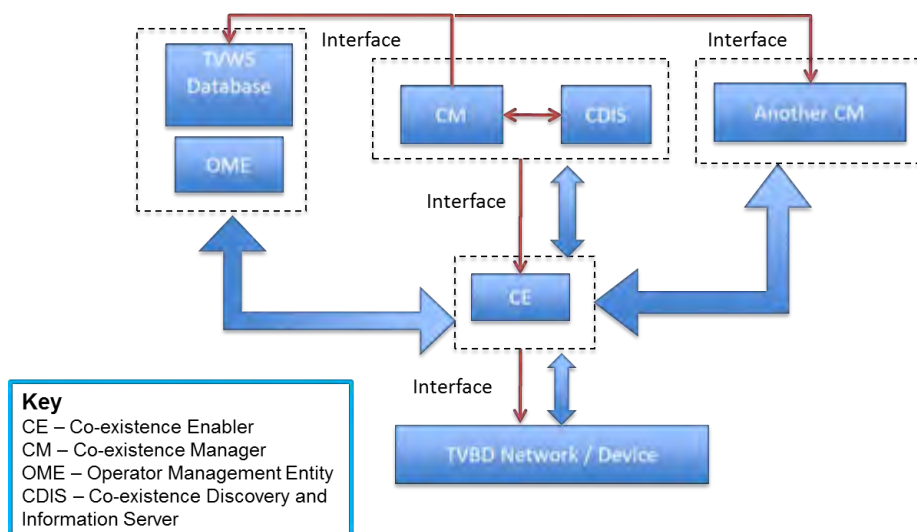


Figure 2.9: IEEE 802.19 Architecture (Source [35])

Table 2.3 presents the logical entities of the IEEE 802.19 architecture with their corresponding functions.

Table 2.3: 802.19 Entities and their functions

Entity	Function
Co-existence Manager (CM)	Discovers other co-existence managers
	Makes co- existence decisions in order to solve co-existence problems among TVWS networks Supports interfaces for the co-existence discovery and information server Supports o-existence commands and control information to co-existence enablers
Co-existence Enabler (CE)	Interface between CM and TVWS networks Translates reconfiguring commands and sending them to TVWS network
Co-existence Discovery and Information Server	Structures the information to be stored in a repository deployed over the Internet Supports the discovery of CM by making the information relevant to co-existence accessible

In particular, the mechanisms proposed to deal with self-co-existence fail to solve the co-existence problem for cognitive radio systems operating under different radio communication standards.

**2.6.3 ECMA 392.** ECMA is a high-speed wireless networking standard for use in the Television White Spaces. The standard makes use of CR to avoid interference with licensed services and other incumbent users in compliance with the Federal Communication Commission (FCC) regulatory rules. The standard strives to deliver more robust wireless connectivity, by extending coverage range as well as offering cost effective networking solutions, both indoors and outdoors. To this end, targeted applications for this standard will encompass in-home high-definition multimedia networking and distribution as well as Internet access for communities.

**2.6.4 Weightless.** A TVWS standard for machine-to-machine communication using TVWS spectrum in the 450-800 MHz range [269]. Currently a new version 1.0 has been developed and will be used as basis for producing inter-operable products. From the perspective of the Weightless Special Interest Group (SIG) this is a ground-breaking cost-saving akin to Bluetooth in wireless personal area network [5]. Another group had previously argued that a common M2M standard for TVWS would drive down the cost of TVWS chipsets to less than 2 dollars. The merits of using TVWS are that the low frequency spectrum has a wider range of coverage up to about 10km as well as high building penetrative capability. Weightless is a global, open, FRAND-Z standard, meaning fair, reasonable, non-discriminatory and zero cost. The Weightless standard certainly complements the IEEE 802.22 standard for TVWS-based Wireless Regional Area Networks (WRANs), which has been designed to deliver 22-29 Mbps over a radius of 10-30 kilometers. While 802.22 is designed to support high-bandwidth, high-power terminals and a relatively small number of users per base station, Weightless is aimed primarily at M2M services that require low bandwidth and low-power terminals and can serve many thousands of devices per base station. To this end, results of this standard have already been rolled-out such as (Iceni chip) of this standard. The chip is capable of tuning across the entire UHF TV white space spectrum (470 – 790 MHz), it draws negligible power while delivering reliable, secure, long range wireless connectivity for next generation M2M applications using the Weightless Standard [269] . One implication of this standard is that it is likely to bring to fruition the notion and idea of smart cities, for example in the transport sector, the quest for smart parking could be achieved through this standard. In the smart parking scenario each parking space is monitored and cars directed

to specific empty spaces as they enter a city or premise. Also in the health sector, telemedicine could be further advanced through this standard, for example sensor devices in pill dispensers, diabetes monitors, scales, heart rate monitors are all linked to external networks. This will be a welcome boost to the Internet of Things (IoT) market as it is estimated to be over a trillion US dollars in value and to enable tens of billions of connected devices by 2020.

## 2.7 Deployment and Use of White Space

Cognitive radio is being touted as the essential enabler for increased spectrum efficiency by finding free spectrum in the TV band called TV White Space. Utilizing TVWS is an emerging technology trend that is fast gaining momentum with leading giants such as Microsoft, Google, etc realizing the potential to offer new innovative services on the market. To this end, network testbeds using cognitive radio platforms are deployed to test the effectiveness of TVWS radio network solutions in real wireless environments [166] in world regions such as Asian pacific, Africa, Europe, North and South America [72]. In this section, we discuss several deployment scenarios of TVWS implementations [43, 149] as shown in Table 2.5. A brief analysis of Table 2.5 reveals that most of the deployments have been made in the USA, Britain as well as in Singapore. The rest of the efforts are concentrated in Africa with South Africa seemingly being the epicentre of the TVWS efforts in Cape Town and Limpopo provinces. The majority of these efforts are targeted at broadband provision with a few exceptions aimed at public safety and other smart grid applications. Interestingly these efforts implement the IEEE 802.11af standard initiative. However, more key trials, pilots as well as commercial deployments of TVWS are still necessary in order to fully understand the practical challenges, relevance as well as the weaknesses of the standard initiatives. The rest of the efforts are concentrated in Africa with South Africa seemingly being the epicentre of the TVWS efforts in Cape Town and Limpopo provinces. The majority of these efforts are targeted at broadband provision with a few exceptions aimed at public safety and other smart grid applications. Interestingly these efforts implement the IEEE 802.11af standard initiative. However, more key trials, pilots as well as commercial deployments of TVWS are still necessary in order to fully understand the practical challenges, relevance as well as the weaknesses of the standard initiatives.

Table 2.4: Summary of TV White Space Standards

<b>Standard</b>	<b>Project</b>	<b>Scope</b>	<b>Current Status</b>	<b>Timeline</b>
IEEE 802.11af	Medium Access ) Control (MAC))  Physical Layer (PHY	PHY to attain legal requirements and coexistence in TVWS	Actual	Approved by 31December 2013
IEEE 802.15M	Low Rate Wireless Personal Area Networks (LR-WPA)	Specification of PHY for IEEE 802.15.4 for TVWS regulatory requirements in a wide variety of domains as well as any as any necessary MAC	Used by M2M Smart grid Smart Building	Completed September 2014
IEEE DySPAN	Dynamic Spectrum Access networks and related technologies that emphasize the improved use of spectrum. New DSA techniques and methods encompassing management of interference as well as coordination of wireless technologies network management and information sharing among dissimilar technologies.	Dynamic Spectrum Access Interference Management coordination of wireless technologies	P1900.1-7 working groups active	Rev Comm Approval by February July 2015
IEEE 802.16h	Wireless High -speed Unlicensed Metropolitan Area Networks (Wireless-HUMAN)	Specification of improved mechanisms policies, and MAC enhancements to enable coexistence among license exempt systems based on IEEE standard 802.16 and to facilitate co-existence of Primary Users (PUs)	WiMAX	Approved

Table 2.5: Deployment Scenarios of TVWS implementations

<b>Deployment</b>	<b>Outcome</b>	<b>Target</b>	<b>Technology Used</b>
Spectrum Bridge , Claudville, Virginia, USA	Internet provision to both students and teachers at 1Mbps. Residents can now use WiFi capabilities built into their laptops and smart phones to access the Internet.	Broadband Access	Wi-Fi
Plumas-sierra. California, USA	Command and Control access for remote substations. Google provides green energy applications for use by Plumas-Sierra Rural Electric Cooperative and Telecommunications applications for use by Plumas-Sierra Rural Electric (PSREC) customers. Broadband access to remote locations.	Smart grid	Super Wi-Fi
Wilmington, North Carolina, USA	“Smart City” applications. Video security cameras in public/county parks. Video traffic security cameras at major thoroughfares. WiFi access in county parks for the public and city/county workers Monitoring of storm water flow. Connection to security cameras. Support for WiFi access to public schools. Provide data transmission for telemedical applications.	Public safety and Last mile & Wi-Fi	Wi-Fi
Motorola Medford, Oregon  USA	Self-forming video network	Wireless connectivity for fixed and mobile video	WiMAX
Garden by the bay, Meadow  Singapore	Internet connectivity offered in sites such as Supertree, meadow and canopy	Wireless connectivity for visitors	Wi-Fi
Weightless, Cambridge , England	Smart city	Smart electricity meters and other devices	Wi-Fi
Tygerburg, Cape Town, South Africa	Internet provision to ten schools	Broadband access	Wi-Fi
Mawingu Kenya	Internet provision to areas lacking basic electricity	Broadband	Wi-Fi

## 2.8 Research Challenges

Fundamental research challenges still need to be addressed for cost-effective, efficient and scalable deployment of white space. To this end, it may be feasible to accelerate the deployment of white spaces for next generation networks if the following challenges are addressed in the near future.

### 2.8.1 Spectrum Sensing Problem.

**2.8.2 Single TVBD.** Spectrum sensing is the task of finding white spaces by sensing the radio spectrum in the local neighbourhood of a Television Band Device (TVBD) in an unsupervised manner. Specifically FCC rules mandate the detecting of the presence of TV signals and wireless microphone signals at a power level of -114 dBm. However, when the Signal to Noise Ratio is low [238], it becomes unreliable and largely impractical to invoke coherent reception techniques as well as implementing signature sequence acquisition. Moreover energy detection, a technique for detecting signals by comparing with a given threshold is also inappropriate at low Signal-to-Noise Ratio (SNR) values. Spectral correlation analysis techniques also fail because their performance degrades with decreasing SNR. While for Frequency Modulated (FM) wireless microphone signals the cyclostationarity is actually too weak to be exploited. Furthermore the Power Spectral Density (PSD) of these wireless microphones tend to exhibit narrow spikes, which with high probability cannot be produced by white Gaussian noise. The central challenge is that narrow band spikes are also present in received signals without the presence of wireless microphones. These narrow band spikes cause interference and may emanate from spurious and unintentional transmissions. Consequently these interference signals tend to exhibit the same strength as the signal being sensed. Spectrum sensing of wireless microphone signals requires a classification mechanism to help mitigate narrow band interference, otherwise a majority of TV channels will be deemed occupied to an extent that no TVBD will be allowed to operate. The classification problem is two-fold: (i) No technical standard exists among microphone manufacturers, as all design parameters vary considerably among models making it difficult to abstract stable and common features among microphones. (ii) Analogue FM signals basically are continuous carrier waves with gradually changing phase.

**2.8.3 Multiple TVBD Spectrum Sensing.** Efficient and scalable deployment of white space networks require that spectrum sensing capabilities be extended to multiple TVBD that constitute network nodes. To this end, collaborative sensing should be employed to collect ideas from distributed detection and data fusion to jointly process the spectrum sensing statistics from multiple TVBDs (nodes). Furthermore, collaborative sensing can be enhanced if co-channel interference from peer TVBDs is minimized. Circumventing the above problem may require novel ideas such as the development of a quieting protocol which can turn off all TVBD transmission circuitry in a geographic locality for a given period so as to facilitate the sensing of TV/microphone signals. The notion of a quieting protocol also raises the question on demarcating a geographic locality and on how feasible will it be to deal with TVBDs from different heterogeneous networks. To address this aforementioned issue, we need a standard protocol to enable interoperability among heterogeneous networks.

**2.8.4 Spectrum measurement and dynamic spectrum access.** Quite a lot of measurement campaigns have been conducted in both the developing and developed world using both state of

the art spectrum analyzers and low cost RF explorers. This has mainly been aimed at building up a case of inefficient spectrum utilization and subsequent abundant fallow (unused) spectrum in the form of TVWS. In parallel with these efforts have been theoretical efforts on dynamic spectrum access as evidenced by large volume of papers existing in literature. A gap still exists between efforts on measurement and the theoretical dynamic access. This is to say, there is a serious need for models that characterize spectrum utilization while acknowledging the dynamic changes in the channel conditions from either a space, time and geographical perspective.

**2.8.5 Geo-Location.** Recently, notable progress has been made towards understanding how TVWS may be used with regards to regulation, technology and potential services. In the process USA has finalized its rules for using TVWS while the UK and some other few countries are on their way. Consensus is forming around the use of geolocation database to manage access to TVWS and this will likely act as a catalyst to further TVWS rule making. To this end, the FCC has stipulated requirements for both fixed and personal or portable TVBDs in operating mode II for them to be directly connected to the database via the Internet. This will provide information about neighbouring TV/wireless microphone signals and peer TVBDs. However, providing incumbent databases requires knowledge of the locations of TVBDs themselves. Federal Communications Commission (FCC) rules stipulate a precision of fifty metres for TVBDs locations. Fixed TVBDs are easy to deal with because their installation is thoroughly planned to an extent that their location is not a problem. However, obtaining the locations of personal or portable TVBDs is a challenge especially when there is no Global Positioning Service (GPS). From the above perspective, Geo-location is critical for a White Space Device (WSD) to acquire access to spectrum in the short-medium term. However, spectrum sensing is another option in the long-term [232].

- **Database algorithms** A geolocation database uses numerous algorithms in its operation. The ability to determine the proper frequency and transmitting power hinges on the accuracy and precision of database algorithm. A database algorithm is tasked with calculating the maximum allowed power for the WSD. Certainly the closer the database output to optimal value for given location input the better the White Space utilization. An optimal value gives an assurance that white space communications uses maximum allowable transmission power, where primary users systems can still be operated normally [200]. Different national geolocation database administrators should not have to use the same algorithms, given the technical parameters, protection margins or information regarding the incumbent service. Consequently depending upon their specific policies as well as environmental variables, different levels of protection will be required. This indicates a need for more adaptive algorithms.
- **Over Protection of Incumbent** The amount of TVWS is influenced by the protection mechanisms, it becomes little when there is over protection. From a business perspective, the amount of TVWS is a critical factor in decisions that will be made in industry. More importantly in the event that indications are that these TVWS will be available for limited potential customers, there will be no investments in industry to avail dedicated wireless WSD to implement WS functionality in other wireless communication devices such as smart phones, tables or laptop computers.

- **Security** When the WSD devices have to access the database via the Internet, then security concerns arise. WSD and database must thus perform some form of authentication which has to be mutual. The database must be sure, that the device has a right to access TVWS and by the same token the devices have a way of knowing which one of the database is the certified one. To this end, data transfer has to be encrypted and the integrity of geolocation data has to be secured. What happens when the database is a target of Denial of Service (DoS) attack? If there is a security collapsing then the entire system is compromised.
- **RF Architectures** White Space, by its nature, varies across space and time and this presents a fundamental challenge. Specifically the available channels are not contiguous and vary with locality. Moreover, the white space available in a given location can change in the event that one or more TV band primary users start(s)/stop(s) operation. To address this problem, it is imperative to design and develop an architecture that can handle frequent changes with respect to the participating links and devices i.e. map the available white space, retune to a new operating channel or tune away to perform sensing measurements. These measurements in which white spaces are identified are according to [289] an important milestone for the wide deployment of white space based networks. Furthermore, the detection tools used for white space discovery are still either in their infancy stage or too expensive to warrant massive adoption for white space exploitation.

To sum up, it is important to take note of the fact that databases are an essential element in the deployment of White Spaces technology, to be complemented in due course with device-distributed cognitive and sensing technologies.

- **TVWS Optimization models and Traffic Engineering** The prospect of white space frequency as a way of providing wireless broadband communication has led to the emergence of many new optimization techniques borrowing from different research fields including economic markets, evolutionary theory and paradigms and exact mathematical models for white space allocation. However, to the best of our knowledge, these models have neither crossed the research area field to be implemented into products nor even been planned to be integrated into existing traffic and network engineering tools used in real networks. This gap between white space optimization models and their implementation as traffic engineering models need to be addressed through:
  1. Efficient mapping between WS spectrum occupancy into sound broadband bandwidth quantification.
  2. Efficient translations of the proposed resource allocation techniques into traffic and network engineering strategies/techniques.

## 2.9 Conclusion

Next generation networks represent a fundamental departure from the older style of classical networks. NGN are set to provide telecommunication services to users by exploiting multiple broadband, Quality of Service (QoS)-enabled transport technologies in which service related

functions will be independent of the underlying transport related technologies. Network users are set to have unlimited access to networks as well as competing service providers from which they are expected to make choices as to who renders service. Additional NGNs will support generalized mobility which is consistent and ubiquitous provision of services to users. For users to fully benefit from NGNs, the envisaged competition must become a reality. Wireless Mesh Networks have demonstrated a tremendously huge potential to fulfil the requirements of Next Generation Networks (NGN). As alluded to in this chapter, the WMN also face specific design challenges that mainly capacity and scalability. The potential of these WMN can be enhanced by leverage on new technological and regulatory developments. The latter to the freeing of large amount of free spectrum referred to as TV White spaces as well as standardization initiatives such as IEEE 802.22, IEEE 802.19.4m, IEEE 802.11af etc., most of which are now active. The former refers to the technology which has a transformative effect on the telecommunication landscape. The trans-formative effect emanates from its ability to increase capacity by utilizing its ability to learn and adapt to the environment. Subsequently, within the context of WMN, capacity increase will translate to scalability that is the network being able to handle increased connections due to increased capacity due to its ability to utilize white spaces.

### 3. Methodology

The mismatch between the increasing demands of wireless spectra and limited radio resources poses an imminent challenge in efficient spectrum sharing and subsequent wireless network design. To this end, Next Generation wireless networks are considered necessary for the support of emerging services with their increasing requirements. More importantly, NGN will typically be characterized by a distributed, dynamic, self organising architecture [8]. However, the emergence of Cognitive Radio Networks and other associated networks (Ad hoc/Mesh, Sensor networks, LTE, etc), which fall in the category of NGN wireless networks, have given rise to many open issues in network design. Consequently more and more researchers are concentrating their efforts in the design of these future networks [174]. To this end, a fundamental approach during the design and engineering of these NGN communication systems, protocols, algorithms and architectures, is the estimation of their performance, as well as understanding and visualization of the micro and macro behaviour of the systems and their components. Classically, this can be achieved by applying three different methodologies, firstly experiments with real systems and prototypes, secondly analytic techniques and thirdly simulation. Figure 3.1 shows the methodological approach adopted in the design and optimisation of our Cognitive Radio Mesh network.

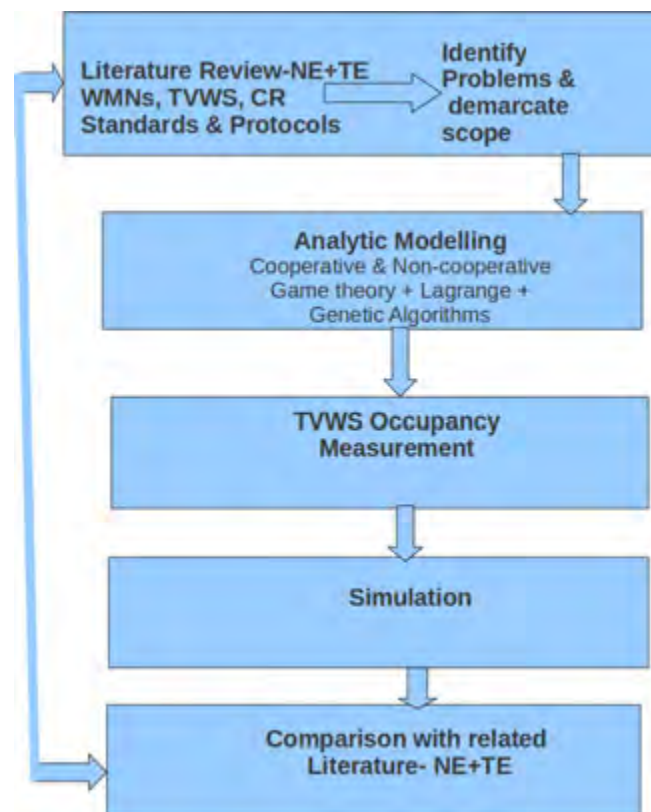


Figure 3.1: Methodology

This chapter is thus structured as follows. Section 3.1 deals with analytic modelling wherein three important theoretic basis for the thesis are optimisation techniques such as game theory, Lagrange

Multiplier, and Genetic algorithms. Section 3.2 presents the TVWS measurement system in the form of hardware and software components. Ultimately, section 3.3 gives an insight into the simulation efforts that are relevant to the thesis.

## 3.1 Analytic Modelling

Analytic tools for network design are currently in the early stages of development. In many ways efforts are at the stage of creating network models which contain enough salient features of the network so that the behaviour of such networks may be predicted from the model behaviour [148]. Within the context of this thesis, several issues need to be taken into consideration for the design of an efficient dynamic spectrum sharing cognitive mesh network and these are: the unreliable and broadcast nature of wireless channels, user mobility and dynamic topology, various network infrastructures, and, most importantly, network users' behaviour. To this end, our analytic modelling leverages game theory, a discipline which strives to model situations in which decision makers have mutual possibly conflicting interests. Moreover, though game theory was initially developed for economics, it is also being extended to the wireless networking design domain. This is because the cooperative and competitive environments in our envisaged cognitive radio mesh network naturally lend themselves to a game theoretic formulation. Furthermore efficient dynamic spectrum sharing can only be achieved if the network users' intelligent behaviours and interactions are to be thoroughly studied and analyzed. Subsequently game theory is an excellent match in nature to dynamic spectrum sharing problems. The importance of studying dynamic spectrum sharing in a game theoretical framework is manifold. Firstly, by modelling dynamic spectrum sharing among network users (Primary and Secondary users) as games, the network users' behaviours and actions can be analyzed in a formalized game structure, by which the theoretical achievements in game theory can be fully utilized. Secondly, game theory equips us with various optimality criteria for the spectrum sharing problem. Specifically, the optimization of spectrum usage in Dynamic Spectrum Access Networks (DSANs) is generally a multi-objective optimization problem, which is very difficult to analyze and solve. Game theory provides us with well defined equilibrium criteria to measure game optimality under various game settings (network scenarios in our context). Thirdly, non-cooperative game theory, one of the most important game theories, enables us to derive efficient distributed approaches for dynamic spectrum sharing using only local information. Such approaches become highly desirable when centralized control is not available or flexible self-organized approaches are necessary. The game in a strategic form is exemplified by an oligopoly. Examples of oligopolies include Cournot, Stackelberg (see Figure 3.2) and Bertrand.

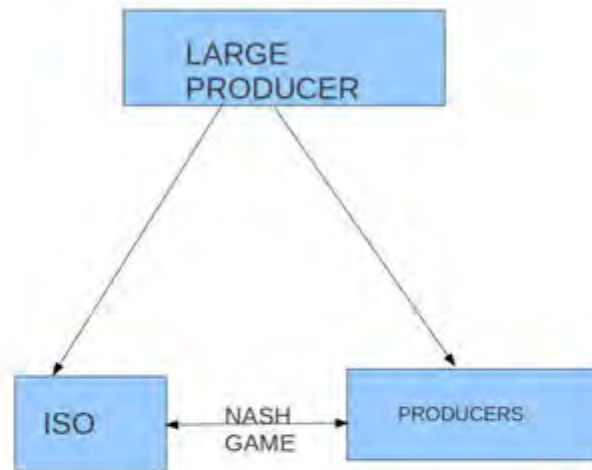


Figure 3.2: *Stackelberg Game between Producers* [156]

**3.1.1 Lagrange Multiplier.** In the analytic modelling phase, the Lagrange multiplier method, named after Joseph Louis Lagrange, provides an alternative method for the constrained non-linear optimization problems. The method is deployed as a strategy to determine the local maxima and minima of a function subject to either equality or inequality constraints [157].

**3.1.2 Genetic Algorithms.** A Genetic Algorithm is an adaptive heuristic search algorithm that mimics the process of natural evolution. In the general case this type of algorithm is deployed when solving optimization and search problems. Thus a genetic algorithm is deployed as an optimization tool of the developed system (envisaged Cognitive radio mesh network) and an appropriate fitness function is developed [85]. Genetic Algorithms fall under the category of evolutionary algorithms which are used to generate the solution of the optimization problems using techniques of natural evolution like inheritance, selection, mutation, and crossover.

## 3.2 TV White Space Occupancy Measurement

The TV White Space measurement system is perceived as a system which comprises hardware and software components.

1. **Hardware Component:** In order to approach the problem of characterizing primary user activity, a tool for monitoring spectrum use was needed. The RF explorer shown in Figure 3.3 is a low cost device which makes use of the energy detection sensing algorithm discussed in chapter 2 in section 2.4.



Figure 3.3: *RF Explorer*

Our low cost RF explorer has the ability to measure frequencies over a frequency range  $240\text{MHz} - 960\text{MHz}$ , display full frequency spectrum in the band including carrier as well as modulated shape [289]. Furthermore the RF explorer device is able to display Spread Spectrum activity if its exist, show bandwidth to monitor collisions, frequency deviation from expected tone, etc. Moreover the RF Explorer model WSUB1G used in the measurement process was fitted with a Nagoya NA-773 wideband telescopic antenna, which has wide band measurement capability. Although a number of commercial instruments are available for this purpose, our choice for the RF explorer is motivated by its low cost which is about 120. Unlike other RF measurement instruments the RF explorer is fully functional as an independent unit though it can be interfaced with the computer for additional features.

2. Software Component: The RF Explorer for Windows PC Client application provides traditional spectrum trace views along with more graphical waterfall views.

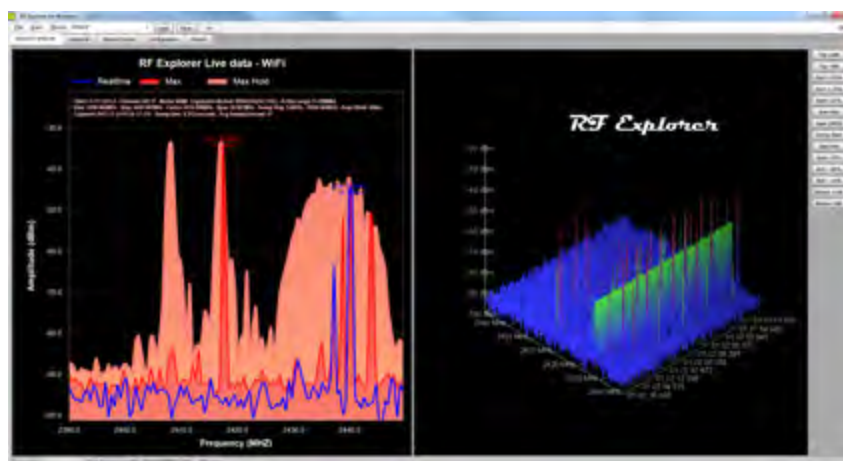


Figure 3.4: *RF Explorer Display [1]*

### 3.3 Simulation

The dynamic spectrum sharing problem is an excellent candidate for discrete event simulation (DES). Discrete event simulation is concerned with the simulation of some system which evolves through time [171]. In the general case, a discrete event simulation is used for systems where the state of a system changes in discrete points in time. A system can change in only a countable number of points in time. A time advance algorithm is relevant in DES and this requires an event list. Practically a simulation clock time will progress only up to that instant when the event is expected to occur. A simulation will generally estimate stochastic, dynamic and discrete model output. In this thesis, for the purpose of validating both our cooperative and non-cooperative analytic models, a discrete event simulator is to be built for the cognitive radio mesh network model. The discrete event simulator is built using C++. Using the simulator built in C++, we will conduct several simulation experiments to analyse the performance of a Time of Day Traffic Engineered (ToD TE) network for different network sizes in section 7.6 and subsection 7.6.3

# 4. System Architecture

## 4.1 Introduction

With the advances in wireless technologies and the explosive growth of the Internet, wireless networks, especially Wireless Mesh Networks (WMNs), are going through an important evolution. Currently wireless mesh networks are fast emerging as a cost-effective technology for providing ubiquitous connectivity to the end user. Typically WMN comprise of mesh routers (MR) forming the backbone of the network, interconnected in an ad hoc manner. Individual MRs can be perceived as access points serving a number of users or clients. Clients can either be mobile users or stationary work stations or laptops that exchange data over the Internet. The clients tend to direct their traffic to MRs which in turn then forwards it to the backbone network in a multi-hop manner, until it reaches the gateway that links to the Internet [60]. However, despite WMNs enhancing performance with flexible network architectures, easy deployment and configuration and fault tolerance, increased network node densities will lower network capacity due to high demand. The ever increasing demand for new wireless services and applications has triggered a corresponding demand for spectrum which is increasing exponentially [229] in the wireless networking domain. Intuitively, the mismatch between the demand for spectrum and the supply has resulted in the spectrum scarcity problem. Consequently, there is a common belief that there is a spectrum scarcity at frequencies that can be used economically for wireless communications. This concern has arisen from the intense competition for use of spectra at frequencies below 3 GHz. The Federal Communications Commission's (FCC) frequency allocation chart indicates overlapping allocations over all of the frequency bands, which reinforces the scarcity mindset [48]. Furthermore, a series of empirical spectrum occupancy studies have revealed a gross under-utilisation of allocated spectrum [289], called White Space (WS). To this end, spectrum scarcity is a consequence of outdated spectrum policies that allow little sharing [205]. Developments in Cognitive radio along with software radio, spectrum sensors, mesh networks, and other emerging technologies can facilitate new forms of spectrum sharing that would greatly improve spectral efficiency and alleviate scarcity, if spectrum policies are in place that support these forms of sharing [206]. However the advent of Dynamic spectrum access (DSA) radio technology increases spectrum sharing and subsequently mitigates the spectrum scarcity problem. CR can help mitigate the spectrum scarcity problem by enabling dynamic spectrum access (DSA), which allows unlicensed users/devices to identify the un-/underutilized portions of licensed spectrum and utilize them opportunistically as long as they do not cause any harmful interference to the legacy spectrum users' communications [243]. Ultimately capacity in Wireless Mesh Networks can be increased by leveraging on technological advancements such as CR and regulatory reforms. The consequence is that of a mode of cognitive radio network that objectively strives to enable a uniform service platform by seamlessly integrating heterogeneous wireless networks through the utilization of advanced and adaptive technologies under a mesh structure [271]. Specifically, a cognitive mesh network should support heterogeneous networks, such as Wi-Fi, WiMAX, Wi-media, Cellular network, Blue-tooth, Wireless sensor network (WSN), Long Term Evolution (LTE), etc.

In this chapter our objective is the design of a system architecture for our envisioned Cognitive Wireless Mesh Network. Specifically standard architectures which we leverage on are described. Owing to the use of a future wireless concept such as CR which targets at a low cost for each of its components, in band sensing, outband sensing as well as not interfering with the PU system. In essence, our envisioned Cognitive Mesh Network should be able to reflect the profit earned by using spectrum in an opportunistic manner to its subscribers. To this end, our system architecture will comprise the system components of the cognitive mesh network, i.e., Primary and Secondary systems, the interfaces (CRs), as well as the relationship between including the behaviour of network nodes. Thus, this chapter leverages on the works on chapters 2 where both wireless mesh networks, TVWS, and cognitive radio systems are discussed as well as the works in chapter 3 that discusses behaviour of Players (nodes).

**4.1.1 Contribution.** Our main contribution in this chapter is a partial response to the first research question: *Can next generation mesh networks be designed to include Cognitive nodes that can learn from their environment and broadcast that information in order to allow the mesh network to optimize its routing performance based on informed decision? Can free spectrum be shared economically over spectrum sharing games.* The contribution is thus a design of a system architecture for sharing the licensed spectrum with multiple cognitive users in a cognitive mesh network as follows:

- a cooperative centralized cognitive radio mesh network architecture wherein a central entity assumes the responsibility of resource management and trading. Specifically the entity gathers information such as spectrum opportunity, demands and subsequently makes a decision on spectrum access, i.e., assignment of TV white spaces and power allocation. Our cooperative centralized architecture wherein full spectrum knowledge is available has nodes working for the common good to improve system utility
- a competitive decentralized architecture wherein there is no central authority and decisions made based on local spectrum knowledge. The nodes are in general selfish and will thus be working to improve their own individual system utility instead of overall network utility. Ultimately, each node is responsible for the spectrum allocation.

The rest of the chapter is organised as follows. Section 4.2 presents a discussion of the main design considerations for our envisaged low cost cognitive wireless mesh network while acknowledging the two possible architectures, i.e., centralized and decentralized. Section 4.3 presents a generic Cognitive Mesh architecture. Section 4.4 details the involvement of a central entity in a centralized architecture while simultaneously addressing the design issues in the process. An alternative decentralised architecture to that in Section 4.4 is presented in Section 4.5 wherein the design issues are again discussed. Ultimately a conclusion is presented in Section 4.6.

## 4.2 Design considerations for Cognitive Mesh Network

Cognitive Mesh networks are critical for the provision of broadband Internet services, since they have the potential to improve the socio-economic status of both rural and urban areas. Several

generic design considerations need to be considered for a cognitive mesh network that mitigates the spectrum scarcity problem and these are enumerated in this section. es

- i. *Topology*: Topology variation has been known to affect WMNs and Cognitive Wireless Mesh Networks (CWMNs) are no exception because routes formed over multiple hops may periodically experience disconnections. This problem is worsened in cognitive mesh networks by the PU activity. To this end, depending on the availability of central control, cost delay, and other network factors, cognitive radio can establish centralized topology or a distributed one so as to optimise the available network resources [24].
- ii. *Information Exchange*: Within and among SUs, available resources vary in time and space, and are also local instead of identical in all SUs. Attempts to establish end-to-end paths are hindered by the fact that an SU has no idea what the other SU has about the environment. Consequently, resource availability information which should at least be disseminated between neighbouring devices, and possibly beyond that, to ensure point-to-point and ultimately end-to-end communications.
- iii. *Routing and Resource allocation*: According to [101], channel allocation in multi-channel multi-radio cognitive mesh networks not only determines the network topology but also directly affects routing. Specifically, routing determines the distribution of network traffic and traffic distribution affects the degree of interference among neighbouring links or nodes again, ultimately impacting on channel allocation. To this end, routing is a critical issue to consider in the channel allocation process as the two are mutually dependent. Consequently a joint consideration of routing and channel allocation is imperative in order to harness full capacity in multi-channel multi-radio cognitive wireless mesh networks. Routing and resource allocation in cognitive mesh networks are more complex than in WMNs because the set of relay cognitive nodes have to be chosen dynamically based on resource and spectrum availability on all links. Each link in the end-to-end path could be chosen on a different channel according to resource availability seen by each cognitive node, and could further be subject to channel switching due to presence of PU. Consequently a coupling between routing and spectrum allocation is imperative so as to establish end-to-end paths. Furthermore from a routing protocol perspective, routing is a key issue in improving the performance of cognitive mesh networks. Owing to the dynamic nature of CR links, classical routing aimed at maintaining end-to-end routing for ad hoc wireless networks is infeasible. Currently a few of the routing protocols used in multi-radio multi-channel Wireless Mesh Networks are extensions of the classical ad hoc routing schemes. Consequently, appropriate routing in cognitive wireless mesh networks for coexisting multi-radio systems remains an open problem. Therefore, new protocols should be designed appropriately to suit the cognitive radio network environment [223]. The authors in [270] recommend six aspects for consideration when designing a more efficient routing scheme. These aspects are:
  - Spectrum utilization
  - Energy efficient routing
  - Good adaptability, reliability, scalability, high robustness routing design in accordance with the characteristics of cognitive mesh network dynamic topology

- End-to-end delay
- High packet transmission
- High throughput routing protocol

From another perspective, discussed in chapter 2, routing protocols can be designed to improve network efficiency by solving the following problems:

- Hidden terminal problem
- Exposed terminal problem
- deafness problem
- cross layer design
- topology

Ultimately we consider some routing protocols that could possibly make use of the metrics we are using based on our proposed architectures.

- iv. *Coordination*: In a cognitive mesh network, devices are wirelessly connected to each other in a multi-hop fashion and they need to agree on a communication channel so as to transmit packets and guarantee Internet access through mesh gateways to the mesh clients. The challenge is how two cognitive nodes that sense different environments, can agree on a common communication channel available to both. Essentially, each cognitive node is aware of its own available resource, but has no knowledge of what is available to its neighbour nodes.
- v. *Spectrum sharing architecture*: To address this challenge for cognitive mesh networks, a coordination mechanism among cognitive nodes is imperative to facilitate some basic network operations such as guaranteed connectivity, end to end paths, resource allocation, spectrum sensing, spectrum decision, and spectrum sharing.
- vi. *Spectrum sensing*: Spectrum sensing is crucial to the successful implementation and deployment of cognitive radio based systems if dynamic spectrum access is to be achieved. It provides the key ability for secondary users (SUs) to detect unused spectrum and sharing it without harmful interference to the primary users (PUs) [195]. Numerous spectrum sensing techniques exist and have been outlined in chapter 2. In our envisioned network, sensing will be influenced by the architecture as well as the behaviour of nodes in the network.
- vii. *Node Behaviour*: In the general case, cognitive mesh nodes may be required to make either centralized or decentralized decisions, and resource allocation strategies should offer appropriate incentives for nodes in ways that are constructive to the entire network. The behaviour of nodes in our envisaged network can be described best by a mathematical model which takes into account the actions or decisions made by the nodes when under certain rules. To this end, we leverage on game theory, which has recently been introduced in wireless network design as a powerful modelling and analysing tool for centralized cooperative environment as well as competitive and completely distributed environments. It is well-suited to describe mutual conflicting situations between multiple devices which attempt to communicate through

a shared medium [209], [104]. When PUs are inactive, SUs can lease spectrum and engage in either cooperative or non-cooperative communication with each other [292]. To this end, for our cognitive radio mesh network, we propose cooperative transmission and resource allocation scheme among nodes other as well as other schemes where nodes are competitive or non-cooperative. Non-cooperative nodes are selfish and are concerned about their own utilities.

- viii. *Spectrum Access technique*: These have already been discussed in chapter 2 and we further discuss them within the context of this chapter. Two main spectrum access techniques in the form of overlay and underlay spectrum access techniques are considered for the design. The former involves a spectrum access technique wherein a node accesses the network using a portion of the spectrum not being used by the PU system and this consequently minimises the interference to the Primary system. The latter exploits the spread spectrum techniques for cellular networks and are such that once a spectrum map is obtained the node begins transmission such that its transmit power at a certain portion of the spectrum is regarded as noise by the licensed users [8]. This technique requires sophisticated spread spectrum techniques and can utilize increased bandwidth compared to overlay techniques.

**4.2.1 Quality of Service (QoS) Parameters.** In both centralized and decentralized architectures, our QoS performance indicators will include the end to end delay, throughput and a mix of the throughput and delay. The end-to-end delay or one-way delay refers to the time taken for a packet to be transmitted across a network from source to destination.

### 4.3 Generic Cognitive Mesh architecture

Our envisaged cognitive mesh network has been designed to comprise cognitive mesh routers (SUs) which coexist with primary users (PUs). The PUs can be, for example, IEEE 802.16 WiMAX or IEEE 802.22 TVWS Base stations, whose technology supports several [115] incorporates several radio transmission techniques ranging from Orthogonal Frequency Division Multiple Access (OFDMA), Adaptive Modulation and Coding (AMC), Adaptive forward error-correction (FEC), and Hybrid automatic repeat request (H-ARQ). WiMAX technology leverages on these techniques to support data rates of up to 100Mbps with a transmission range of 30 km. The IEEE 802.16 supports two types of architectures, namely last mile and mesh network architectures. Our design adopts the mesh network architecture wherein, subscriber stations (SS) can relay traffic from other SSs in a multi-hop fashion to the base station. Cognitive mesh routers are wireless devices endowed with multiple Wi-Fi radio interfaces. One of the interfaces is reserved for control messages exchanges between the routers and the other interfaces are used to receive and transmit packages in different channels. To this end, the interface used to exchange control messages is reserved for the common control channel (CCC) to disseminate routing information and update channel status. Routing and switching channels of cognitive wireless mesh network For every network including cognitive mesh networks, routing is very important. Routing is the backbone of communication for transferring data from one machine to another in a multi-hop fashion. A good routing protocol is required for efficient communication and a good routing protocol is based

on channel selection strategy. Routing protocols enable routers to discover multiple paths toward gateways or any other specific destination. Intuitively when the initial route is not available or when the path is congested due to traffic from other routers or under the PU presence alternative routes are used. To this end, the management of cognitive mesh networks can be done either in a centralized or decentralized manner [109] and this constitutes the architecture of the network. Our architecture is cognisant of the fact that most of the frequency bands suitable for mobile communications have already been assigned to existing wireless services, and the remaining bands are limited. Consequently optimization of the radio resource usage of the wireless network is a very important issue in the current wireless networks and thus motivates our architectural design.

## 4.4 Centralized Architecture

Figure 4.1 depicts our proposed architecture which is centralized and is similar to [144]

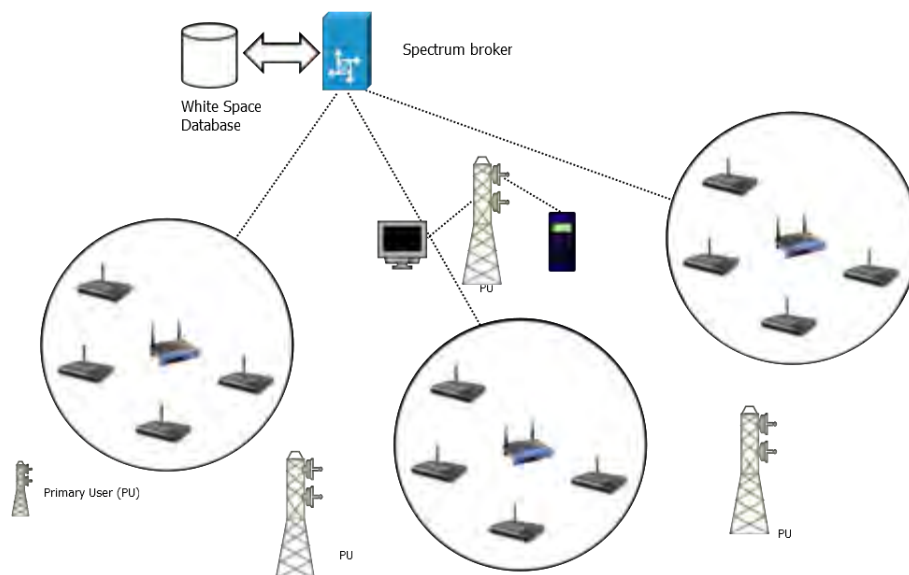


Figure 4.1: *Centralized Cognitive Radio Mesh Architecture*

A centralized architecture depicts an infrastructure network wherein TVWS allocation among unlicensed systems is administered by a central entity which carries out radio resource management and spectrum trading in real-time. The entity which assumes the responsibility of resource management and trading is called the Spectrum Broker (SB). Specifically the spectrum broker gathers information such as spectrum opportunity, and spectrum demands, and subsequently makes a decision on spectrum access, i.e., assignment of bandwidths and transmit power allocation. Furthermore, the management responsibilities of the central entity extend to setting appropriate parameter such as capacity, throughput, and delay. To this end, the optimization process in a centralized architecture has a global perspective for the social benefit with regards to the interaction among different nodes [115]. The behaviour of the nodes is in this context set to be cooperative wherein a centralized server maintains a database of spectrum availability and

access information based derived from a group of SUs, say through a dedicated control channel. A centralized system architecture is shown in Figure 4.1, wherein nodes are configured to cooperate. The main components of the centralized cognitive mesh network [257] are:

- Primary User (PU): The PU is the licensed network component. This could be a TVWS BS for TVWS and WiMAX for WS.
- Spectrum Broker (SB): The PU owns the license and may at times prefer to lease or sell its white space through a third party, called a Spectrum broker(SB).
- Secondary User (SU): A main beneficiary of the PU's leased spectrum is the secondary user (SU). Clearly, for simplicity and analysis, our design will not consider the licence exempt devices such as 24 GHz vehicle radar, 79 GHz Vehicle radar and citizens radio as accessing this spectrum. It should be noted that in our design, the SU is only limited to leasing spectrum from the PU The SU buys white space from the PU via the spectrum broker so as to service its clients which in this case are the mesh clients. In terms of the functionality, the SU performs:
  - Collaborator Selection: In the event that multiple SBs are offering WS, the SUs select the suitable SBs to collaborate with. This covers the evaluation of the gain (e.g., the amount of white spaces with sufficient SNR) and cost.
  - Determination of SU's Channel Access Time: The amount of WS needed is the prerogative of the SU and this subsequently determines the amount of access time. The amount and access time are a function of the price imposed by the PU which is announced by the SB. As an example, in a Time-Division Multiple Access (TDMA) system, SUs must determine the optimal time duration in which they must involve as relay to transmit PU packets and to transmit their own packets
  - Packet transmission: Firstly, the SUs relay PU packets. To ensure continuous collaboration with PUs, the SUs must achieve a certain level of network performance enhancement while relaying the PUs' packets. Secondly, the SUs transmit their own packets. Spatial reuse is possible, and so the SUs must minimize interference among themselves.

With cooperation through negotiation, the radio entities can bargain with each other for the limited resource to achieve a fair and efficient solution. However yet another form of centralized architecture exists wherein a Base Station controls and coordinates the transmission activities of the SUs as shown in Figure 4.2. The cognitive base station controls the transmissions over both the licensed and unlicensed bands, by collecting all the spectrum-related information from the mesh routers. On the basis of the information collected, the base stations take global spectrum access decisions for all nodes. This kind of architecture is exemplified by IEEE 802.22 network model.

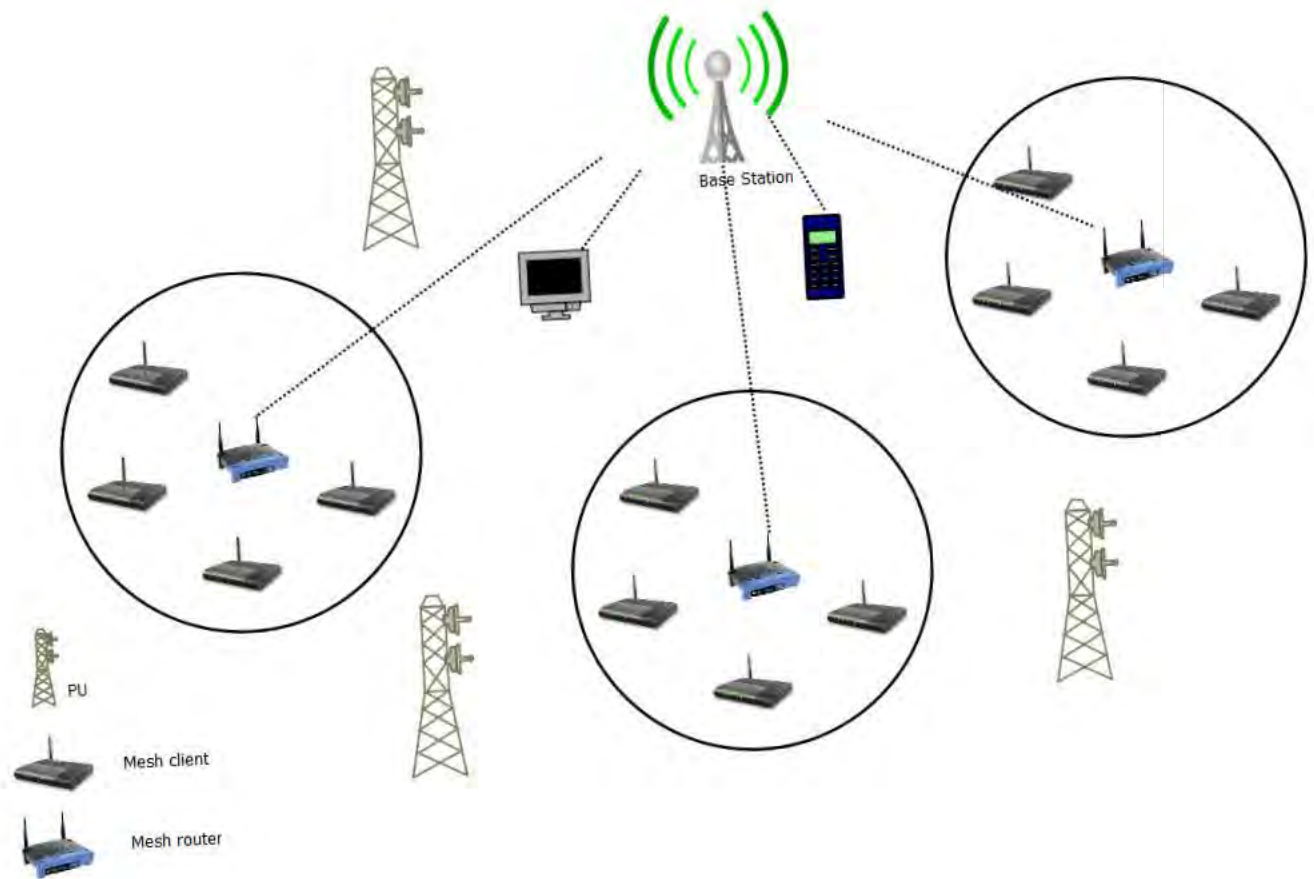


Figure 4.2: *Centralized architecture using Base station*

The IEEE 802.22 was discussed in detail in section 2.6 of chapter 2. The main merit of the cooperative centralized approach is in its ability to permit regulators to remain in control of the spectrum usage as well as allowing them to dictate how the spectrum is used. Owing to its centralized control a cognitive mesh network that exhibits this type of architecture is called a full-spectrum knowledge network, premised on the fact that each SU has full spectrum knowledge of the entire network [120]. However, cooperation typically incurs more communication overhead. We proceed to employ classical optimization theory to solve the cooperative access problem in a centralized setting. Specifically a game theoretic approach introduced in chapter 2 and detailed in chapter 3 is used to model and solve the spectrum access problem in chapter 5. Our design issues are considered as follows:

**4.4.1 Topology.** In a multi-hop network like the envisaged cognitive mesh network, multiple links may be affected if they operate on the channel used by the PUs. Prior to switching to other available links channels, a network partition may occur, resulting in packet SUs [295]. Network topology will be controlled by spectrum assignment. Centralized topology can include central control and peripheral nodes to be static or mobile. According to [24], when a particular node falls out of range, the central entity is able to communicate with the node via other nodes that may be fixed or mobile in a relay fashion.

**4.4.2 Centralized Cooperative Spectrum sensing.** In the cognitive mesh network SUs need to continuously monitor spectrum so as to detect the presence of Primary users (licensed). Specif-

ically the sensing is a key function that prevents harmful interference of SUs with licensed users and identifies the available spectrum for improving the spectrum's utilization. In the practical setting sensing is often marred by multi-path fading, shadowing and uncertainty issues consequently cooperative sensing is employed to mitigate the impact of these issues and has proved to effective in dealing with detection performance by exploiting spatial diversity [9]. In centralized cooperative sensing, a central entity called Fusion centre (FC) controls three step process of cooperative sensing as shown in Figure 4.3. In the first step the fusion centre avails a channel of a frequency band for sensing and mandates all cooperating SUs to individually perform local sensing.

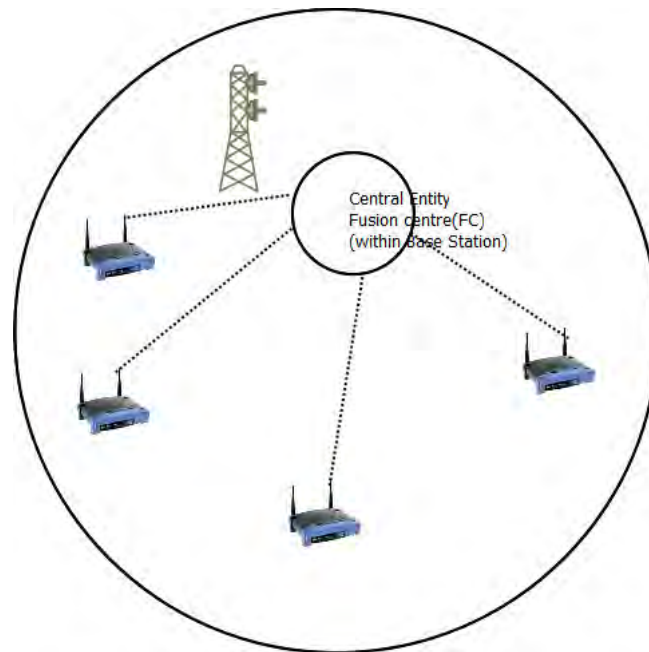


Figure 4.3: *Centralized Sensing*

The second stage involves all SUs communicating the results of their sensing via the control channel. Ultimately the FC integrates the sensed information with a view to determining the presence of PUs and gives feedback to the cooperating SUs. In summary, centralized sensing, a central unit collects sensing information from cognitive devices, identifies the available spectrum, and broadcasts this information to other cognitive radios or directly controls the cognitive radio traffic [24]. Advantages of the cooperative sensing are that they are robust against impairments in wireless communication systems. Furthermore they improve coordination and cooperation between SUs. Centralized cooperative spectrum sensing incurs significant overhead. The overhead refers to any extra sensing time, delay, energy, and operations devoted to cooperative sensing and any performance degradation caused by cooperative sensing [9]. To this end, techniques have been proposed to reduce the overhead in centralized cooperative sensing such as Sequential centralized cooperative sensing [236], Compressive sensing [216],[161] and efficient Information Sharing. In our context we believe the overhead can thus be significantly reduced by adopting the sequential centralized cooperative sensing. In the scheme, each cognitive radio computes the Log-Likelihood ratio for its every measurement, and the base station sequentially accumulates these Log-Likelihood statistics and determines whether to stop making measurement [304].

**4.4.3 Node Access behaviour.** Nodes in the cognitive mesh network will either behave cooperatively or non-cooperatively. In designing the cognitive mesh network, we stipulate a cooperative behaviour for the cognitive network nodes. In the cooperative access the effect of the node's communication on other nodes is considered. The implication is that the SUs or nodes may increase their effective quality of service (measured at the physical layer by bit error rates, block error rates, or outage probability) via cooperation [197]. Cooperation may also be perceived as a zero sum game wherein in terms of power and bandwidth of mobiles in the network. Specifically the premise of cooperation is that certain allocation strategies for power and bandwidth of mobiles lead to significant system performance. Furthermore while allocating spectrum, the allocation algorithms will also incorporate the information. The centralized solution in our case will be considered cooperative. Mesh networks provide an enormous application space for user-cooperation strategies to be implemented [54].

**4.4.4 Spectrum access technique.** Our spectrum sharing technique will be the overlay wherein a node accesses a network using a part of the spectrum that is not being actively used by the PUs thereby consequently minimizing interference. A centralized dynamic spectrum access scheme may be implemented by elaborating on the economic interactions with a view to spectrum sharing [285]. A game theoretic approach studies this process with a view to providing a solution to the radio spectrum trading approach. To this end, the radio spectrum trading problem is then formulated as a game among two or more entities i.e. the spectrum broker or BS and SU systems with incentives to cooperate.

**4.4.5 Coordination-CSCC Protocol.** For the coexistence of IEEE802.11b and 802.16a networks, the common spectrum coordination channel (CSCC) protocol [218] is proposed in our envisioned cognitive mesh network. Conceptually a common spectrum coordination channel is a narrow control channel which is shared by all users of the band intended for spectrum coordination purposes. Each individual node has an extra narrow band (low bit-rate) radio for exchange of control information over the CSCC channel. In the event, that different devices(nodes) require to use spectrum, all users will in accordance with this approach, need to periodically broadcast spectrum usage information (Including User ID, such as MAC address, frequency band used and transmit power as well as optional parameters such as technology type, service type, multi-hop forwarding capabilities if any, user priority etc.) using a standardized packet transmission protocol in the pre-defined sub channel at the edge of the unlicensed band (WiFi). Clearly, this approach is justifiable on the basis of the negligible cost of the dual-mode radio compared to the benefits accrued by the end-user in terms of QoS as well as the societal value i.e.improved spectrum utilization. Receipt of such announcements makes it possible for newly active users to visualize through a map of spectrum activity as well as select suitable frequencies, if any. Specifically it is only those devices that request spectrum or those already transmitting that will announce their spectrum usage information through the CSCC broadcast. Meanwhile other users will remain silent and in listening to the CSCC broadcast. When a scenario arises in which there is no clear channel available then a contention message is broadcast on the coordination channel. This thus triggers distributed execution of the specified etiquette procedure which results in distributed sharing of radio resources (i.e., frequency, power, time) in the congested region.

1. Protocol stack: In terms of the protocol stack, the spectrum etiquette protocol comprises of standardized CSCC-PHY and CSCC-MAC layers with an etiquette policy module as shown

in Figure 4.4.

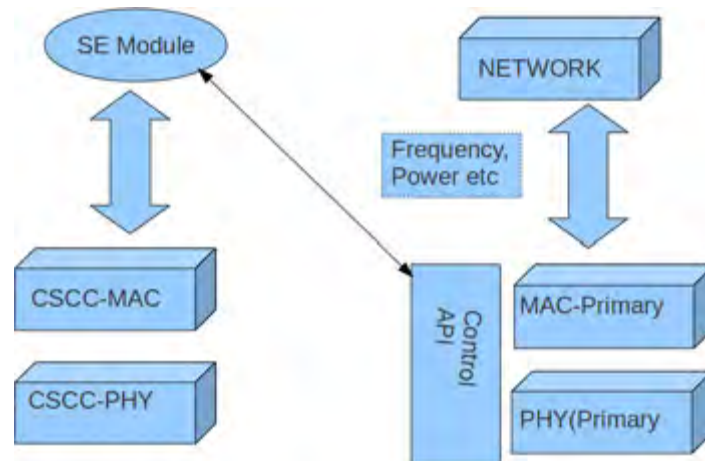


Figure 4.4: *Protocol stack*

The SE etiquette module is standardised for specific usage settings (e.g. home, indoor office, outdoor public, etc.) or for different regions, though the standards can be set independently from CSCC protocol. With regards to the CSCC-PHY the basic 1Mbps 802.11 standard is adopted so as to leverage on existing hardware designs and to reduce complexity. The CSCC PHY must be standardised for edge of band operation in the WiFi band with control information at the MAC layer to cover multiple frequency bands. A possible CSCC-MAC layer packet with control payload extensions is adopted as the basis. The 48-bit MAC address (source address) is used as the unique identifier, along with spectrum etiquette information elements for frequency band, power etc. Specifically, network conditions such as frequency assignment, power control and (potentially) multi-hop collaboration algorithms to be used by a specific SE policy module are communicated. The Ethernet address used to represent multi-cast groups that specify classes of potential neighbours which are expected to participate in the etiquette procedure.

2. CSCC MAC Access: CSCC MAC Access is achieved through the randomization of the transmit cycle to eliminate repeated collisions. Individual stations transmit the CSCC packet periodically with a repetition interval of about 100ms to few seconds. The packet format is as shown on the diagram wherein the CSCC of user  $X$  collides with that of user  $Y$ , but this collision is resolved by way of randomization transmission interval.
3. Etiquette Policy: Numerous policies premised on the shared use of the channel, time, frequency and power etc or even micro-auctions are available for adoption in design of next generation networks. Furthermore priority is also an optional policy for coexistence between different classes of users such as police, fire, ambulance and general purpose data users. In our scenario we, adopt a policy based on dynamic pricing wherein micro-auctions between contending users are used to decide who has transmission rights. Consequently, when a channel is congested, each user offers to pay a price for accessing spectrum resources and the winner of the auction has the right to transmit. The efficient use of resources can also be further achieved using cognitive radios and or collaborative multi-hop routing models

that are implementable in this framework leveraging on the CSCC's ability to provision a map of current usage thus eliminating the complex and slow frequency scanning procedures.

**4.4.6 Centralized Routing.** Centralized routing entails a design that utilizes the Central Node (CN), such as Routing Control Centre (RCC), to gather network information from all other nodes in the network. Thus, CN achieves overall view of the network. To this end, CN computes the best route from each node to its all possible destinations by using certain algorithm based on the overall information, and then broadcasting the updated routing table to each node. It means that routing table is determined centrally by CN and shared by all nodes. Simultaneously, all gathered information and routing table will be stored in a global database which eases network management [272].

- i. Open Shortest Path First: This algorithm falls under the Link state Protocols wherein the shortest path first algorithm (Dijkstra) is used to calculate loop free routes. The algorithm is designed to respond quickly to topology changes using minimal protocol traffic. OLSR is adapted for cognitive mesh routing by employing two control messages namely, PU-aware Hello (P-Hello) and PU aware TC. Each SU is thus permitted to transmit data packets in licensed channels by CR without interfering with the PU activities. Consequently the challenge of OLSR failing to efficiently utilize link state information such as channel and spectrum condition is dynamically resolved so as to estimate alternative paths resulting in reduced delay [99],[254], [145].
- ii. Centralized routing with CSPF: A central entity performs the computation after learning the complete topology by receiving ISIS/OSPF link state packets of each AS [39]. It performs a CSPF computation for each LSP. Such a centralized solution could be envisaged when MPLS LSPs are entirely contained

The advantages of centralized routing are given in [160] as follows:

- i. centralized routing can do traffic engineering meaning it is possible to optimize routing wherein the throughput can be maximized by balancing load over all feasible routes. Moreover this approach makes Use of link costs that vary often. Furthermore the traffic engineering optimization can be accomplished by minimizing the use of energy by shutting down nodes and links.
- ii. Can apply a consistent policy including any administrative constraints to all paths and traffic demands. This implies it is possible to combine trust and routing. By coupling the routing and spectrum management modules it is possible to combine payment and routing i.e., pricing can influence routing decisions. To this end, the load can be restricted to avoid network collapse under heavy load.
- iii. Particularly suitable for the case of network provisioning
- iv. Optimized routing: The centralized routing approach has the advantage of a global view of the entire SU network, thus making it possible to make optimal routing decisions.

- v. Ability to deal with failures: A global view of the SU network makes identifying and mitigating failures an easy task. Thus mechanisms can easily be put in place.
- vi. Easy configuration: centralized routing protocols are deployed on one or more nodes in a SU network. Only those specific nodes will need to be reconfigured when applying a different algorithm.

Centralized routing has the following limitations [247]:

- Central entity must have perfect knowledge of network topology.
- Communication is done by accessing central databases for spectrum statistics
- Each node is not able to take its own routing decisions
- solution based on theoretical tools like graph abstraction, mathematical programming provides upper bound and benchmarks for routing performance.
- provide static cognitive multi-hop network
- separates the sharing and sensing functionalities

## 4.5 Decentralized Architecture

Figure 4.5 shows a distributed architecture for a cognitive mesh network. The network nodes include the PU, SU (Mesh router) and its clients. The PU owns the spectrum license and it deals directly with the SUs, providing the following functionalities:

- Determination of the Cost of White Spaces: PUs determine the cost of white spaces to be imposed on SUs.
- Determination of PUs' and SUs' Channel Access Time: As the licensed owners of the spectrum, the PU determines the appropriate channel access time for transmission opportunities for both PUs and SUs. The objective is to maximize the network performance (e.g., throughput) of PUs and SUs.
- SU' Packet Transmission. PUs transmit their own packets to destination in order to enhance their network performance.

In a decentralized architecture, the secondary users communicate with each other in an ad-hoc manner. Spectrum sensing operation in decentralized architecture is usually performed collaboratively. This type of architecture also encompasses coexistence of two or more wireless networks operating in unlicensed bands. An example of this type is the coexistence of IEEE 802.11 with IEEE 802.16 [152]. Thus a decentralized approach enables each user to perform spectrum sensing or access based on partial knowledge of network status, can be adopted to address challenges aforementioned and subsequently lead to a new paradigm i.e., self organization [159].

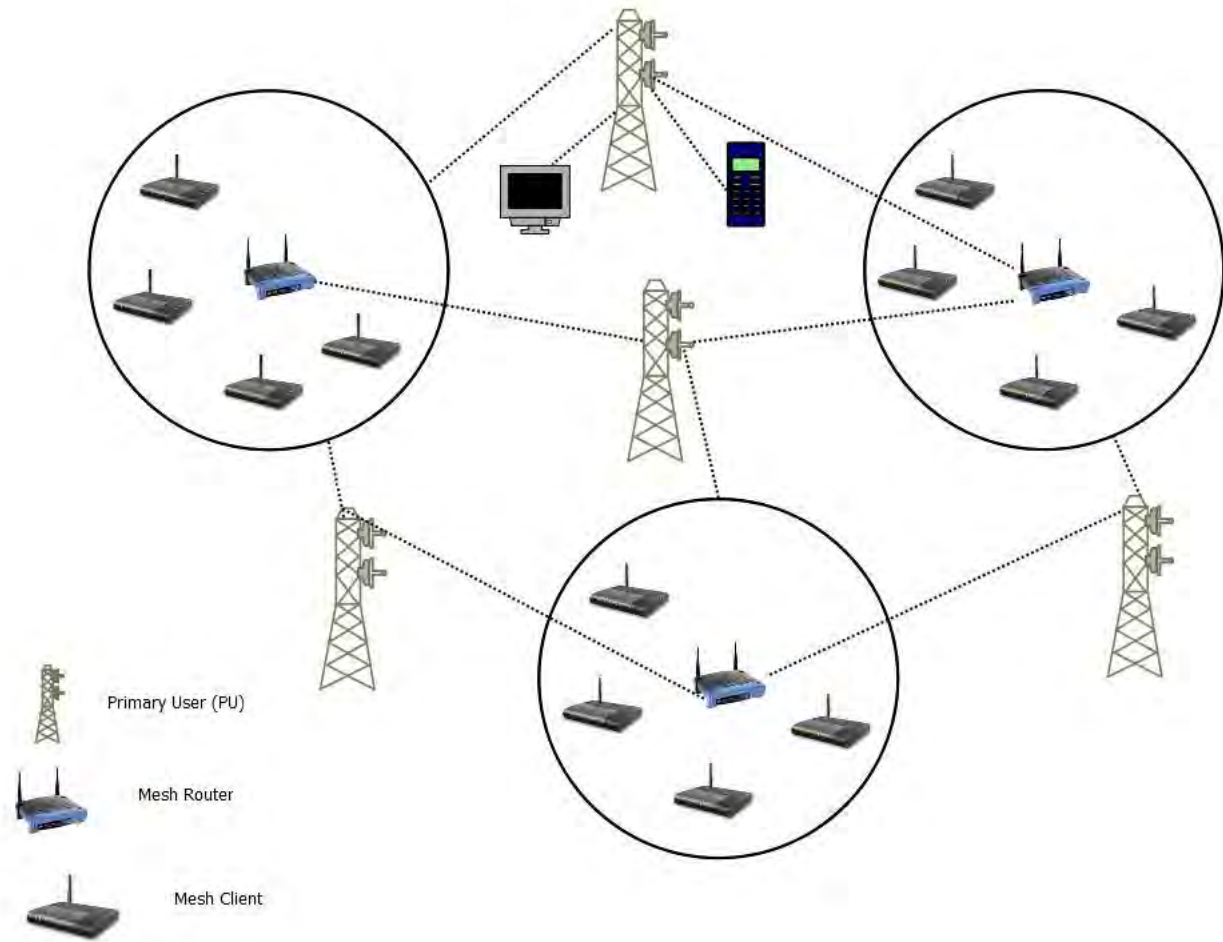


Figure 4.5: *Cognitive Radio Mesh Architecture*

Essentially two SUs that are within communication range can exchange information directly, while secondary users who are not within direct communication range can exchange information over multiple hops. We propose the use of a game theory based method wherein multiple cognitive users competing for the spectrum resources are considered selfish and may thus compete against each other so as to maximize their own utility for example maximizing their own service quality or revenue. To this end a game theoretic framework is considered appropriate for the study a non-cooperative spectrum access in a decentralized cognitive mesh network [59]. Node behaviour in this context is considered to be non-cooperative and the requirement of frequent message exchange among and between neighbours waived and this introduces a trade-off for practical utilization. The key benefit of this type of architecture is the decentralized management scheme where nodes can be added or deleted without the involvement of the central authority where the CR managers in all nodes make the decisions [58]. Decentralized MAC protocols consider different aspects such as the number of transceivers, channel access mechanism, spectrum sensing techniques, and selection criteria for control channel [235]. Furthermore the communication overhead in the decentralized spectrum sharing architecture is considerably lower than that in the centralized setup owing to the use of local spectrum knowledge. In the following subsections we discuss the associated design issues as follows:

**4.5.1 Topology control.** Distributed environments network nodes are able to join or leave the network at any stage such that cognitive radio has to re-arrange that network between source and destination. Appropriate leader within a domain of nodes, or sub-nets based on location, available resources, and behavioural patterns. Consequently the mesh routers act as bridging nodes between different types of networks. Ultimately the mesh network becomes more robust and time-invariant

**4.5.2 Decentralized Spectrum sensing.** Cooperative spectrum sensing by SUs in the cognitive mesh network can help avoid interference with transmissions by the primary user. Spectrum sensing can be performed either in centralized or decentralized manner [284]. In decentralized cooperative spectrum sensing (DCSS) cognitive radio nodes share information through local communications, in-order to make their own decisions as to which portion of the spectrum can be used.

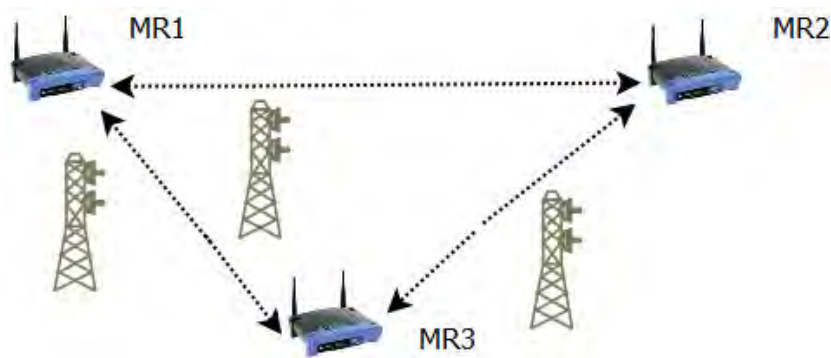


Figure 4.6: *Decentralized Sensing*

In Figure 4.6 the cognitive mesh routers are exchanging information at local level and subsequently make decisions that suit them. The key action is that of communication with neighbours with a view to cooperating [240]. A drawback of decentralized approach is that some duration is involved in making decisions that is there is a duration for sensing and the duration for node duration. In the first stage cognitive mesh routers use a spectrum-sensing model to make measurements about primary users at the beginning of detection. This stage is followed the time frame for cooperation the time when the mesh routers are establishing links with neighbours to locally exchange information among them and subsequently make computations

**4.5.3 Information exchange.** To efficiently manage available spectrum resources in a decentralized manner, information exchange among users is necessary and important. Each node is assumed to be equipped with two transceivers, one which is a reconfigurable transceiver that can dynamically adjust its waveform and bandwidth for data transmission. The other is a conventional transceiver employed on the common control channel. Scanner equipped CR can detect neighbouring transmissions by sensing the data channel. Environment learning can be achieved by combining scanning results and information from control packets exchanged by combining channel that contain info about transmissions and power used on different minibands. A medium access control protocol on common control channel access information exchange among network nodes is required for nodes to efficiently learn and keep adapting to the changing network dynamics [242]. To this end, owing to the informational-decentralized nature of the cognitive mesh

network, the exchanged information is only useful when it can be conveyed in time. The timeliness constraint of the information exchange is a function of the delay deadline of the applications, the information in terms of its impact on the users utilities will need to be quantified for the different settings of the cognitive mesh network. Consequently this information will impact the accuracy with which the nodes can model the behaviour of other nodes and hence efficiency with which they can respond to this environment by adequately optimizing their transmission strategies [201].

**4.5.4 Node behaviour.** The decentralized cognitive mesh network is non-cooperative meaning the nodes in the network are selfish. Thus a node attempts to maximize its profit by taking a series of actions. Whether or not a node receives a profit is decided by the success of its actions. The node focuses on its individual utility as opposed to that of the network [241]. The behaviour is modelled as a non-cooperative spectrum access game where secondary users access simultaneously multiple spectrum bands left available by primary users, optimizing their objective function which takes into account the congestion level observed on the available spectrum bands [79].

**4.5.5 Coordination.** In the general case, a major challenge in cognitive radio networks is the adaptation to time and space variability of the available resources, namely chunks of the frequency called channels. However in cognitive mesh networks this problem is compounded by the fact that there exists no direct communication among devices which cannot establish a global common control channel to coordinate the entire network [92]. On the contrary only local control channels that vary depending on the time instant and location, can be established to coordinate device among themselves. To this end, among the decentralized adaptive MAC protocols analysed in [235] such as , cognitive radio-Enabled Multi-channel MAC (CREAM), Opportunistic cognitive MAC (OC-MAC), Statistical Channel Allocation MAC (SCA-MAC) and Adaptive MAC (A-MAC) protocols, we adopt the A-MAC [133] for the coordination within our proposed cognitive Mesh network. The AMAC protocol considers cognitive devices that can communicate in both industrial, scientific and medical (ISM) spectrum and licensed spectrum. Furthermore the protocol also considers the existence two non-cooperative types of network users- the primary users and the secondary users. Primary users are the licensed user of a frequency band. Secondary users use free spectrum opportunistically for communication which is not used by the primary users [118]. We adopt the synchronized coordination protocol [150] with the following assumptions

- Every node is assumed to be equipped with two radios. One of the two radios is used for just listening (listening radio) to the control signals and the other for both receiving and transmitting data (data radio).
- The maximum number of channels at each node is  $M$ , but the channels available at each node may vary with the primary user's traffic.

The synchronization coordination protocol will in this context be discussed with regards to the network initialisation state when when there are no cognitive users (nodes) to form a network or when the new user wants to form a sub-group independent of the existing users.

- Initialization state: At inception, initialization involves a first node dividing time into  $M$  number of equivalent time slots of fixed time duration  $T_x$ . For the purpose of control

signal exchange, each time slot is dedicated to one channel. To this end, the node then beacons in all its available channels at the beginning of the corresponding time slots. Consequently the other nodes choose one of the channels and listen for beacon messages to synchronize their listening radios. Since the first node broadcasts in all its available channels, the follower nodes can choose any channel and be sure to receive a beacon message within  $MT_x$  seconds. After it receives a message, the nodes exchange information about their channel sets. If it did not receive a beacon, then it is considered to be the first node. When the initialization state ends, all nodes are synchronized and every node has the information about its neighbours and their respective channel sets. The implication of node synchronization is that the listening radio of every node tunes to the respective channel which the slot represents and listens in that channel. This depicts a continuous scanning which has the benefit of keeping track of the primary system, facilitates control signal exchange and more importantly mitigates the multichannel hidden node problem.

- Exchange of control signals and data: Communication is initiated by way of control signal exchange which serves the purpose of identifying a common channel between the initiating node and its neighbour. It then waits for the time slot which represents the chosen channel. Nodes should also exchange data and this is done asynchronously by employing the second radio (data radio). To this end, control signals or information is exchanged among the nodes whenever an event occurs. These events are called information events (IEs). for practical purposes our cognitive mesh network coordination protocol shall consider the following IEs:
  - When a new node enters the network, it should notify its arrival to its neighbouring nodes.
  - When the available channel list at a node changes due the primary user traffic, the node's neighbours have to be updated about its new channel list.
  - When a node starts, stops or changes its channel of communication, the information is forwarded to its neighbours to enable them to know whether the data packets can be forwarded through the communicating node.
  - When a node wants to communicate with its neighbour, it sends a set of control signals to inform its intent to start a communication in a particular channel. This event is followed by an acknowledgement by the neighbour to convey its acceptance/denial. On acceptance, data transfer takes place on the negotiated channel without any delay.

Benefits of this coordination protocol include improved throughput, mitigating the multi-channel hidden terminal problem by introducing synchronization into the protocol as well as maximum connectivity in a cognitive mesh network environment.

**4.5.6 Spectrum access Technique.** Spectrum in the decentralized cognitive radio mesh architecture can either be accessed spatially or temporally [14]. In the latter, SUs strive to exploit the temporal spectrum opportunities resulting from the bursty traffic of primary users and in the former cognitive users aim to exploit frequency bands that are not used by PUs in a particular geographic area [296]. A typical example is in the reuse of TV white spaces that are not used by TV broadcasting system, TV bands assigned to adjacent regions are different to avoid co-site interference.

**4.5.7 Decentralized routing protocols.** Decentralized routing protocols are premised on approaches that consider only local spectrum knowledge obtained via distributed procedures and protocols [52]. Specifically, each node is informed of network status from other nodes in the same network, and stores that information in their own local databases. For convenience we consider two critical routing protocols that can possibly use our routing metrics and these are distance vector routing protocol and link state routing protocols [272]

- i. Distance vector routing This routing protocol determines the routing tables of each node according to the calculation of distance vector from every node to its possible destination in the network periodically. Each individual node transmits its routing table which includes the number of hops that must be traversed to each destination as well as the next hop only to its neighbour routes. Neighbour routes and nodes will also set up their own routing tables in accordance with received information. This process continues till the network converges
- ii. Link State: This routing protocol leverages on Dijkstra's algorithm for computation of routing tables for each node. Each of the routers sends link state Advertisements (LSA) over all adjacent nodes. An LSA describes all of the route's links, interfaces and state links. All routers receiving an LSA from neighbours will capture the LSA in its state database and replicate the LSA to all its neighbours. Ultimately each node has copy of the entire network map from which the best route is computed [13].

The advantages of decentralized routing are:

- i. Robustness: The routing function and information is distributed across all servers in the network. Basically the routing protocol remains in operation for as long as the network is connected.
- ii. Effective routing decisions: The routing decision based on information derived from local and neighbour nodes thereby reducing the time and effort required to gather information about the entire network.
- iii. Minimal overhead: SUs do not need to exchange routing and spectrum information across a wide area and this conserves bandwidth.

## 4.6 Conclusion

In this chapter we have created a list of the important design considerations that render feasible, the design of the system architecture, facilitating spectrum sharing in our envisaged cognitive radio mesh network. The design is a partial response to our first research question: *Can next generation mesh networks be designed to include Cognitive nodes that can learn from their environment and broadcast that information in order to allow the mesh network to optimize its routing performance based on informed decision? can free spectrum be shared economically over spectrum sharing games.* The architecture can be in centralized form wherein it is feasible for the network to

Table 4.1: Summary of Architectures

<b>Parameter</b>	<b>Centralized</b>	<b>De-Centralized</b>
Components	PU,SU,BS,SBr, white Space Database, clients	PU, SU, Clients
Sensing	Cooperative	decentralized cooperative
Node behaviour	Cooperative	Non-cooperative
Information exchange	centralized	decentralized
Coordination	Common spectrum coordination Protocol	Adaptive MAC Protocol
Routing	global spectrum knowledge	local spectrum knowledge

function with full spectrum knowledge in an environment where cognitive nodes are cooperating i.e., working for towards improving system utility. The implication of this architecture is that the central authority facilitates the sharing of spectrum by broadcasting to the entire network all the information that has been sensed by individual nodes. Thus each of the nodes will have a global perspective of the network. Furthermore an alternative decentralized architecture for spectrum sharing has been designed for a scenario where nodes make decisions based only on their local environment. To this end, the nodes behave non-cooperatively meaning they are only self-interested and strive to improve their own utility. The implication is that individual nodes are able to perform spectrum allocation. The centralized and decentralized architectures, summarised in table 4.1, have been designed by considering such issues such as topology, spectrum sensing, coordination, node behaviour etc.

# 5. Cooperative TV White Space Spectrum Sharing Framework

## 5.1 Introduction

Heterogeneity of next generation wireless networks means diverse multiple wireless technologies including, but not limited to Wi-Fi, WiMaX, GPRS, Satellite and WLAN networks are set to coexist. The coexisting wireless networks all have different and sometimes conflicting spectrum requirements ranging from tenth hundreds of Kbits/sec provided by technologies such as GPRS, to tens of Mbits/sec provided by Broadband wireless LANs such 802.11a [114]. However recent developments in wireless technology such as wireless Mesh network technology are an important step towards the realization of heterogeneous next generation networks. To this end, Wireless Mesh Networks (WMN) are increasingly and justifiably being touted as a candidate technology set to facilitate ubiquitous connectivity to the end user. Mesh networks basically comprise wireless routers and clients, which are endowed with the ability to self-organize and configure to such an extent that the nodes are capable of maintaining connectivity among themselves. The characteristic low upfront cost, ease of maintenance, robustness as well as reliable service coverage has justified the candidature of this technology. Consequently, WMN have become an intelligent community network capable of provisioning data and multimedia services to urban, rural and remote communities. A significant rise in the volume and variety of data-hungry mobile devices, including more affordable smart-phones, tablets and e-readers, has resulted in fundamentally increased spectrum use and subsequent demand for more spectrum as well as apparent lack of or non-existence of connectivity in some communities. The much demanded spectrum is a scarce and non-reproducible finite resource. To this end, the inability to meet the increased demand for spectrum has resulted in the spectrum scarcity problem [69, 253]. The implication of spectrum scarcity is that for the first time ever since RF transmissions were first regulated through a static allocation policy, the access to spectrum is chronically limited. Fundamentally this has constrained the performance, growth and spread of WMN to under-served areas. With the developments in TV White Space (TVWS) and Cognitive radio (CR), overcoming spectrum scarcity is feasible through a major expansion of spectrum supply by dynamically sharing the spectrum more intensively. Cognitive radio is being intensively researched as the enabling technology for secondary access to the so-called TV White Spaces (TVWS), large portions of spectrum in the Ultra High Frequency (UHF) as well as Very High Frequency (VHF) bands which became available on a geographical basis after digital switchover. Ultimately, leveraging on these developments, WMN routers are equipped with Cognitive radios that are aware of and can sense the environments, learn from the environments, and perform functions to best serve their users without causing harmful interference to other authorized users. With this development WMN can perform better, and more areas can be reached in terms of service provision as licensed primary users (PUs) are able to lease their spectrum to unlicensed secondary users (SUs). Intuitively, the routers belong to diverse networks with certainly diverse spectrum requirements and consumption habits. An important research direction in this context is to guarantee Quality of Service (QoS) dynamically for diverse services of next generation network (NGN), specifically to guarantee their required

bandwidth resource [106]. In this chapter, we partly respond to the first research question of our thesis focussing on the network engineering problem by leveraging on game theoretic approach in chapter 3, where we employ an IEEE 802.22 based centralized spectrum sharing architecture designed in chapter 4 to tackle the problem of spectrum resource allocation in a heterogeneous network environment by using cooperative Stackelberg [114] games wherein the nodes exhibit a cooperative behaviour discussed in chapter 3. According to [230], the IEEE 802.22 system can operate in two modes: point-to-multipoint and point-to-point. Formulating the problem as a cooperative Stackelberg game allows individual networks to cooperate with each other by forming coalitions. Therefore the objective of each network is to maximize the overall objective of the heterogeneous network and to fulfil the resource allocation requests from users. Every member of the coalition provides some of the requested resources according to its own operation constraints. For concreteness we consider a centralized Cognitive Mesh which is a heterogeneous network comprising a TVWS Base Station (BS) and Wi-Fi Access points (APs) that belong to different operators engaged in trading of TV White Space (TVWS) wherein it is assumed the auction i.e., spectrum trading is in accordance with the properties in chapter 2, section 2.5. The interaction of the BS and APs is considered to be a pricing problem wherein a BS strives to maximize its profit by selling secondary spectrum and Wi-Fi APs strive to satisfy customer demand by acquiring as much secondary spectrum as possible. The pricing problem is subsequently translated to a leader-follower Stackelberg game in an oligopolistic market setting. The BS station is considered to be the leader and the APs followers. Ultimately a TVWS spectrum sharing framework which improves spectrum utilisation in three ways is developed. The degree of efficient spectrum utilization by the framework is a function of the model or QoS parameter deployed in the network.

**5.1.1 Contribution.** Our main contribution in this chapter, is that of a cooperative TVWS spectrum sharing framework based on an IEEE 802.22 centralized architecture designed in chapter 4, comprising three tractable analytic models based on inter-operator agreements between the leader (BS) and follower (APs). The three tractable analytic Stackelberg inspired models are as follows:

- **Delay QoS based Model:** One of the critical QoS requirements is the delay requirement for real-time or delay sensitive applications. Based on delay QoS metric, this model adopted from [189], analytically attempts to characterize how spectrum can be dynamically shared to simultaneously satisfy QoS of the SU traffic which carries real-time or delay sensitive services while protecting the PU transmission (proposed in section 5.6).
- **Throughput QoS based Model:** The model strives to dynamically share spectrum between the primary user represented by the WiMAX BS or TV Transmitter and the Wi-Fi routers in a Cognitive Mesh based heterogeneous network. The model characterizes a scenario of maximizing overall network throughput for SU in the heterogeneous network, while protecting the QoS of the PU [193] (proposed in section 5.7).
- **Composite Metric QoS based Model:** The model is formulated from a combination of the throughput and delay QoS parameter metrics. Real-time applications require more reliable and time invariant channels to satisfy stringent service requirements like delay constraints and sustainable rates. The appeal of maximizing total network capacity cannot be ignored and must thus be explored. Consequently our model tries to characterize efficient

cooperative spectrum sharing through analytic model in which a combination of delay and throughput is investigated (proposed in section 5.8). A performance evaluation (section 5.9) to ascertain the performance of the models on the designed wireless Cognitive mesh network based on some suitably set parameters.

The rest of the chapter is organized as follows. Section 5.2 introduces and defines the general notion of a cooperative game. The Stackelberg game which is a form of a strategic game in economics is introduced in its generic form together with some basic derivations for a generic commodity in section 5.3. Next we focus on a TV White Space (TVWS) market pricing wherein a PU is engaged in TVWS trading with WiFi (APs) in section 5.5. In sections 5.6 to section 5.8, Stackelberg oligopolies markets are designed in the form of analytic models based on delay, throughput and composite QoS parameters. A performance evaluation of the framework is carried out in section 5.9 through the evaluation of the analytic models based on the set parameters. Finally a conclusion of the chapter is given in section 5.11

## 5.2 Cooperative Games

Spectrum sharing is one of the key functionalities of CR which allows devices to coordinate to prevent multiple users' conflict in overlapping portions of the spectrum. Spectrum sharing can be cooperative and non-cooperative as previously discussed in our methodology in chapter 3. In this section we focus on the former which we subsequently transform to an oligopoly Stackelberg game while we defer the latter to the chapter 6 for a competitive context. Formally according to Brandenburger [45], a cooperative game generally comprises two vital elements:(i) set of players, and (ii) a characteristic function specifying the value created by different subsets of players in the game. Let  $N = \{1, 2, \dots, n\}$  be the finite set of players and at the same time, let  $i$ , which runs from 1 through  $n$  index the various members of  $N$ . The characteristic function is a function  $v$ , which associates with every subset  $S$  of  $N$ , a number denoted  $v(S)$ . The number  $v(S)$  is interpreted as the value created when the members of  $S$  come together and interact. In summary, a cooperative game is a pair  $(N, v)$ , where  $N$  is a finite set and  $v$  is a function mapping subsets of  $N$  to numbers. From an application perspective, cooperative games are used to model scenarios, where

- players can benefit by cooperating
- commitments are fully binding and enforceable.

Commitments may for example be in the form of agreements, promises, or threats. Khan et al. [142] consider the problem of multi-resource allocation in a generic heterogeneous wireless networks which is subsequently tackled through a cooperative game approach. The networking technologies cooperate with each other to attain the ultimate goal of user satisfaction. We adopt and leverage on these particular efforts to formulate a cooperative game for a heterogeneous wireless network contextualized by a Cognitive mesh network in which WiMAX and Wi-Fi networking technologies cooperate. This cooperative game can be reformulated as an oligopoly

market in which a few entrepreneurial firms (owners of the cooperating technologies) participate in commodity trading. Subsequently in the next section, we present a suitably generic oligopoly Stackelberg model in which two generic entrepreneurial firms are engaged in commodity trade in an oligopoly.

### 5.3 Generalized Stackelberg

The Stackelberg game is a strategic game in economics wherein according to [37] a decision maker at one level of the hierarchy may have his objective function and decision space determined, in part, by decisions taken at other levels. Thus in this type of game, one player acts as a leader and the rest as followers. Stackelberg games can be characterized as:

- the system has interacting players within a hierarchical structure.
- the leader begins the game by announcing his decision, and the process continues for each player down through the hierarchy. Each subordinate player executes his policies after, and with the full knowledge of, his superior players.
- the decision of a player can impact any other player's objective function, and a subsequent player's set of feasible choices.

The problem is then to find an optimal strategy of the leader, basing on the assumption that the followers react in a rational way such that they optimize their objective functions given the leader's actions [187]. Assuming the existence of two firms  $X$  and  $Y$ , producing individual product quantities  $q_x$  and  $q_y$  respectively. Collectively, the concerned quantities all together, sum to a total of  $Q$  expressed as:

$$Q = q_x + q_y \quad (5.1)$$

The pricing policy is such that each quantity will cost  $P(Q)$  which itself is given by:

$$P(Q) = \alpha - Q, \text{ if } Q \leq \alpha \quad (5.2)$$

$$P(Q) = 0$$

if

$$Q > \alpha \quad (5.3)$$

$$P(Q|Q < \alpha) = \alpha - Q \quad (5.4)$$

$$P(Q|Q > \alpha) = 0 \quad (5.5)$$

The implication of equation 5.2 is that if demand is exceeded, then there is no profit. If the production process, pegs the cost of each of the items at a cost which is less than  $\alpha$  then there will be no profit accrued. The implication of this premise is that there is a threshold for profitability. Subsequently, the cost functions of each the firms  $X$  and  $Y$  are expressed as:

$$C_x(q_x) = cq_x \quad (5.6)$$

$$C_y(q_y) = cq_y \quad (5.7)$$

Intuitively, each of the firms has a unique utility function as follows:

$$\phi_x(q_x, q_y) = q_x(P(Q) - C_x(q_x)) \quad (5.8)$$

$$\phi_y(q_x, q_y) = q_y(P(Q) - C_y(q_y)) \quad (5.9)$$

The utility function relates together parameters such as the quantity, pricing and cost for both firms  $X$  and firm  $Y$ . The utility functions are transformed by substituting the cost and quantities respectively, yielding:

$$\phi_x(q_x, q_y) = q_x(\alpha - q_x - q_y - c) \quad (5.10)$$

for firm  $X$  and

$$\phi_y(q_x, q_y) = q_y(\alpha - q_x - q_y - c) \quad (5.11)$$

for firm  $Y$ . The optimal solution for this game is the Nash equilibrium (N.E) obtainable by way of backward induction. The logic in this approach is to initiate the solution search from bottom level towards the upper level. Imperatively it is feasible to determine what firm  $Y$  will produce at equilibrium. Considering the utility function of  $Y$  in equation 5.11, the function is simplified by removing the brackets in equation 5.11 wherein the whole terms inside the brackets are multiplied by  $q_y$  thereby yielding equation 5.12

$$\phi_y(q_x, q_y) = \alpha q_y - q_x q_y - q_y^2 - cq_y \quad (5.12)$$

The equilibrium point is determined at the moment when the derivative of the utility function  $\phi_y$  with respect to the quantity  $q_y$  is equivalent to zero. To this end,

$$\frac{d\phi_y(q_x, q_y)}{dq_y} = 0 \quad (5.13)$$

$$\frac{d\phi_y(q_x, q_y)}{dq_y} = \alpha - q_x - 2q_y - c \quad (5.14)$$

At this point, the solution value of  $q_x$  which maximizes the value of player  $Y$ 's utility is determined from

$$0 = \alpha - q_x - 2q_y - c \quad (5.15)$$

$$2q_y = \alpha - q_x - c \quad (5.16)$$

$$q_y^* = \frac{\alpha - q_x - c}{2} \quad (5.17)$$

The leader-follower game is sequential and as such we revisit firm ( $X$ )'s utility function as follows:

$$\phi_x(q_x, q_y) = q_x\left(\alpha - q_x - \frac{\alpha - q_x - c}{2}\right) - c \quad (5.18)$$

Further manipulation of this utility, transforms it to:

$$\phi_x(q_x, q_y) = q_x\alpha\frac{1}{2} - \frac{1}{2}q_x^2 - \frac{1}{2}cq_x \quad (5.19)$$

Taking the first derivative as in the first instance

$$\frac{d\phi_x(q_x, q_y)}{dq_x} = \frac{1}{2}\alpha - q_x - \frac{1}{2}c \quad (5.20)$$

On equating the derivative to zero, the value of  $q_x$  is determined as:

$$q_x = \frac{\alpha - c}{2} \quad (5.21)$$

Our ultimate step is to substitute the optimal value into the optimal value of  $q_y$ . Recall

$$q_y = \frac{\alpha - q_x - c}{2}$$

transforms to

$$q_y = \frac{\alpha - q_x - c}{4}$$

The N.E is thus achieved at the values

$$(q_x^*, q_y^*) = \left(\frac{\alpha - c}{2}, \frac{\alpha - c}{4}\right) \quad (5.22)$$

Graphically, we depict this analytic solution as in Figure 5.1:

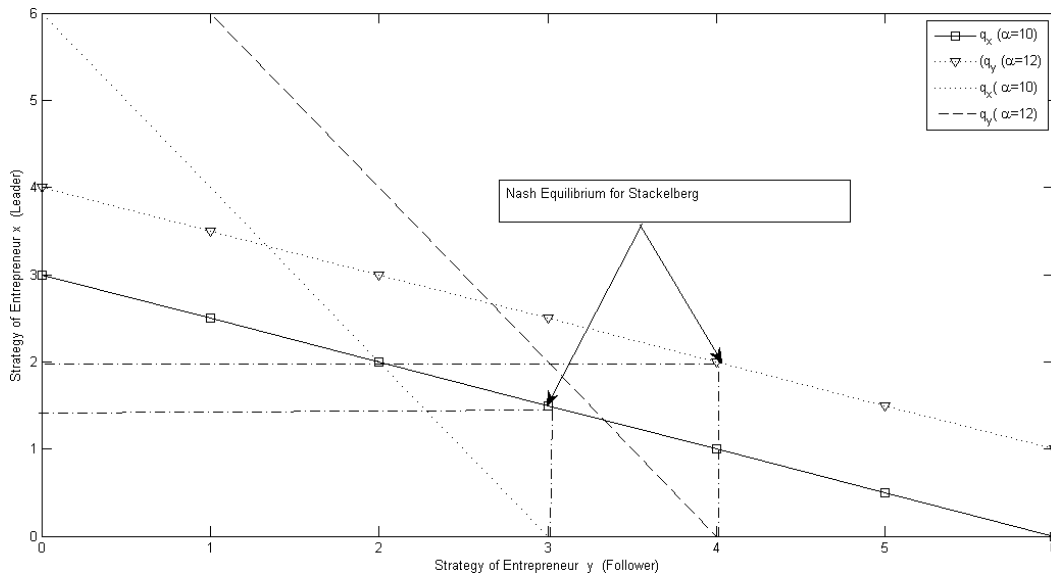


Figure 5.1: Stackelberg Game between Firms

Table 5.1: Leader-Follower (Stackelberg) Game

Firm	Role	Strategy	Cost	Revenue	Profit	Equilibrium
X	Leader	Price	$cq_x$	$q_x(P(Q))$	$\phi_x$	$\frac{\alpha - c}{2}$
Y	Follower	Price	$cq_y$	$q_y(P(Q))$	$\phi_y$	$\frac{\alpha - c}{4}$

Prior to engaging on TV white space Market for spectrum pricing we wrap up this section with a summary of the leader-follower game between firm  $X$  and firm  $Y$  in Table 5.1. The table depicts in clear terms the role played by each of the firms, the associated strategies that are aimed at profit and revenue maximization. The associated costs incurred are also given and the functions of the quantities of the two firms. Ultimately the N.E of the two players is also given. The implication of this analysis is that the generalized Stackelberg can be applied to TVWS trading wherein the players will be the different networks i.e., where one assumes the role of leader and the other the role of follower.

## 5.4 Architecture and System Operation

Architecturally our proposed cognitive wireless mesh network mainly comprises of cognitive mesh routers (SUs) which are in coexistence with Primary Users (PUs). The cognitive mesh routers are wireless devices that are endowed with multiple Wi-Fi radio interfaces to the extent that one of the interfaces may be utilised for control message exchange. It is through such kind of interfaces that routing and spectrum (channel) status is exchanged and updated. The primary user in our network is a WiMAX base station which although it has its own client nodes or subscribers to service, will most of the time be able to have free spectrum. To this end, the free spectrum can be shared as well as utilised by the SUs. We propose a centralised spectrum sharing approach in the cognitive mesh network by employing a centralised entity called the Spectrum Broker. Thus each PU will avail to the market a portion of its unused spectrum via the spectrum broker. Consequently Spectrum broker is a centralised entity which will be able to control the spectrum allocation and procedures. Objectively the Broker strives to maximize its revenue from the sale of the white space spectrum. The cognitive wireless mesh leverages on a spectrum etiquette protocol for efficient coordination of radio devices in unlicensed bands. Thus the coordination of the coexistence between the PU and SU is done by the Common Spectrum Coordination Channel (CSCC) protocol as described in section 4.4.

## 5.5 TV White Space Market Pricing

We consider an oligopoly wherein the PU and SU are engaged in spectrum trading while in coexistence based on an inter-operator agreement QoS metric such as delay or throughput. A market pricing model for spectrum sharing is proposed wherein dynamic spectrum access is achieved by way of an inter-operator agreement between a TVWS BS and Wi-Fi networks on the basis of a QoS metric. In WS this arrangement will be between WiMAX BS and Wi-Fi. Objectively the model aims to simultaneously achieve improved revenue as well as efficient spectrum utilization. The heterogeneous configuration is that the TVWS BS by virtue of being licensed attains primary user status ostensibly charges the Wi-Fi routers or Access Points (APs) for the shared use of its spectrum when servicing its clients as shown in Figure 5.2.

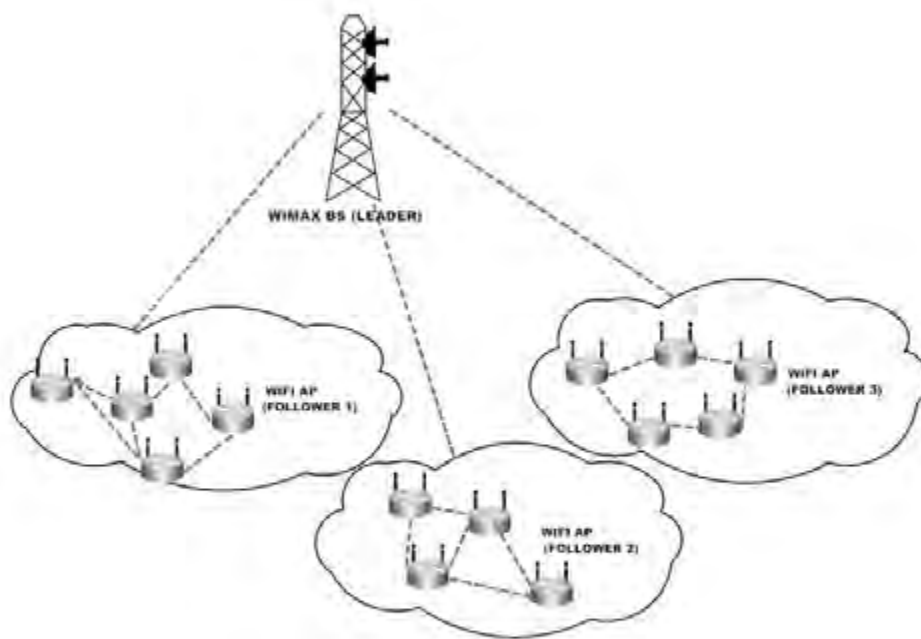


Figure 5.2: Cognitive Radio Mesh Network Comprising of Integrated Wi-Fi and WiMAX Networks

The subscribers of the PU tend to subscribe at a flat rate by virtue of their fixed bandwidth requirement. To this end, the Wi-Fi nodes have variable bandwidth requirements, characterized by an elastic demand function in which the number of nodes as well as preference are important variables. The WiMAX BS levies the Wi-Fi node routers with variable pricing ( $P_1$  and  $P_2$ ) to cater for the diverse spectrum consumption habits. This pricing problem is subsequently generalized into a Stackelberg oligopoly presented in section 5.3 where WiMAX BS profit is maximized and the Wi-Fi routers are satisfied with the spectrum sharing and pricing. Clearly, the Stackelberg Equilibrium is the solution to this game and is obtainable when all the information about all the players i.e. service providers is available. In reality the BS may not be familiar with the preferences of the Wi-Fi routers. Furthermore the Wi-Fi routers may also not be familiar with the demand functions of its subscriber nodes and may thus necessarily have to learn these from historical data. Attainment of such a task is possible by way of a Darwinian approach where a genetic algorithm is employed for learning purposes so as to achieve the desired objective. In the coming subsections we focus on three analytic models with all notation defined in table 5.2

Table 5.2: Notation Summary

<b>Symbols</b>	<b>Description</b>
$\lambda_i$	Arrival rate
$Q_i$	Quantity/Spectrum demand
$R^{SD}$	Revenue generated based on Delay
$a_i$	Fixed Revenue
$e_i$	Decreasing revenue rate
$b$	Bandwidth demand
$c_i$	Fixed bandwidth
$d_i$	demand function slope
$R_M^r$	Revenue generated by Wi-Fi network
$C_M^{Dr}$	Cost (TVWS-delay perspective)
$D_i$	Delay
$\psi^{BS}$	Payoff (BS)
$T(n, b_i^{(s)})$	Throughput
$R^{ST}$	Revenue due to Throughput
$C_M^{Tr}$	Cost ( TVWS-Throughput perspective)
$C_i^D$	Cost due to Throughput
$C_i^\zeta$	Cost due to Composite parameter
$\zeta$	Composite Measure (Throughput and delay)
$\varepsilon$	Tuneable parameter (delay)
$\Lambda$	Tuneable parameter (Throughput)
$T$	Throughput
$\phi_i^{CM}$	Profit (Throughput and delay)
$\phi_M^{Tr}$	Profit (Throughput)
$\phi_M^{Dr}$	Profit (Delay)
$\beta$	Throughput factor (constant)
$N$	Number of Subscribers

Prior to the formulation of our models, the reader should note that, with regards to Table 5.2, the subscripts  $i$  and  $M$  denote the Leader  $i$  and  $M$  denotes the follower which is our WiFi router. However, where superscripts are involved with regard to cost,  $C_i^D$ ,  $C_i^{Tr}$ ,  $C_i^\zeta$ , these denote costs due to QoS parameters such as delay( $D$ ), Throughput( $T$ ) and Composite ( $\zeta$ ). The same applies to the corresponding profit which is denoted as either,  $\phi_i^{Dr}$ ,  $\phi_i^{Tr}$ ,  $\phi_i^{CM}$ , these will refer to the payoff due to the delay, throughput and composite QoS parameters respectively. The revenue variable also uses the superscript,  $R^{SD}$ ,  $R^{ST}$ ,  $R^{CM}$  and  $R_M^r$ . These will denote revenue generated by providing a service to the secondary using delay (superscript  $SD$ ), throughput (superscript  $ST$ ), Composite (superscript  $CM$ ). The superscript  $M$ (WiFi router) in  $R^M$  denotes revenue generated by WiFi router.

## 5.6 Delay Model

In this section we propose a delay QoS guaranteed model as part of a cooperative TVWS spectrum sharing framework in which SUs in the radio environment sense spectrum available over the PU band spectrum. The spectrum availability is dependent on the activity of the PU, this is to say availability depends on whether the PU is transmitting or not. Practically our PU role is played by the BS ((can either be TV Transmitter(TVWS) or WiMAX (WS)) which ca and the SU by the WiFi Access Point (AP). Thus the model studies the problem of spectrum sharing based on a QoS delay metric inter-operator agreements between PU and SU( Wi-Fi). Specifically, we adopt a model used in [189] for TVWS, to characterize the interaction between the two wireless technologies within an envisaged Cognitive wireless network context. From a Stackelberg oligopoly perspective the leader role is assumed by the BS and the WiFi APs assume the follower roles. In the course of characterizing the interaction between BS and WiFi, five important functions are considered. The functions are the revenue generated by BS based on the delay QoS, the demand made by SU on PU spectrum, revenue generated from servicing the demand at a particular price, the cost associated with TVWS provision and ultimately the pay-off function.

The revenue generated BS based on a delay QoS metric [189] is formulated as follows:

$$R^{SD} = \sum_{i=1}^N [a_i - e_i D(\lambda_i, Q_i^s)] \quad (5.23)$$

The constant  $a_i$  denotes the fixed revenue and its value tends to influence the revenue so much such that when the value of the fixed revenue is higher then the overall revenue is likely to be higher. Conversely when the fixed revenue is lower then the overall revenue may be correspondingly low. Apart from the fixed revenue constant parameter there exists another parameter in equation 5.23 which is  $e_i$  and denotes the decreasing rate of revenue in the revenue generated by the base station. Intuitively when the decreasing rate of revenue parameter is set to a low value then the cost due to the delay QoS is lower and this gives rise to higher BS revenue. However when the value of the decreasing revenue parameter is set to a higher value then the cost due to the delay is higher and this consequently gives rise to a low BS revenue generation. The parameter  $N$  denotes the number of subscribers. A more important and influential parameter in the equation 5.23 is that of the QoS delay (queueing) which in turn is dependent on the traffic

arrival rate  $\lambda_i$  as well as the allocated bandwidth. The allocated bandwidth is the TVWS and according to our system design, the price charged by the Wi-Fi wireless technology router/AP is dependent on the level of demand for this commodity (TVWS). The demand function is itself linear and is expressed as:

$$b(P_M^{(r)}) = c_i - d_j P_M^{(r)} \quad (5.24)$$

A parameter  $c_i$  depicts the fixed bandwidth which is proportional to the demand, to an extent that when demand is high it is also equally high. The constant  $d_j$  denotes the gradient of the demand function and is referred to as the elasticity of demand. The implication of this constant is that when its value is high then the elasticity of demand is high. To this end, the Wi-Fi network also generates revenue from the sale of this TVWS spectrum. The generated revenue is obtainable from the product of the price  $P_M^{(r)}$  as well as the bandwidth  $b_j$  for all the network nodes  $N$  concerned as shown in equation 5.25:

$$R_M^{Dr} = \sum_{j=1}^N P_M^{(r)} b_j \quad (5.25)$$

The implication of equation 5.25 is that more revenue is generated when there is high demand and conversely less revenue is realized for lower demands. The associated cost of providing the TVWS is dependent on the price levied by the BS  $P_M^{BS}$ , the amount of required bandwidth  $b_j$  and a fixed cost  $F_M^r$  associated with the WiFi router as shown in equation 5.26:

$$C_M^{(Dr)} = P_M^{(BS)} \sum b_j + F_M^r \quad (5.26)$$

Equation 5.26 points to a joint dependence of price charged by BS and demand of SUs on the cost associated with providing TVWS. In the final analysis, there is a benefit associated with provisioning, the transmission service through availing TVWS by the BS and on the part of the AP router there is a benefit associated with the acquisition of the TVWS and the benefit is called a payoff. The payoff of the router is expressed as the difference between the revenue generated by the router (equation 5.25) less the cost involved in providing the bandwidth (equation 5.26) as expressed in equation 5.27:

$$\phi_M^{(Dr)} = R_M^{(Dr)} - C_M^{(Dr)} \quad (5.27)$$

This equation is simplified by substituting equation 5.24 and equation 5.25 into equation 5.27 to obtain equation 5.28 which represents the payoff of the router:

$$\sum_{i=1}^N P_M^{(r)} (c_i - d_j P_M^{(r)}) - P_M^{(BS)} \sum_{i=1}^N (c_i - d_j P_M^{(r)}) - F_M^r \quad (5.28)$$

The WiFi router payoff is a function of the router price, the price of the BS as well as the fixed cost of the Wifi router. The behaviour of the wifi router payoff function may be investigated by fixing the BS price and varying the WiFi router price. The BS also has a payoff function which is obtainable by combining the BS revenue function (equation 5.23) and the revenue of the WiFi router (equation 5.28). The combination of the equations gives rise to the payoff of the BS as expressed in equation 5.29:

$$\phi^{(BS)} = R^{(Ds)} + \sum_{M=1}^N P_M^{(BS)} b_M^{(r)} \quad (5.29)$$

Table 5.3: Leader-Follower (Stackelberg) Game-Delay QoS Model

Network	Role	Strategy	Cost	Revenue	Payoff
WiMAX	Leader	Price	$P_M^{(BS)} \sum b_j + F_M^{(r)}$	$R^{SD} = \sum_{i=1}^N [a_i - e_i D(\lambda_i, Q_i^s)]$	$\phi^{(BS)}$
Wi-Fi	Follower	Bandwidth		$R_M^r = \sum_{j=1}^N P_M^{(r)} b_j$	$\phi_M^{(Dr)}$

The BS payoff is thus seemingly dependent on the QoS delay parameter, the BS price and the bandwidth demand. The implication of this relation equation 5.29 is that the QoS delay parameter may be adjusted to achieve some target payoff.

A summary of the delay based model is given in table 5.3, showing each network component of the Cognitive mesh, its status with regards to the leader-follower game, cost, revenue as well as payoff. The model characterizes an interaction between the PU and SUs and that SUs may in reality have to relinquish some spectrum in the event of the PU being busy. The practical implication of this fact is that in the case of delay sensitive applications, the QoS cannot be guaranteed in this model. We defer the performance evaluation to section 5.9 for a detailed insight into the network behaviour on the basis of this model.

## 5.7 Throughput Model

Our first model on delay cannot guarantee QoS for delay sensitive applications and this calls for an alternative metric like throughput to be used in the sharing of spectrum so as to handle delay sensitive applications. Throughput is defined as the whole data moved successfully from one point to another in a given period of time [267]. It is measured in bits per second (bits/s or bps). The maximization of throughput is a major challenge of any communication system because throughput represents the overall performance of a system. For this reason, we propose a throughput QoS based model as part of a cooperative TVWS spectrum sharing framework in which SUs in the radio environment sense spectrum available over the PU band spectrum. Specifically the model strives to maximize throughput for a Cognitive mesh network that is allowed to share its frequency band with the PU. This translates to the Wi-Fi APs being allowed to share the WiMAX spectrum band. The QoS parameter to be used is the throughput and is expressed in [75] as:

$$T(n, b_i^{(s)}) = \sum_{i=1}^N \frac{\beta b_i^{(s)}}{\sqrt{n \log n}} \quad (5.30)$$

The price charged by the Wi-Fi AP/router tends to influence the level of demand by a Wi-Fi node. The demand function is linear and is expressed as follows:

$$b_i^{(s)}(P_M^{(r)}) = c_i - d_j P_M^{(r)} \quad (5.31)$$

The fixed bandwidth  $c_i$ , is directly proportional to the bandwidth demand, if it is high, the bandwidth demand is correspondingly high. In utilizing the throughput as the QoS metric, the

Leader (BS) revenue is accordingly expressed in equation 5.32 in terms of the throughput in equation 5.30 as:

$$R^{ST} = \sum_{i=1}^N [a_i - e_i T(n, b_i^s)] \quad (5.32)$$

As for the Wi-Fi network, its revenue is obtainable from

$$R_M^{(r)} = \sum_{j=1}^{N_M^{(r)}} P_M^{(r)} b_j(P_M^{(r)}) \quad (5.33)$$

The revenue is thus a joint function of the price and the bandwidth on demand. When the demand for bandwidth is high, the price also increases with a consequent increase in revenue. Similarly when the bandwidth demand drops the price correspondingly drops and this results in reduced revenue. The associated cost is calculated in a similar manner as in the delay model in section 5.6 and is given by equation 5.34 in terms of the price levied by the BS, the bandwidth demand function and some fixed cost for the Wi-Fi router  $F_M^{(r)}$ .

$$C_M^{(r)} = P_M^{(BS)} \sum b(P_M^{(r)}) + F_M^{(r)} \quad (5.34)$$

Ultimately all the players must realize some payoff, for concreteness we initially delve into the issue of follower payoff. Such a payoff is attributed to the Wi-Fi router on the basis of a price charged by the WiMAX BS. Consequently the payoff is expressed in equation 5.35 by computing the difference between equation 5.34 and equation 5.33 as follows:

$$\phi_M^r = R_M^r - C_M^r = \sum_{i=1}^N P_M^{(r)} (c_i - d_i P_M^{(r)}) - P_M^{(BS)} \sum_{i=1}^N (c_i - d_i P_M^{(r)}) - F_M^{(r)} \quad (5.35)$$

The next step is that of determining the optimal price charged by the Wi-Fi to a node by invoking basic calculus through computing the derivative of the profit function and setting it to zero.

$$\frac{d(\phi_M^{(r)})}{d(P_M^{(r)})} = c_i - 2d_i P_M^r + d_i P_M^{(BS)} = 0 \quad (5.36)$$

Given the price  $P_M^{(k)}$  the bandwidth function then computes bandwidth demand for the entire node set existing within the vicinity of hot-spot  $M$ . On the basis of the perceived response of the Wi-Fi router/AP, the WiMAX BS gains a leverage to adjust its price  $P_M^r$  charged to router  $M$  so as to achieve the highest possible payoff. The WiMAX BS payoff is defined as the computational difference between revenue in equation 5.32 and the cost in equation 5.34. Formally the WiMAX BS payoff is then expressed by equation 5.37 as follows:

$$\phi^{(BS)} = R^{(s)} + \sum_{m=1}^N R_M^{(r)} = \sum_{i=1}^N [a_i - e_i T(n, b_i^{(s)})] + \sum_{M=1}^N P_M^{(BS)} b_M^{(r)} \quad (5.37)$$

The payoff is thus influenced by the QoS throughput parameter as well as the price the BS levies on the Wi-Fi networks and the level of bandwidth demand. A practical reality in this model is that

when the demand function is completely known (i.e., the preferences of the SUs), the equilibrium can be ascertained by applying calculus to the profit function of the WiMAX and subsequently obtaining the optimum price. However in the event that such information is not completely known a genetic algorithm which is described in chapter 2, subsection 2.4.5 and chapter 3, section 3.1.2 is applied to estimate and adapt both the leader and follower strategies at equilibrium. The genetic algorithm uses a total of eight steps to estimate the leader strategy as follows:

1. Random generating of population of  $N$  chromosomes
2. Each chromosome denotes an action of the leader ( BS)
3. For  $i= 1$  to  $N$  do
4. The leader plays action  $\phi^{BS}$  i.e. announce a set of prices
5. The WiFi/APs react by adjusting demand action.
6. Evaluate the fitness (Profit,  $\phi^{(BS)} = R^{(s)} + \sum_{m=1}^N R_M^{(r)} = \sum_{i=1}^N [a_i - e_i T(n, b_i^{(s)})] + \sum_{M=1}^N P_M^{(BS)} b_M^{(r)}$ ) of action based on the price and demands
7. end for
8. A new generation of chromosomes is created by using the reproduction, crossover and mutation operators of the GA.
9. Steps 3 – 8 is repeated until a terminal iteration or convergence

The genetic algorithm steps are explained in terms of phases as follows:

- **Initialisation:** In this phase, a random population of chromosomes that comprises of the available solutions is generated. The size of the population is influenced by the number of cognitive users (SUs). The BS breeds a population of potential actions to better anticipate the APs's reactions (demand). Conversely the APs also breed a population to better respond to the BS's actions.
- **Evaluation:** Every individual strategy must be evaluated to calculate its fitness. In our case the fitness is represented by the revenue obtained by every strategy. Thus, each strategy must be evaluated to set its fitness, i.e., the strategy is played during a market cycle.
- **Selection:** In the selection phase the strategies that will survive are chosen. The selection criterion is based on each individual's fitness, i.e. individuals with higher fitness are more likely to survive. The probability of surviving is proportional to the fitness parameter; like a roulette wheel with elements with different probabilities, it selects  $N$  new elements for generating the next population. The number of strategies selected is the size of the population, and the same strategy may be selected multiple times, so strategies more fit are selected more times that strategies that are not that desirable. The strategies that are not selected do not survive, and are erased.

Table 5.4: Leader-Follower (Stackelberg) Game-Throughput QoS Model

Network	Role	Strategy	Cost	Revenue	Payoff
BS	Leader	Price	$P_M^{(BS)} \sum b_j + F_M^{(r)}$	$R^{ST} = \sum_{i=1}^N [a_i - e_i T(n, b_i^s)]$	$\phi^{(BS)}$
Wi-Fi	Follower	Bandwidth	WiMAX charge	$R_M^r = \sum_{j=1}^{N_M^{(r)}} P_M^{(r)} b_j (P_M^{(r)})$	$\phi_M^r$

- **Crossover:** After the selection process the selected individuals are paired up and combined on the crossover phase. On the crossover, the genes of the 2 individuals are interchanged from a splitting point selected randomly. That is, the crossover mechanism will interexchange some variables between the two strategies selected, e.g. if there are two variables involved in the learning process, bandwidth requested to the spectrum broker and price charged to the end user, a possible new strategy will be choosing the price of one good strategy and the bandwidth of another good one. This phase is not a strict step in the learning cycle, but only performed occasionally, based on the parameter crossover probability of the algorithm.
- **Mutation:** In the same way, depending on the mutation probability, the individuals will mutate. When there is a mutation, one gene is chosen randomly and it is mutated. On our project, as the genes are variables with a range of possible values, the mutation consists on small variations on the value of the selected variable: Where  $v$  is the mutated variable value,  $v$  the value previously to the mutation phase, is the proportion of the range the variable is allowed to vary and range is that range. uniform  $-1$  to  $1$  generates a random number distributed uniformly between  $-1$  and  $1$ . Once a new population is generated by these four steps, the process starts again, evaluating the just generated population and on. As the time goes by, the only survival strategies will be the ones that produce more revenues; therefore the strategies played by the service provider would be wise choices.

Finally we summarise the most important functions as shown in table 5.4.

## 5.8 Composite QoS Metric Model

Throughput and delay are two mutually conflicting QoS performance measures. In this context, our contribution is that of developing a model in which the performance measure is a composite QoS metric derived from the combination of throughput and delay QoS performance measures. Furthermore we lay our theoretical foundations for our model by following the same analytic approach as in the two previous models in section 5.6 (Delay) and section 5.7 (Throughput). The composite metric is defined in equation 5.38

$$compositeMetric(CM) = Delay + Throughput \quad (5.38)$$

Equation 5.38 can be further simplified into equation 5.39 by considering the relationship between the delay and throughput QoS parameters as predicted by the scaling laws in [75]. Furthermore

we introduce some tuneable parameter  $\epsilon$  which takes values between 0 and 1. The tuneable parameter  $\epsilon$  is vital in the adjustment of the composite QoS parameter.

$$CM = (1 - \epsilon)D(\lambda_i, b_i^s) + \epsilon T(b_i^s, n) \quad (5.39)$$

The revenue realizable from the composite QoS metric for the BS is:

$$R_{CM(BS)} = \sum_{i=1}^N (a_i - e_i(1 - \epsilon)D(\lambda_i, b_i^s) + \epsilon T(b_i^s, n)) \quad (5.40)$$

The demand remains deterministically the same, while the revenue of the Wi-Fi network is a combination of that revenue realizable due to the delay and that due to the throughput as follows:

$$R_{CM(WF)} = R_{D(WF)} + R_{T(WF)} = \sum_{i=1}^N P_{MD}^{WF} b_{iD} + \sum_{i=1}^N P_{MT}^{WF} b_{iT} \quad (5.41)$$

The prices will clearly be different hence the spectrum demand induced from a QoS throughput metric and that delay QoS will attract different amounts. To this end, the cost is calculated from

$$C_{M(CM)}^{WF} = P_M^{BS} \sum b_{DT} + F_M^{WF} \quad (5.42)$$

where  $b_{DT} = b_{iD} + b_{iT}$ . The TV White Space Base station charges the router  $M$ , a price of  $P_M^{BS}$  for the use of its spectrum, the cost for fixed router  $M$  is  $F_M^{WF}$ . The payoff of the follower is intuitively the profit, which is the computational difference between the revenue and the cost associated with the provision of bandwidth expressed in equation 5.43 as:

$$\phi_{M(CM)}^{WF} = R_{WF(CM)} - C_{M(CM)}^{WF} = \sum_{i=1}^N P_M^{WF} b_{iD} + \sum_{i=1}^N P_M^{WF} b_{iT} - P - M^{BS} \sum_{i=1}^N b_{DT} + F_M^{WF} \quad (5.43)$$

It is from this payoff of the Wi-Fi network that the optimal price charged to the Wi-Fi (Follower) can be obtained by way of differentiation, where at the critical point the derivative can be equated to zero.

$$\frac{d\phi_{M(CM)}^{WF}}{dP_M^{WF}} = 0 \quad (5.44)$$

Similarly, like in the other two previous models, the strategy of the follower is availed and this subsequently assists the TV White Space BS to make an informed choice as it appropriately adjusts its price to maximize its profit expressed as:

$$\phi^{BS} = \sum_{i=1}^N (a_i - e_i((1 - \epsilon)D(\lambda_i, b_i^s) + \epsilon T(b_i^s, n)) + \sum_{i=1}^N P_M^{BS} b_{iD} + \sum_{i=1}^N P_{iT}^{BS}) \quad (5.45)$$

Taking the derivative of the payoff function with respect to TV White Space BS price:

$$\frac{d\phi^{BS}}{dP_M^{BS}} = 0 \quad (5.46)$$

Table 5.5: Leader-Follower (Stackelberg) Game-Composite QoS Model

Network	Role	Strategy	Cost	Revenue	Payoff
WiMAX	Leader	Price	$P_M^{(BS)} \sum b_j + F_M^{(r)}$	$R^{CM} (Eqn.5.40)$	$\phi^{(BS)} (Eqn.5.8)$
Wi-Fi	Follower	Bandwidth	WiMAX charge	$R^{WF} = (Eqn.5.41)$	$\phi^{(WF)} (Eqn.5.43)$

yields the optimal value for the TVWS BS. However the lack of information as in the previous model (section 5.7) requires the use of a genetic algorithm as calculus cannot provide a sufficient solution in this kind of setup. Intuitively we adopt the same algorithm and follow the steps in section 5.7 with the difference being the fitness function now represented by equation 5.8 and is stated as  $\phi^{BS} = \sum_{i=1}^N (a_i - e_i((1 - \epsilon)D(\lambda_i, b_i^s) = \epsilon T(b_i^s, n) + \sum_{i=1}^N P_M^{BS} b_{iD} + \sum_{i=1}^N P_{iT}^{BS}$

In the final analysis we summarise the important functions(cost, revenue, payoff) for both networks i.e. WiMax (PU) and Wi-Fi (SU) in table 5.5 as well as the role and strategy of each network.

## 5.9 Performance Evaluation

As part of responding to the first research question stated as: **Research Question 1:** (“**Cognitive nodes:**”) *Can next generation mesh networks be designed to include Cognitive nodes that can learn from their environment and broadcast that information in order to allow the mesh network optimize its routing performance based on informed decision? can free spectrum be shared efficiently over spectrum sharing games?* In this section we carry-out a performance evaluation of the cooperative spectrum sharing framework by using three different analytic models to demonstrate how spectrum can be shared cooperatively in different ways. Specifically we show through the design of a low cost heterogeneous Cognitive mesh network, how the Cognitive nodes will as part of cooperating, exchange and consolidate the information learned from the radio environment so as to optimize the payoff of the entire network system. Our heterogeneous system design is a Cognitive Radio Mesh Network Comprising of Integrated Wi-Fi and WiMAX Networks as shown in Figure 5.2 wherein the leader is engaged in an interactive game with the followers. For purposes of evaluation we envisage our Cognitive mesh to be having a leader entity (WS BS) with 20MHz of spectrum. In the next subsections we carry out the evaluation as follows. In subsection 5.9.1 we deal with the delay analytic model proposed in section 5.6, this is followed by an evaluation of a throughput model in subsection 5.9.2 as proposed in section 5.7. Finally the composite metric based model proposed in 5.8 is evaluated in subsection 5.9.3. In the Throughput and Composite models we make use of a genetic algorithm with the parameter settings in table 5.6.

Table 5.6: GA parameter setting

Parameter	Value
Initialisation method	Random
Selection method	roulette
Crossover operation	two point
Mutation operation	gaussian
Fitness Function	Eqn 5.37, Eqn 5.8
Elitism	4
Population size (N)	100
Mating pool size	0.8*N
Crossover probability	0.01
Number of iterations	50

**5.9.1 Delay model.** An evaluation of the QoS delay based model proposed in section 5.6 is carried out, starting from Figure 5.3 through to Figure 5.6. A variation of the SU demand with price levied by the White Space-BS is depicted in Figure 5.3 in accordance with the predictions of equation 5.24. As the price levied by White Space-BS increases the demand for spectrum by the SU decreases, this is attributed to the Wi-Fi router passing on the costs to the Wi-Fi nodes by also imposing higher prices. Subsequently this impacts on the profit to be realized. The demand function is also investigated with variable number of nodes at the same price upon which there is a realization that there is a correlation between the number of nodes and the level of spectrum demand. The correlation is such that the higher the number of nodes the higher the demand for spectrum. In Figure 5.4, an investigation of the price dependency on arrival rate is carried out. Notably when the arrival rate is increased the price charged to the Wi-Fi routers must also increase.

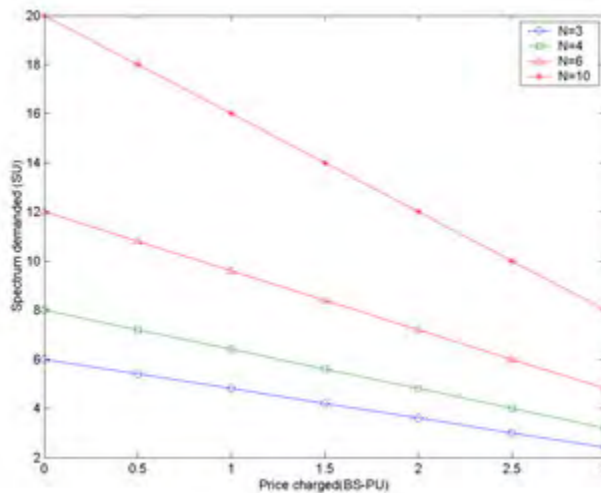


Figure 5.3: Secondary User (SU) Spectrum Demand Dependence on Price Charged by WiMAX Base Station (BS)

The investigation is carried out for a variable of nodes ranging from 10 to 16 nodes. In view of this variation, it is important to note that at the beginning the curves representing the different node sets half nearly the same price of nearly 2.5 units. The difference in price then becomes apparent as the number of nodes vary so much such that, the more the number of nodes the greater the price charged. Furthermore the same investigation is extended to the bandwidth and arrival rate dependency as shown in Figure 5.5.

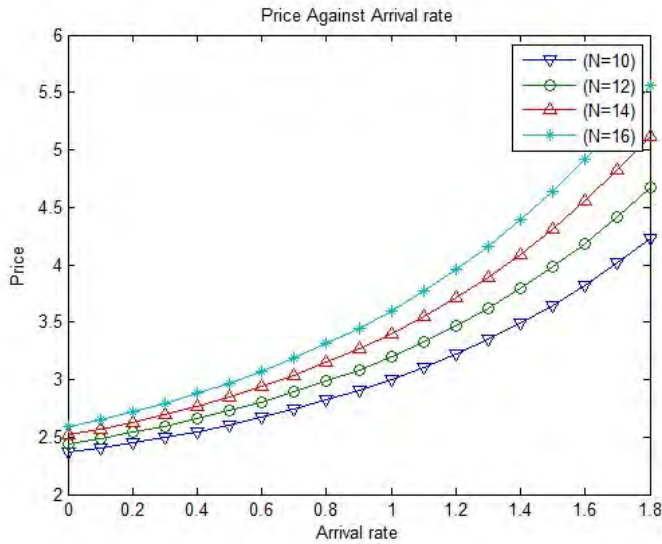


Figure 5.4: Arrival rate and its dependence on Price charged to Wi-Fi routers

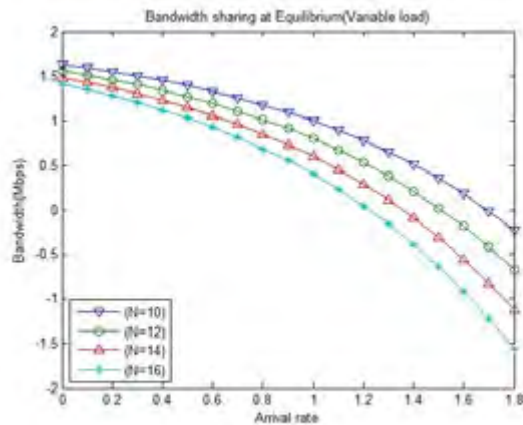


Figure 5.5: Bandwidth Requirement Dependence on Arrival rate for Wi-Fi nodes

A smaller arrival rate is associated with a larger bandwidth and as the arrival rate increases the bandwidth requirement drops. However, for the same batch of node groups, a smaller group of

10 nodes has higher bandwidth requirement than a larger group of 16 nodes. Ultimately the variation in the arrival rate influences the price and subsequently the profit attained by the WS BS. The objective of the White Space BS is thus to maximize its profit derived from the leasing of its bandwidth with price being a fundamental variable in the equation 5.37. To this end, we focus on Figure 5.6 wherein the graph depicts the variation of profit of the White Space BS with price. The price regime is such that there are two prices  $P_1$  and  $P_2$  and the profit attained takes the form of a reverse Dijong shape. Finally the relation between the price and number of nodes is explored from equation 5.24, in Figure 5.7 with investigations revealing that there is a direct dependence between the price at equilibrium and number of nodes served.

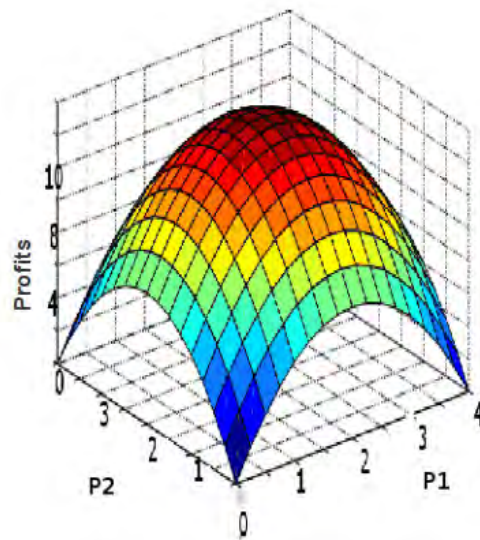


Figure 5.6: Profit of the Base station (BS) and its dependence on prices

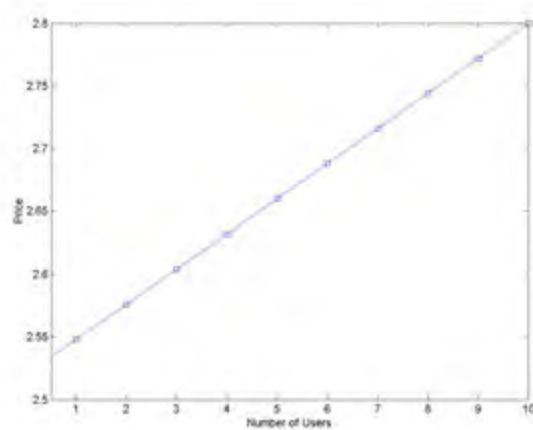


Figure 5.7: Price dependence on Number of Wi-Fi (SU) Nodes

The same investigation is extended to the bandwidth and number of routers and results indicate an increase in bandwidth is experienced with an increase in number of routers as shown in Figure 5.8.

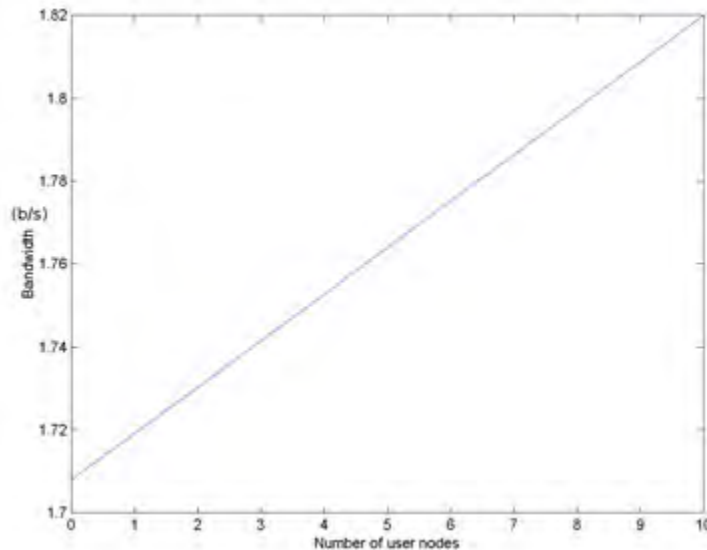


Figure 5.8: Bandwidth variation with Number of User Nodes

**5.9.2 Throughput.** The throughput based model proposed in section 5.7 seeks to understand the influence and contribution of this QoS metric towards efficient TV white space exploitation and utilization by SUs and the benefits accrued by the PUs in allowing part of their spectrum to be utilized. Our analysis on the influence of this metric spans from Figure 5.9 to Figure 5.12. Starting from the profit function, it takes the reverse De Jong form, the point at which the profit function is maximal is deemed to be the equilibrium point. A more practical approach in the form of a genetic algorithm optimisation briefly introduced in chapter 2 subsection 2.4.5 and detailed in chapter 3, section 3.1.2 is adopted. Specifically the genetic algorithm is deployed at the WiMAX and Wi-Fi APs to ascertain knowledge such as TVWS spectrum demand as well as price adjustment. The objective function is the profit function in Equation 5.37 with the parameters as in table 5.6. Clearly from a genetic algorithm perspective a more practical approach yields an equilibrium value after about fifty generations as shown in Figure 5.11. Compared to the theoretically predicted value in the reverse De Jong test function, the genetic algorithm attained value is lower. Intuitively, increasing the number of Wi-Fi nodes generates nearly the same amount of profit, this perhaps could be an indication of the costs being simple shared between the nodes. A further analysis of the throughput QoS metric shows that it varies directly with bandwidth as predicted by equation 5.30 this is to say as the bandwidth increases so is the achieved throughput and by the same token when the bandwidth decreases the throughput correspondingly decreases as shown in Figure 5.9. However, if the bandwidth is fixed and the number of users varied, an inverse relationship exists between throughput and number of nodes, the throughput is initially higher and seems to fall nearly in an exponential fashion as the number of users increase. Four

cases are simultaneously investigated with the bandwidth fixed at the values between 5MHz to 20MHz as the number of users increase, which in some way is an investigation of scaling as shown in Figure 5.10. As expected a high number of users are associated with a higher throughput and a lower number is associated with low throughput. The ideal thing to do is to acquire more bandwidth so as to sustain more nodes as the network scales

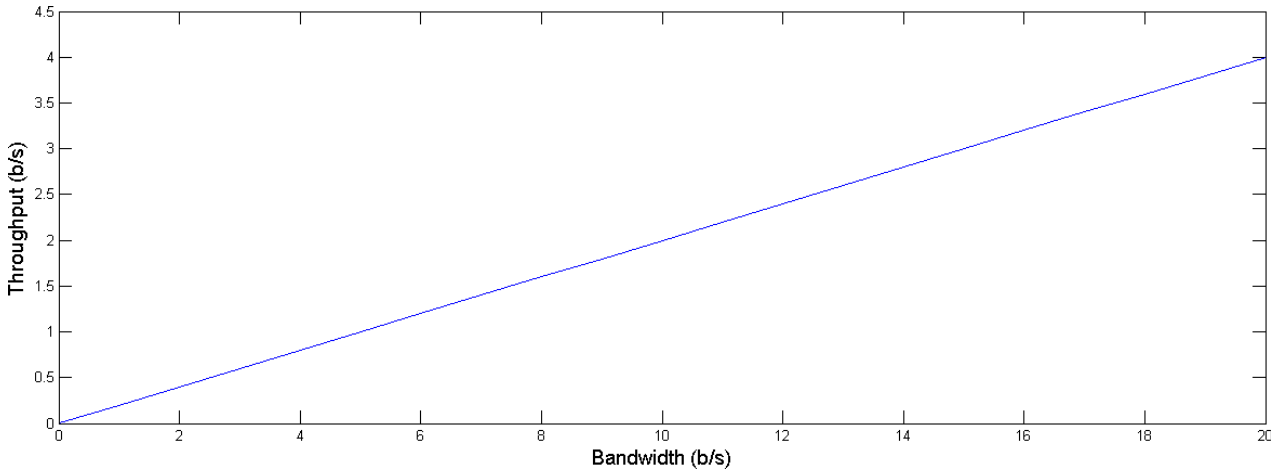


Figure 5.9: Interdependence between Throughput and available Bandwidth

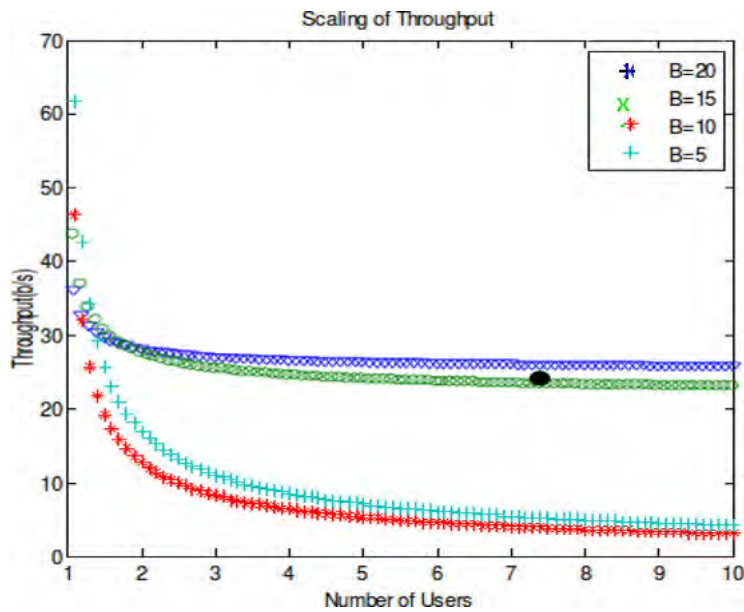


Figure 5.10: Behaviour of Throughput with increasing number of users (Scaling)

It thus suffices to investigate the relationship between throughput and price since bandwidth and throughput are directly related as shown previously. Certainly as the price is increased the throughput also correspondingly increases as shown in Figure 5.12. The implication of this result

is that more has to be paid for more throughput. This further implies the QoS is price dependent as predicted earlier by theory, a subscriber will determine their QoS by their willingness to pay. An exception to the rule is however noted at the price value of five which is suggestively an equilibrium value where the price is the same regardless of the network size given in this context.

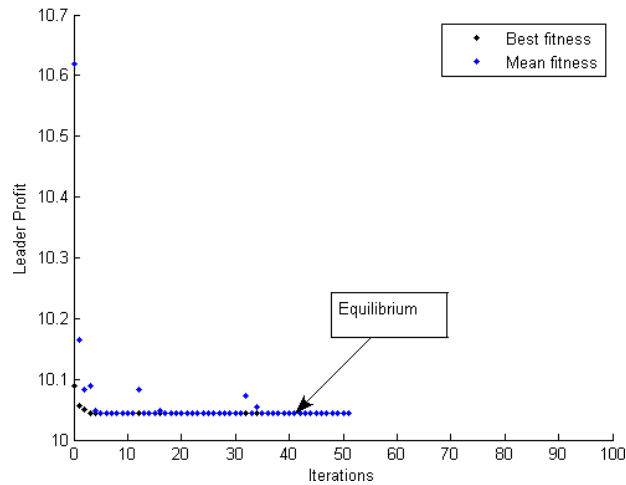


Figure 5.11: Profit of BS at Nash Equilibrium Equilibrium using a Genetic Algorithm

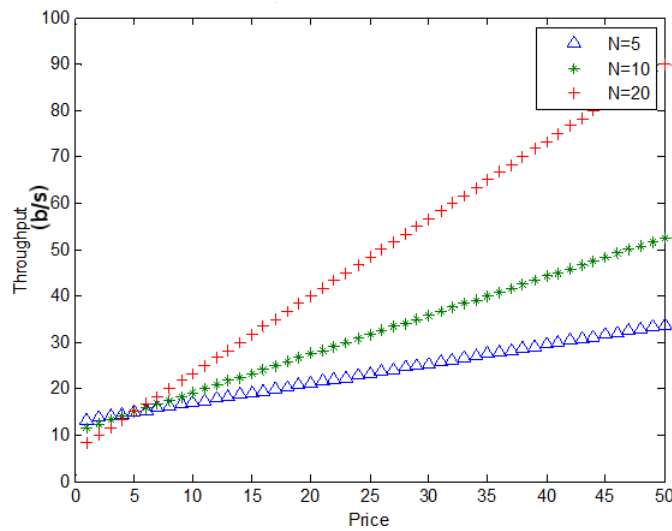


Figure 5.12: Interdependence between Throughput and Price charged

**5.9.3 Composite Metric.** The composite metric model proposed in section 5.8 is the third and final model that has been studied and its performance evaluation spans from Figure 5.13 to Figure 5.18. With regards to the Composite QoS metric, the variation between bandwidth and arrival rate is initially investigated wherein it is revealed that the bandwidth generally drops with

the increase in the arrival rate. The initial values for the bandwidth are however a bit higher than those in the delay model. Furthermore investigations are further extended to the number of SU nodes to be supported and the behavioural pattern seems to match those of the Delay model.

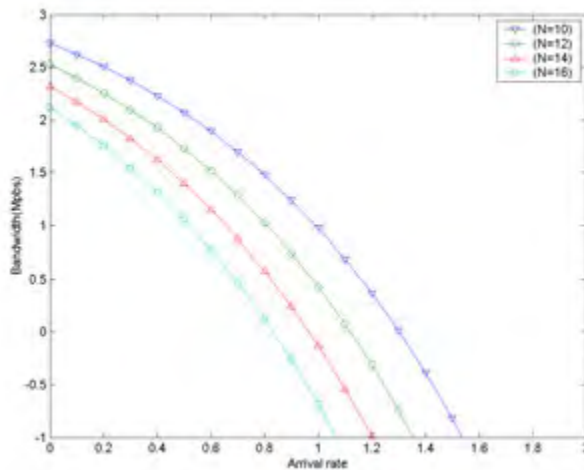


Figure 5.13: Bandwidth variation with the arrival rate for Wi-Fi nodes (Composite metric)

The pattern is such that a high number of nodes require a lower amount of bandwidth and the smaller number of nodes requires a higher amount of bandwidth as shown in Figure 5.13. This variation could possibly be suggestive of the delicate balancing act that is required in this metric. Since this is primarily a pricing problem, our focus is also extended to pricing and arrival rate relations as shown by Figure 5.14. To this end, the price is seen to increase with an increase in the arrival rate. This is however also further extended to a scenario of a variable number of nodes. The higher the number of nodes the higher the price as depicted by the curve for  $N = 16$  and the lower the number of nodes the lower the price as depicted by the same curve for  $N = 10$ . Since this is a pricing problem we investigate willingness to pay with regards to the composite metric (bits/s) with the outcome depicted in Figure 5.15. As the composite metric in bits/s increases the price correspondingly increases as predicted by equation 5.39. However in general, for a group of nodes as the composite metric increases the price also increases. Notably, though the composite metric seems to linearly increase with price, there is a common point which is suggestively an equilibrium point at which irregardless of the number of nodes, the price and thus the composite metric remains the same as shown by the point (10, 5). Finally, network scaling with regards to the composite metric is investigated and the outcome depicted in Figure 5.17 and is consistent with the theoretical prediction  $CM \propto \frac{1}{\sqrt{n}}$ . As the number of users increases the composite metric output decreases almost in an exponential manner though in a much more steeper manner than the throughput scenario. This can possible be perhaps due to the delicate balancing act in achieving a trade-off between the delay and throughput. Finally in Figure 5.18 the profit of the Leader which is the BS is presented from a genetic algorithm perspective. Compared to the throughput metric the value of the profit is slightly lower and again this could possibly be attributed to the need for a balancing act in this kind of QoS metric.

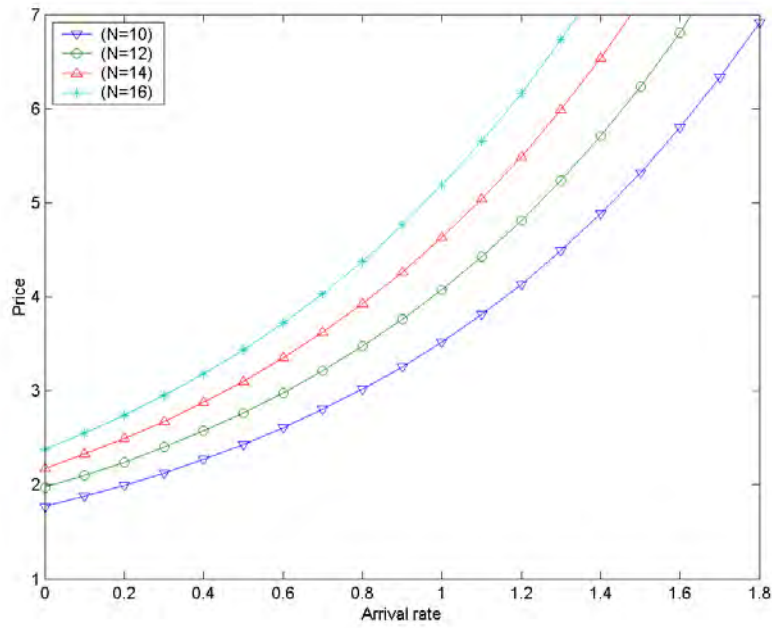


Figure 5.14: Price dependence on the arrival rate for Wi-Fi nodes (composite metric)

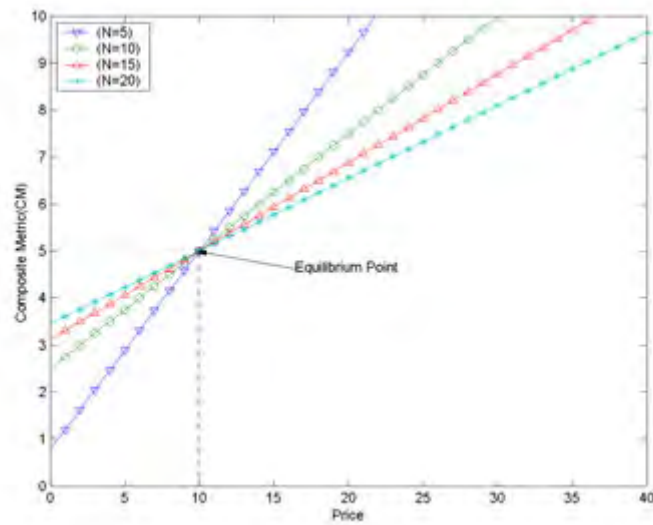


Figure 5.15: Composite Metric variation with Price charged to Wi-Fi Secondary (SU) nodes

The composite metric is also dependent on the bandwidth and this dependence is depicted in Figure 5.16. A direct dependence is observed between the composite metric and the bandwidth, this is to say as bandwidth increases the output due to the composite metric increases.

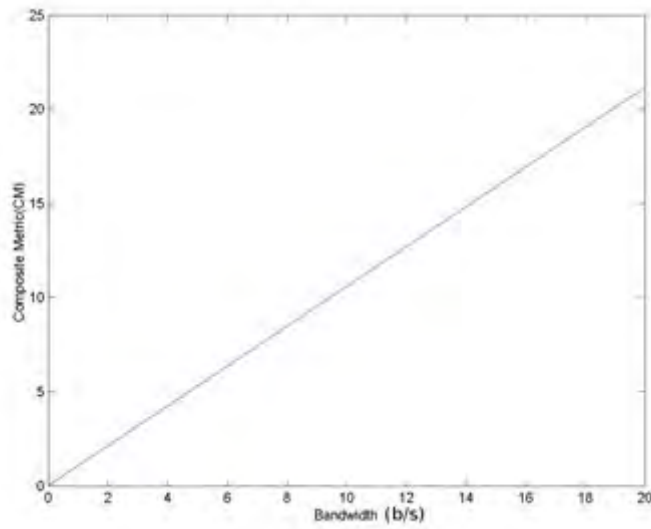


Figure 5.16: Dependence of Composite Metric on Bandwidth requirements of Wi-Fi Nodes

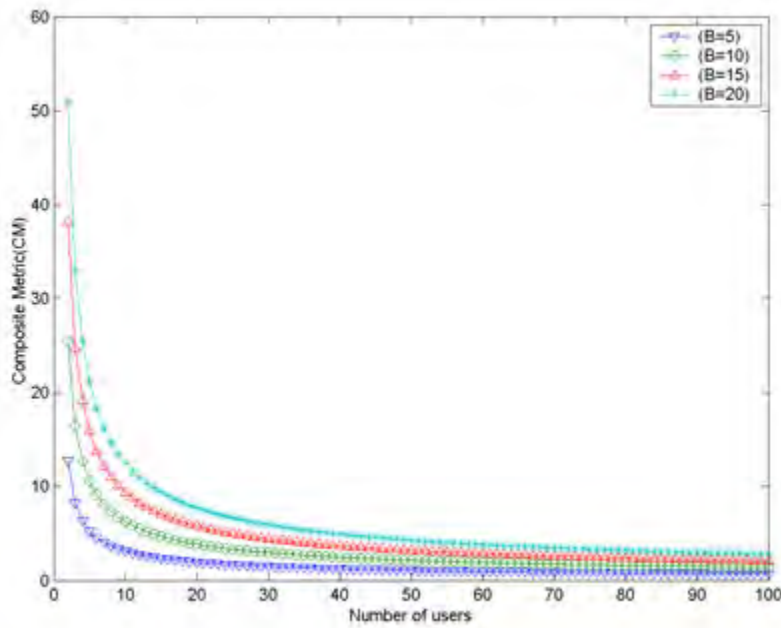


Figure 5.17: Dependence of Network Throughput on Number of users (SU) from a Composite metric perspective-Scaling of Network

Finally, network scaling with regards to the composite metric is investigated and the outcome depicted in Figure 5.17 and is consistent with the theoretical prediction  $CM \propto \frac{1}{\sqrt{n}}$ . As the number of users increases the composite metric output decreases almost in an exponential manner though

in a much more steeper manner than the throughput scenario. This can possibly be perhaps due to the delicate balancing act in achieving a trade-off between the delay and throughput. Finally in Figure 5.18 the profit of the Leader which is the BS is presented from a genetic algorithm perspective. Compared to the throughput metric the value of the profit is slightly lower and again this could possibly be attributed to the need for a balancing act in this kind of QoS metric.

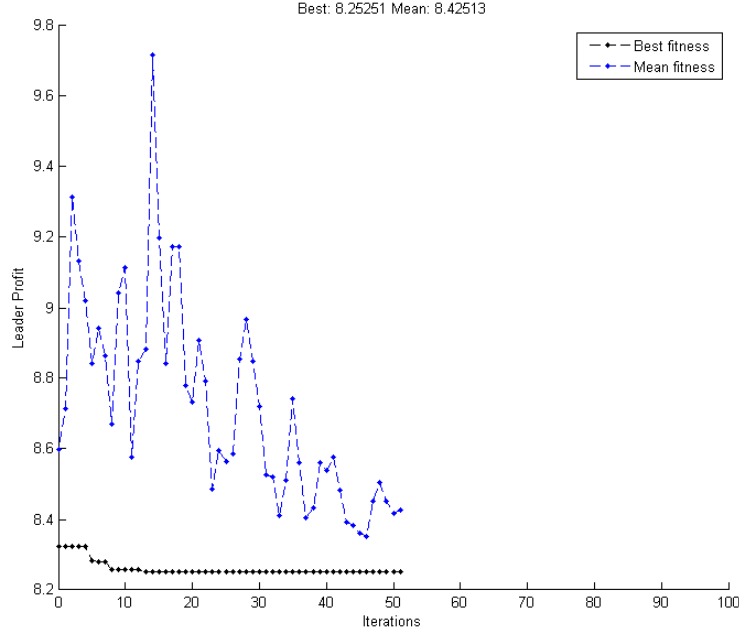


Figure 5.18: Leader Profit from a Composite metric (Throughput+Delay) Perspective)

## 5.10 Comparison of Analytic Models

In section we compare the analytic models from an Primary User perspective i.e. from which of the models is the PU likely to benefit. The performance evaluation function at this stage is the profit function. Thus we compare the profit functions as follows:

$$\phi^{(BS)} = R^{(Ds)} + \sum_{M=1}^N P_M^{(BS)} b_M^{(r)} \quad (5.47)$$

$$\phi_M^r = R_M^r - C_M^r = \sum_{i=1}^N P_M^{(r)} (c_i - d_i P_M^{(r)}) - P_M^{(BS)} \sum_{i=1}^N (c_i - d_i P_M^{(r)}) - F_M^{(r)} \quad (5.48)$$

$$\phi^{BS} = \sum_{i=1}^N (a_i - e_i((1 - \epsilon)D(\lambda_i, b_i^s) = \epsilon T(b_i^s, n) + \sum_{i=1}^N P_M^{BS} b_{iD} + \sum_{i=1}^N P_{iT}^{BS}) \quad (5.49)$$

Figure 5.19 shows the comparison of the profit levels from the perspective of a PU for each of the models i.e., Delay (Equation 5.47), throughput (Equation 5.48) and composite (Equation 5.49) models. The bar graph shows a high profit level for the throughput model, followed by the delay and finally the composite model. Intuitively it would make sense from a business perspective to use the throughput model given its profit levels. This kind of model would suit an urban setting where real time traffic and applications are important. Furthermore in a rural setting where non real-time applications are used the delay model also gives reasonable profit levels. The composite model has the lowest profit margin which from an SU perspective may be indicative of lower prices. However for the PU this could also be indicative of additional overhead costs.

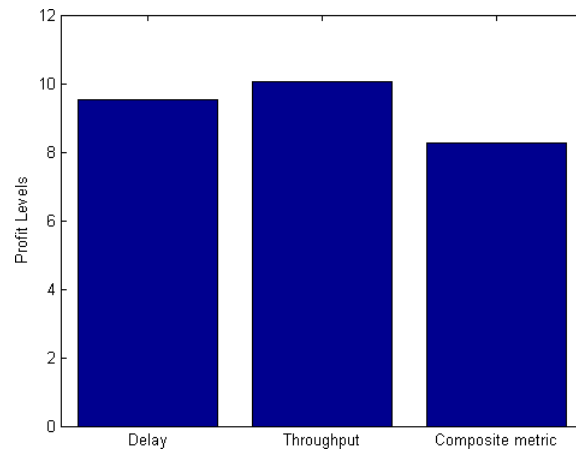


Figure 5.19: Comparison of Profit Levels for different Models

The practical implication of the cooperative framework is the provision of Internet to both small and large communities. In the former the Base Station is the central entity responsible for the pricing and resource allocation as shown in Figure 5.20.

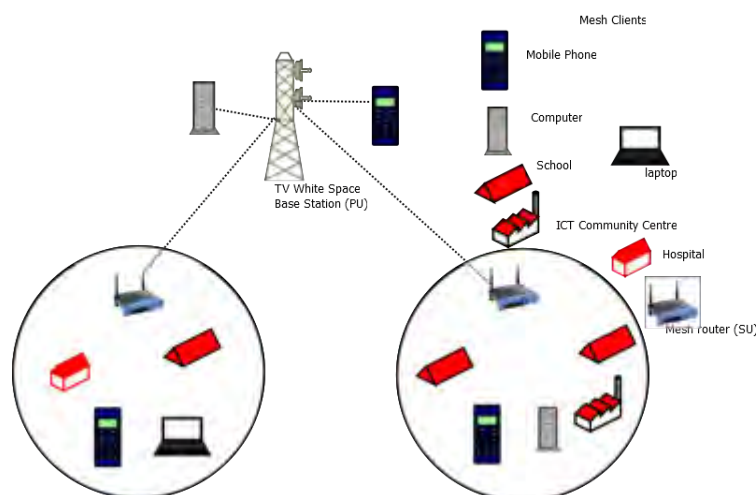


Figure 5.20: Internet Provision to Small Rural Community

The community which contains a small population is able to receive Internet connection to schools so as to facilitate learning and hospitals so as to improve health care through telemedicine. Ordinary citizens in these communities may be able to access Internet through mobile phones, Personal Computers, laptops and other services such as information for farmers may be acquired at an Information and Communications Technology (ICT) community centre. However in a high populated community, this kind of setup will require a much larger network as shown in Figure 5.21. This translates to more Base Stations (BS) being involved and these offer their bandwidth via a Spectrum Broker (SB). Practically the services are acquired through the SB which is responsible for the pricing depending on the demand. The SB continuously queries the TV White Space Database (TVWS DB) so as to determine the availability of free spectrum, i.e., free channels to satisfy the demand. The centralized cooperative cognitive mesh network is designed in accordance with the parameters discussed in section 4.4 of chapter 4.

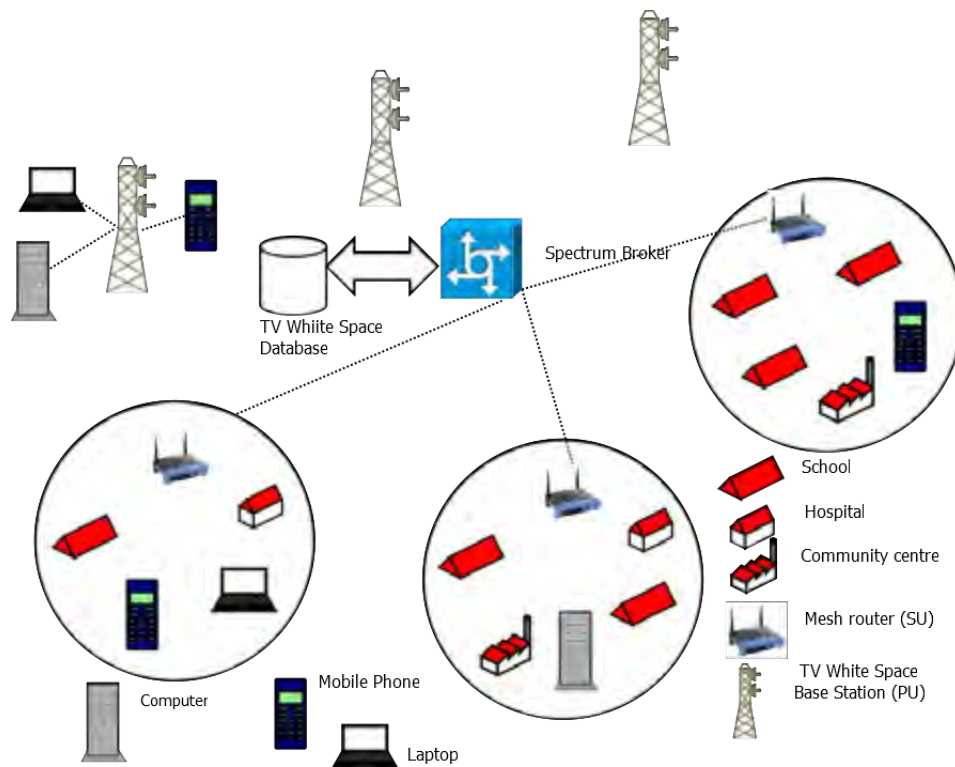


Figure 5.21: Internet Provision to large Rural Community

## 5.11 Conclusion

In this chapter we have partly responded to the first research question wherein a cooperative analytic framework for TVWS sharing has been developed. The framework has been developed within the context of a Cognitive mesh which is a hybrid network of a WiMAX BS and Wi-Fi access points which belong to different operators engaging in TVWS trading. In the Cognitive

mesh, the interaction between the BS and Wi-Fi operators is viewed as pricing problem, wherein the BS which is a leader and has a primary user status strives to maximize its revenue as it avails its spectrum to secondary users. The Wi-Fi attains the follower role with an SU status with its strategy being to acquire as much spectrum as possible in an attempt to satisfy its customer's demand. Thus the pricing problem was generalized into a Stackelberg game in an oligopolistic market. Intuitively the interaction between the leader and follower is based on inter-operator agreements. These inter-operator agreements have subsequently gone onto to inspire the names of the models in the framework as follows:

- Delay Model based on delay QoS
- Throughput Model based on throughput QoS
- Composite Model based on a combination of delay and throughput

A performance evaluation of the models was evaluated on parameters such as arrival rate, price, revenue generated and scalability.

# 6. Non-Cooperative TV White Space Spectrum Sharing Framework

## 6.1 Introduction

Next generation wireless networks will certainly likely comprise of multiple radio technologies and subsystems managed by competing network providers. To this end, wireless technologies, including those using unlicensed spectrum are becoming an important part of the telecommunication landscape. Clearly effective spectrum management is becoming a key policy issue as the range of technologies making the demands on spectrum is rapidly growing in such a set-up. In this chapter we partly respond to the first research question on node and environment interaction, wherein we study the problem of scarce spectrum allocation from a competitive spectrum management perspective. In our study we leverage on the latest developments and innovations in wireless networks such as Mesh networks, TV White Spaces and cognitive radio to gain insight into the efficient spectrum utilization and subsequent economic viability of next generation networks. We approach the problem from a game theoretical perspective as discussed in chapter 3 by considering the interaction between numerous competing technologies such as a non-cooperative game with Nash Equilibrium as the solution. For concreteness, we consider a suitable next generation network in the form of a competitive decentralized low cost cognitive wireless mesh network comprising of licensed users (Aka primary users (PUs)) that compete to offer services to a group of unlicensed Secondary users (SUs) in the form of mesh routers belonging to different entrepreneurial network providers engaged in TV White Space Trading. The non-cooperative interactive engagement of PUs is viewed as a pricing problem wherein each PU strives to maximize its pay-off/profit. Subsequently the problem is reformulated into a Bertrand game, described in chapter 3, in an oligopolistic market with the PUs and SUs as the players involved. In this oligopolistic market, PUs are players that are responsible for selling TV White Space Spectrum while the SUs are the buyers as described in chapter 4. A PU strategizes by way of price adjustment, with a general trend that SUs tend to naturally favour the lowest prices when buying. Ultimately an initially generalized Bertrand game is derived and subsequently adapted for TVWS, to develop three tractable analytic models on the basis of Inter-operator agreements based on QoS performance metrics.

**6.1.1 Contribution.** Our contribution is a response to the first research question and depicts a deviation from the previous cooperative scenario wherein the cognitive radio nodes exhibit cognition but they maximize individual pay-offs using the information gathered within the radio environment. Furthermore, the scenario is further varied by increasing the number of PUs to two. Consequently, competition is both among PUs who strive to maximize revenue by servicing SUs, and SUs compete to sense and attain services from the PUs. Thus our contribution is in the form of a decentralized TVWS spectrum sharing framework with a diametrically different logic (Competition) as compared to the centralized cooperative TVWS spectrum sharing framework in chapter 5. The TVWS spectrum sharing framework comprises three analytic models based on QoS parameters as follows:

- delay model (proposed in section 6.4).
- throughput model (proposed in section 6.5).
- A combination of delay and throughput (proposed in section 6.6).

In the final analysis,

- a performance evaluation of all the analytic models is performed with regards to parameters such as revenue, cost, demand, profit, best response to price adjustment and channel quality (in section 6.7).

The rest of the chapter is organized as follows. A generalized competitive market model is introduced in section 6.2. This is followed by a proposed system model for the TVWS trading between PUs and SUs in section 6.3. Our first analytic model based on delay QoS parameter is formulated and presented in section 6.4. Furthermore a model that is set to handle delay sensitive traffic based on throughput is formulated in section 6.5. Moreover the need to handle both delay and non-delay sensitive traffic is recognised and a model based on a composite (delay +throughput) parameter is formulated and presented in section 6.6. A performance evaluation of the models within the competitive TVWS spectrum sharing framework is carried-out in section 6.7. A conclusion which summarizes the work done in the chapter is presented in section 6.8.

## 6.2 Generalized Competitive Market Model

Our derivation of a generalized Bertrand competition begins with a listing of the assumptions and subsequent explanation of the notation to be used in table 6.1 wherein we consider the existence of two entrepreneurial firms in an oligopoly. With regards to Table 6.1, the subscripts  $i$  and  $j$  denote the firms  $i$  and  $j$  which are coincidentally Primaries  $i$  and  $j$ . In instances where cost is involved the subscript  $f$  denotes fixed cost. However, where superscripts are involved with regard to cost,  $C_i^D$ ,  $C_i^T$ ,  $C_i^\zeta$ , these denote costs due to QoS parameters such as delay( $D$ ), Throughput( $T$ ) and Composite ( $\zeta$ ). The same applies to the corresponding profit which is denoted as either,  $\phi_i^D$ ,  $\phi_i^T$ ,  $\phi_i^\zeta$ . In the existing Bertrand oligopoly a study of the interdependence between player's decisions with regard to pricing, is studied under the following assumptions:

- i Entrepreneurial firms in the market,  $i$
- ii Goods produced are homogeneous, the products are perfect substitutes.
- iii Firms set prices simultaneously.
- iv Each firm has the same constant marginal cost of  $C$

$$Q_i(P_i, P_j) = A - P_i + \Delta P_j \quad (6.1)$$

$$Q_j(P_i, P_j) = A - P_j + \Delta P_i \quad (6.2)$$

Table 6.1: Notation Summary

<b>Symbols</b>	<b>Description</b>
$\lambda_i$	Arrival rate
$Q_i$	Quantity/Spectrum demand
$P_i$	Price strategy $i$
$p_j$	Price strategy $j$
$\Delta$	Substitutability
$C$	Cost
$C_f$	Fixed Cost
$k_i^s$	Spectral efficiency for $i$ (SU)
$k_j^s$	Spectral efficiency for $j$ (SU)
$k_i^p$	Spectral efficiency for $i$ (PU)
$D_i$	Delay
$\psi$	Utility Function
$W_i$	Spectrum(PU)
$R$	Revenue
$C_i^T$	Cost due to Throughput
$\zeta_i$	Composite metric
$C_i^D$	Cost due to Throughput
$d$	Constant
$C_i^\zeta$	Cost due to Composite parameter
$y_j$	Channel quality(player $j$ )
$\phi_i^\zeta$	Profit(Throughput and delay)
$\zeta$	Composite Measure(Throughput and delay)
$\varepsilon$	Tunable Parameter (delay)
$\Lambda$	Tunable paramete (Throughput)
$T$	Throughput
$\phi_i^D$	Profit(Delay)
$\phi_i^T$	Profit(Throughput)
$\beta$	Throughput factor (constant)

The symbols are as explained in the table 6.1, with  $\Delta$  representing the substitutability of the market product. The revenue is a product of the demand and price, computer as follows:

$$R = Q_i P_i \quad (6.3)$$

To drift towards and obtain N.E the individual profits must be computed and then the derivatives obtained with respect to the respective price tariffs. We proceed to express the profits for the entrepreneurs as follows:

$$\phi_i(P_i, P_j) = P_i Q_i - C Q_i - C_f = (A - P_i + \Delta P_i) P_i - C(A - P_i + \Delta P_j) - C_f \quad (6.4)$$

The derivative of  $\phi_i(P_i, P_j)$  with respect to price tariff  $P_i$  is computed as follows:

$$\frac{d\phi_i(P_i, P_j)}{dP_i} = A + \Delta P_j - 2P_i + C = 0 \quad (6.5)$$

$$P_i^* = \frac{A + C + \Delta P_j}{2} \quad (6.6)$$

The expression of the price, for entrepreneurial firm  $j$  is correspondingly obtained as:

$$P_j^* = \frac{A + C + \Delta P_i}{2} \quad (6.7)$$

. The best response strategy is at N.E,  $P_i = P_j$ , this condition subsequently facilitates the computation of the optimal price as

$$(P_i^*, P_j^*) = \left( \frac{A + C}{2 - \Delta}, \frac{A + C}{2 - \Delta} \right) \quad (6.8)$$

We then show the relationship and interdependence between the strategies of firms  $P_j$  and firm  $P_i$  in Figure 6.1.

From Figure 6.1, we deduce the following:

- 1 Firms will never price above the monopoly price. Assuming firm  $i$  believes that firm  $j$  would opt for a price  $P_j$  above the monopoly's price then the best response of firm  $i$  is to price at the monopoly price as its profit will be maximized at that point. Subsequently firm  $j$  would be driven out of the market, on this basis no firm will ever price above the monopoly price.
- 2 At equilibrium, all firm's prices are the same. If firm  $j$  opts to price at the monopoly price, firm  $i$  might decide to price at a slightly lower price and hence capture the entire market given that the goods are perfect substitutes i.e.  $P_i = P_M + \Delta$ , where  $P_M$  is the monopoly price and  $\Delta > 0$ . Logically the equilibrium where firms charges different prices cannot be an equilibrium.
- 3 At equilibrium, prices must be at marginal cost. To understand this rationale, assume  $P_i = P_j = P^* > c$ . Then each of the firms will always find it to be in their best interest to undercut competition and capture the entire market by reducing their prices. By induction, it is thus not possible to have equilibrium above the marginal cost, since it is only at marginal cost that firms have no incentives to deviate from the equilibrium prices [21]. In the next section, we leverage on this generalized competitive market model for TVWS trade within the context of a wireless cognitive mesh network.

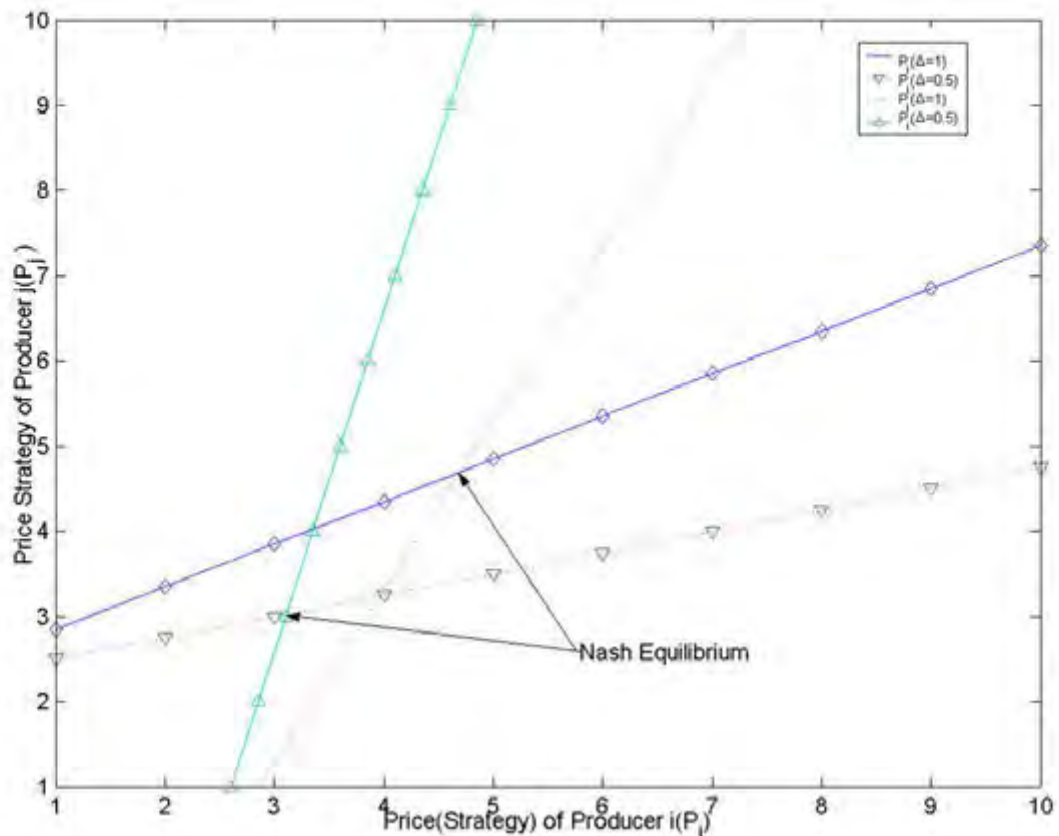


Figure 6.1: *Bertrand Equilibrium*

### 6.3 System Model

We present a competitive scenario within the context of spectrum management wherein licensed users of spectrum called Primary Users (PU) compete to offer services to unlicensed users called Secondary Users (SU). The SUs are equipped with Cognitive radio devices. From a primary user perspective, the cost of providing a service to a secondary user is modelled as a function of QoS degradation. This being a game, Nash Equilibrium is considered to be the optimal solution.

Bertrand model generally depicts competition for an oligopoly market scenario comprising a homogeneous product with static and non-discriminatory prices. In the classical case, this model fits well for a case of two firms bidding in a project in which the winner subsequently takes the entire project. Alternatively two firms may attempt to dominate a market and each one of the firms has sufficient manufacturing capacity to make the entire product. Ultimately the lowest bidder gets the business. We however adapt the model to deal with the spectrum market scenarios within the context of a decentralized Cognitive Wireless Mesh Network (CWMN) as shown in Figure 6.2. We consider the existence of  $N$  primary users operating on dissimilar frequency spectrum and a grouping of secondary users desiring to share the spectrum with the concerned

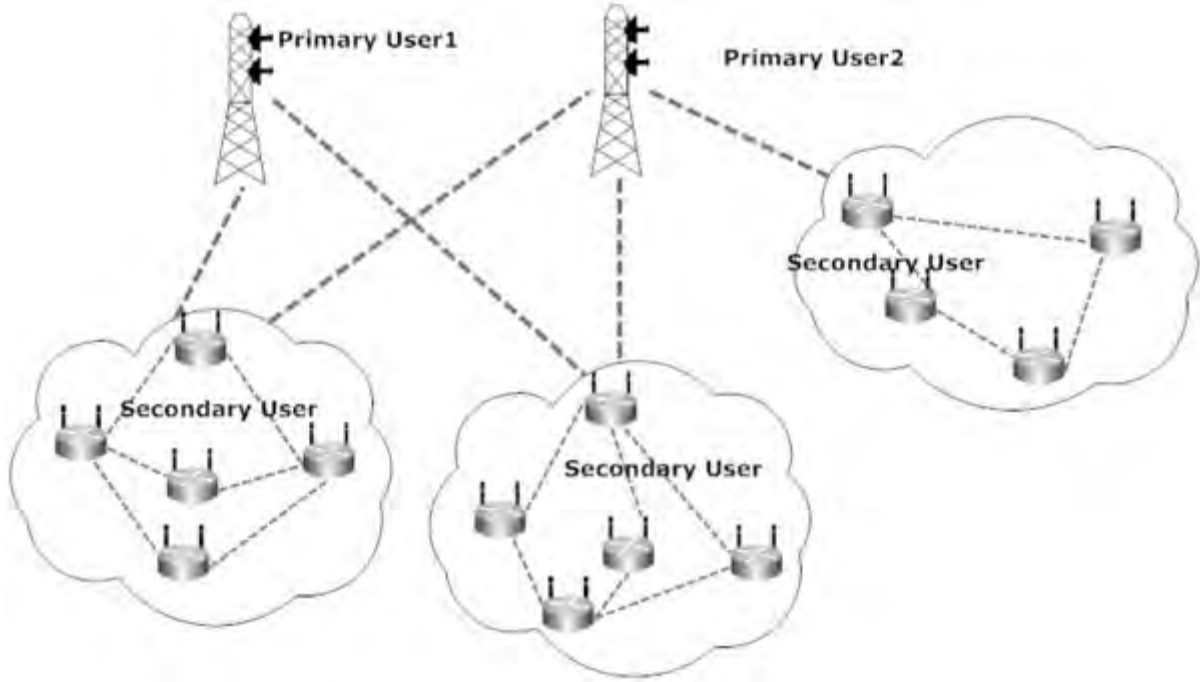


Figure 6.2: *Decentralized Cognitive Mesh Network*

primary users. If  $P_i$  is the tariff/pricing policy at which primary user  $i$  provides a QoS guarantee, then each of the secondary subscribers strives to subscribe at the given tariff so as to attain a QoS sufficient to satisfy individual needs. The secondary users implore adaptive modulation for transmissions in the allocated spectrum in a time-slotted manner. In this kind of modulation, transmission rate is a function of channel quality. In this type of modulation, bit error rate (BER) must be maintained at specified target levels. Accordingly, the spectral efficiency of transmission for secondary user  $i$  can be expressed as:

$$k_i = \log_2(1 + Ky_i) \quad (6.9)$$

where

$$K = \frac{1.5}{\ln\left(\frac{0.2}{BER_i^{tar}}\right)}$$

The secondary user  $i$  transmits with spectral efficiency  $k_i$  to the extent that the demand of the secondary users is a function of transmission rate in the allocated frequency spectrum as well as the price charged by the primary users.

**6.3.1 QoS Measure.** The QoS performance of a primary user is degraded in the event of some portion being shared with the secondary user. Thus price function must be considerate of the QoS performance of the primary user. On this basis we consider three QoS measures as follows:

- 1 . Average delay measure
- 2 . Throughput measure

### 3 . Combined delay and throughput measure

as QoS measures obtained for the transmissions at the primary user based on an M/D/1 queuing model [147].

**6.3.2 Utility Function.** The utility gained by the secondary users makes it possible to ascertain the level of spectrum demand. A quadratic utility function defined as in [244]:

$$\psi(\mathbb{Q}) = \sum_{i=1}^M Q_i k_i^s - \frac{1}{2} \left( \sum_{i=1}^M Q_i^2 + 2\Delta \sum_{i=1}^M Q_i Q_j \right) - \sum_{i=1}^M P_i Q_i \quad (6.10)$$

where  $\mathbb{Q} = Q_1, \dots, Q_i, \dots, Q_M$

$$J = - \sum_{i=1}^M P_i Q_i \quad (6.11)$$

The spectrum substitutability is included in the utility function by way of parameter  $\nabla$ . This parameter permits the secondary users to switch between frequencies depending on the offered price. The demand function of the secondary user is obtainable from differentiating the utility function w.r.t  $Q_i$  as follows:

$$\frac{d\psi(\mathbb{Q})}{dQ_i} = 0 \quad (6.12)$$

The demand function is the size of shared spectrum that maximizes the utility of the secondary user given the prices offered by the primary service

$$Q_i = \frac{k_i^{(s)} - P_i - \Delta(k_j^{(s)} - P_j)}{1 - \Delta^2} \quad (6.13)$$

**6.3.3 Bertrand Game Model.** The Bertrand Game is formulated with the players being the PUs. The PUs are competing and using price as the strategy. The price is that of unit spectrum. The profit realized by each PU denotes its pay-off as a result of the adopted strategy. The Bertrand oligopoly is formulated as in Table 6.2

Table 6.2: Bertrand game formulation

Entity	Description
<i>Players</i>	Primary users
<i>Strategies</i>	Price per unit of spectrum ( $P_i$ )
<i>Payoffs</i>	The pay-off for each player is the profit of primary user

## 6.4 Analytic Delay Model

According to Yang et.al, [278] predicting the end-to-end delay and understanding the Internet dynamics is of great importance for many real-time and non real-time applications, especially

for the provisioning of the QoS for various sources. This assertion holds true for both the cooperative and the non-cooperative node interactive scenarios within the radio environment. Given the differences in diametrically different logic between the cooperative and non-cooperative scenarios, our delay for the competitive scenario is a deviation from that of the cooperative case. Our model is based on the delay QoS parameter, as a way of formulating the model and understanding the dynamics of node interaction in a competitive radio environment, the functions such as delay, demand, cost, revenue and profit. It is from the delay that the cost of sharing TVWS is ascertained. The revenue is product of the price and the demand. The payoff is obtained from the revenue less the cost of sharing the TVWS. Next we embark on the actual formulation the delay model and its associated dynamics starting from the delay. The delay QoS measure, is defined as:

$$D_i(Q_i) = \frac{1}{2} \frac{\lambda_i}{(k_i^{(p)}(W_i - Q_i)^2 - \lambda_i k_i^{(p)}(W_i - Q_i))} \quad (6.14)$$

with the symbols meaning as given in the table 6.1, it is worth to note that  $k_i^{(p)}(W_i - Q_i)$ , denotes the service rate. The cost function is defined as:

$$C_i^D = dD_i(Q_i) \quad (6.15)$$

The revenue is the product of the demand as well as the price as previous defined in equation 6.3 in section 6.2 and is expressed as follows:

$$R = Q_i P_i \quad (6.16)$$

The profit due to a delay QoS performance is the revenue in equation 6.16 less the cost in equation 6.15

$$\phi(\mathbb{P})_i^{(D)} = Q_i P_i - C_i^{(D)} \quad (6.17)$$

The solution to this game is the Nash Equilibrium ( $NE$ ) obtainable by way of the best response. For a best response of a Primary user  $i$  given the prices of other primary users  $P_i$ , where  $j \neq i$  is defined as

$$\mathbb{BR}_i(\mathbb{P}_{-i}) = \text{argmax} \phi_i(\mathbb{P}_{-i} \cup P_i) \quad (6.18)$$

The set  $\mathbb{P}^* = \{P_1^*, \dots, P_N^*\}$  represents the N.E of this Bertrand game, if and only if

$$P_i^* = \mathbb{BR}(\mathbb{P}_{-i}^*), \forall i \quad (6.19)$$

The  $NE$  value in the context of delay QoS measure is obtainable by differentiating

$$\frac{d\phi(\mathbb{P})_i^D}{dP_i} = 0 \quad (6.20)$$

for all  $i$  where

$$\phi(\mathbb{P})_i^D = P_i \frac{k_i^s - P_i - \Delta(k_j^{(s)} - P_j)}{1 - \Delta^2} - \frac{d\lambda_i}{2(W_i - Q_i)^2 - 2\lambda_i(W_i - Q_i)} \quad (6.21)$$

The derivative of this profit function is equated to zero as follows

$$0 = \frac{k_i^{(s)} - 2P_i - \Delta(k_i^{(s)} - P_j)}{1 - \Delta^2} + \frac{d \frac{\lambda_i}{1 - \Delta^2(4Q_i - \lambda_i)}}{(2Q_i^2 - 2Q_i\lambda_i)^2} \quad (6.22)$$

$$Q_i = W_i - \frac{k_i^{(s)} - P_i - \Delta(k_j^{(s)} - P_j)}{1 - \Delta^2}$$

## 6.5 Throughput Model

The delay model may in practice not be able to adequately provide QoS to all kinds of applications. We propose a model based on the throughput as an alternative QoS parameter. Objectively our model will strive to maximize system throughput or to maximize spectrum utilization within the TVWS spectrum sharing framework. However, the same network conditions as well as same network architecture as in Figure 6.2 are assumed to exist. Furthermore the utility is considered the same as in section 6.4. For convenience sake we restate the utility as well as the demand functions within the context of a throughput model as follows: Utility function

$$\psi(\mathbb{Q}) = \sum_{i=1}^M Q_i k_i^s - \frac{1}{2} \left( \sum_{i=1}^M Q_i^2 + 2\Delta \sum_{i=1}^M Q_i Q_j \right) - \sum_{i=1}^M P_i Q_i \quad (6.23)$$

where  $\mathbb{Q} = Q_1, \dots, Q_i, \dots, Q_M$

$$J = - \sum_{i=1}^M P_i Q_i \quad (6.24)$$

is still the same as in subsection 6.3.2. The demand function is also restated for convenience as in equation 6.25.

$$Q_i = \frac{k_i^{(s)} - P_i - \Delta(k_j^{(s)} - P_j)}{1 - \Delta^2} \quad (6.25)$$

The demand function is the same and still depends on the spectral efficiency, the substitutability as well as the price. A departure from the previous model in subsection 6.4 is that of using throughput QoS parameter as our measure. The throughput QoS measure is expressed in [75] as:

$$T(Q_i) = \sum_{i=1}^N \frac{\beta Q_i}{\sqrt{n \log n}} \quad (6.26)$$

Equation 6.26 theoretical predicts a direct dependence between the spectrum demand and the throughput. Furthermore the same relation has in existence an inverse relationship between throughput and number of nodes. In provisioning a service such as the Internet where throughput is the QoS measure, there is an associated cost. The cost due to this measure is expressed as:

$$C_i^T = dT_i(Q_i) \quad (6.27)$$

A more fundamental quantity is the revenue which is computational the product of the demand function for the TVWS and the price as in equation 6.28.

$$R^T = Q_i P_i \quad (6.28)$$

The revenue is so much jointly directly dependent on the demand for spectrum as well as the price levied. The throughput based profit is computed from the revenue depicted in Equation 6.28 less the cost depicted in Equation 6.27 as shown in Equation 6.29

$$\phi(\mathbb{P})_i^{(T)} = Q_i P_i - C_i^{(T)} \quad (6.29)$$

The  $NE$  value in the context of Throughput QoS measure is obtainable by differentiating the profit (Equation 6.29) with respect to the levied price as shown in equation 6.30

$$\frac{d\phi(\mathbb{P})_i^T}{dP_i} = 0 \quad (6.30)$$

Prior to differentiating with respect to price, we further simplify the profit function 6.29 as shown in Equation 6.5

$$\begin{aligned} \phi(\mathbb{P})_i^T &= P_i \frac{k_i^s - P_i - \Delta(k_j^{(s)} - P_j)}{1 - \Delta^2} \\ d\beta \frac{k_i^s - P_i - \Delta(k_j^{(s)} - P_j)}{1 - \Delta^2 \sqrt{n \log n}} & \end{aligned} \quad (6.31)$$

The derivative of the profit function is then given by equation 6.32.

$$\frac{k_i^s - 2P_i - \Delta k_j^s + P_j}{1 - \Delta^2} - \frac{1}{1 - \Delta^2 \sqrt{n \log n}} = 0 \quad (6.32)$$

Equation 6.32 enables us to determine at equilibrium the influences of price, spectral efficiency and channel quality on the designed network architecture.

## 6.6 Combined Delay and Throughput Model

A combined metric which we shall refer to as a composite metric is a combination of the delay and throughput QoS measures. Thus the Composite QoS measure is expressed as :

$$\zeta(Q_i) = \varepsilon(D(Q_i)) + \Lambda(T(Q_i)) \quad (6.33)$$

The relation between  $\Lambda$  and  $\varepsilon$  is given by:

$$\Lambda = 1 - \varepsilon \quad (6.34)$$

For convinience sake, we again emphasise that the same system model in Figure 6.2 is used as in the previous two models (Delay and Throughput) in sections 6.4 and sections 6.5 respectively.

For the same network conditions and structure, the demand remains the same and can be restated as

$$Q_i = \frac{k_i^{(s)} - P_i - \Delta(k_j^{(s)} - P_j)}{1 - \Delta^2} \quad (6.35)$$

Prior to computing the revenue generated as a result of the demand under the new composite metric, we compute the cost due to the metric as:

$$C_i^\zeta = d\zeta(Q_i) \quad (6.36)$$

The cost is a function of the QoS to be provided. The profit due to the composite metric is obtainable from the revenue less the cost of the TV white space. For this reason, we conveniently compute the revenue as the product of the demand and price levied in Equation 6.37.

$$R^{TD} = Q_i P_i \quad (6.37)$$

The profit function is obtainable by computing the difference between the revenue (Equation 6.37) and the cost (Equation 6.36).

$$\phi_i^{TD} = Q_i P_i - d(\varepsilon(D(Q_i)) + \Lambda(T(Q_i))) = \frac{P_i k_i^s - P_i^2 - P_i \delta(k_j^s - P_j)}{1 - \Delta^2} - d(\varepsilon(D(Q_i)) + \Lambda(T(Q_i))) \quad (6.38)$$

Equation 6.38 reveals the profit's dependence on the composite metric, the spectral efficiency as well as the price. To obtain N.E, we take the first derivative of the profit equation 6.38 and equate in to zero as in equation 6.39.

$$\frac{d\phi_i^{TD}}{dP_i} = 0 \quad (6.39)$$

for all i. We further expand the profit function in equation 6.40 to facilitate the differentiation process.

$$\phi_i^{TD} = \frac{P_i k_i^s - P_i^2 - P_i \delta(k_j^s - P_j)}{1 - \Delta^2} - \left( \frac{d\lambda_i}{(2W_i - Q_i)^2 - 4\lambda(W_i - Q_i)} + \frac{dk_i^s - P_i - \Delta(k_j^s - P_j)}{(1 - \Delta^2)(\sqrt{n \log n})} \right) \quad (6.40)$$

The derivative thus becomes

$$0 = \frac{k_i^s - 2P_i - \Delta(k_j^s - P_j)}{1 - \Delta^2} + \frac{\frac{d\lambda_i(4Q_i - \lambda_i)}{1 - \Delta^2}}{(2Q_i^2 - 2Q_i \lambda_i)^2} - \frac{1}{(1 - \Delta^2)\sqrt{n \log n}} \quad (6.41)$$

where

$$Q_i = W_i - \frac{k_i^s - P_i - \Delta(k_j^s - P_j)}{1 - \Delta^2}$$

Ultimately, prior to a performance analysis exercise which we defer to section 6.7, we summarize all the models as shown in table 6.3.

Table 6.3: Summary of Models

Model	Strategy	Revenue	Cost	Payoff
Generalized	Price	$R = Q_i P_i$ (Eqn 6.3)	$C$	$\phi_i(P_i, P_j)$ (Eqn 6.4)
Delay(Eqn 6.14)	Price	$R = Q_i P_i$ (Eqn 6.16)	$C_i^D$ (Eqn 6.15)	$\phi_i^D$ (Eqn 6.17)
Throughput(Eqn 6.26)	Price	$R = Q_i P_i$ (Eqn 6.16)	$C_i^T$ (Eqn 6.27)	$\phi(\mathbb{P})_i^{(T)}$ (Eqn 6.29)
Composite(Eqn 6.33)	Price	$R = Q_i P_i$ (Eqn 6.16)	$C_i^C$ (Eqn 6.36)	$\phi_i^C$ (Eqn 6.40)

## 6.7 Performance Evaluation

In this section, we focus on a performance evaluation of the three proposed models in the non-cooperative spectrum sharing framework. More importantly we provide a partial response to the first research question which is concerned with node cognition i.e., *Can next generation mesh networks be designed to include Cognitive nodes that can learn from their environment and broadcast the information in order to allow the mesh network optimize its routing performance based on informed decision?*

As a way of responding to the above question, we consider the existence of a decentralized cognitive mesh network wherein two primary users are existence and each one of the PUs has to service a set of secondaries on a competitive basis. By exhibiting a competitive behaviour, we evaluate the three models in the context of a decentralized Cognitive mesh in subsections 6.7.1, subsection 6.7.2 and subsection 6.7.3 using the parameters in table 6.4. These parameters describe close to a real-practical setting for a decentralized cognitive mesh network.

**6.7.1 Delay model.** For the delay model proposed in section 6.4, Figure 6.3 characterizes the interaction between the secondary and primary routers using the following functions:

- demand of the secondary user ( Equation 6.13)
- revenue (Equation 6.16)
- cost (Equation 6.15)
- profit of the primary user (Equation 6.17)

under variable pricing options in accordance with the analytic QoS delay model. The dynamics of the interaction are such that when the primary user (router) strategizes by increasing the spectrum price, the secondary user responds by correspondingly demanding less spectrum owing to the utility of the allocated spectrum. Moreover, the cost for the primary user decreases as a result of the smaller demand from the secondary user. Consequently, the size of the residual TV white space spectrum remains bigger giving rise to a lesser delay. However, the other two functions, namely, the revenue and profit clearly, traverse a parabolic path with an initial increase followed by attainment of optimal point and a subsequent decrease. Furthermore we progressively focus on Equation 6.22 wherein we deal with best response in Figure 6.4 and Figure 6.5 respectively.

Table 6.4: System Parameters

Parameter	Value
PU Spectrum	$5MHz$
BER	$10^{-4}$
Traffic Arrival Rate	$1Mbps$
$d$	1
Channel Quality Span	$10 - 20dB$
$\lambda_i$	$4Mbps$
$y_1$	$15dB$
$y_2$	$18dB$
$\Delta$	0.4
$P_2$	1
Primary users	2

With regards to the best response Equation 6.22, for a small price, the first primary user can sell a bigger spectrum size to the secondary user; this translates to an increase in revenue as well as profit. The analytic delay model also characterizes the interaction between the two primaries with regards to their best responses as depicted by Figure 6.4. This in a way depicts attempts to catalyse spectrum price decrease and a subsequent increased access to Internet services. The price catalysation is brought about by a change in strategy by both Primary 1 and Primary 2 as they seek to attain the best price and subsequently capture a larger market share which ultimately means increased profit. The price strategy is itself a function of channel quality, thus when channel quality increases, the spectrum demand increases as it gives the secondary user a higher rate due to adaptive modulation. Consequently as in accordance with the law of demand and supply in economics, the primary user sets a higher price. The intersection of the best response lines from both primary 1 and primary 2 depicts the location of the optimal point which is also the N.E point. The N.E points for the delay metric are located at a lower position value points as compared to those of the throughput performance metric. This intuitively means it may be advisable to implore this performance metric in attempts to catalyse a decrease in service prices and subsequently enable entrepreneurs to achieve increased access in the rural and remote parts. Next we investigate and analyse, Nash Equilibrium under variable channel quality depicted by Figure 6.5 for both performance metrics. A higher channel quality is deliverable via the delay QoS metric as compared to its throughput counterpart. This translates to a higher Nash Equilibrium point for the delay QoS metric. This is a result of a higher demand emanating from the secondary users. The channel quality offered by one primary impacts the strategies adopted by the other primary. Consequently, when the demand offered by one player is varied, the other player must responsively adopt the price to attain higher price.

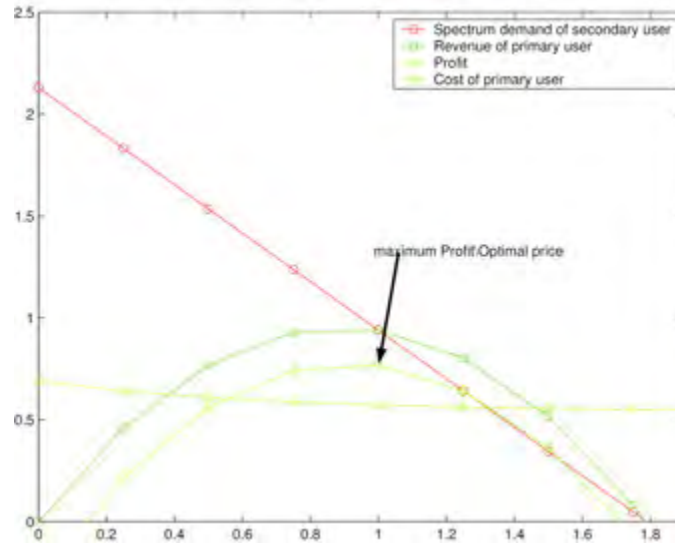


Figure 6.3: *Demand-Revenue-Cost and Profit (Delay)*

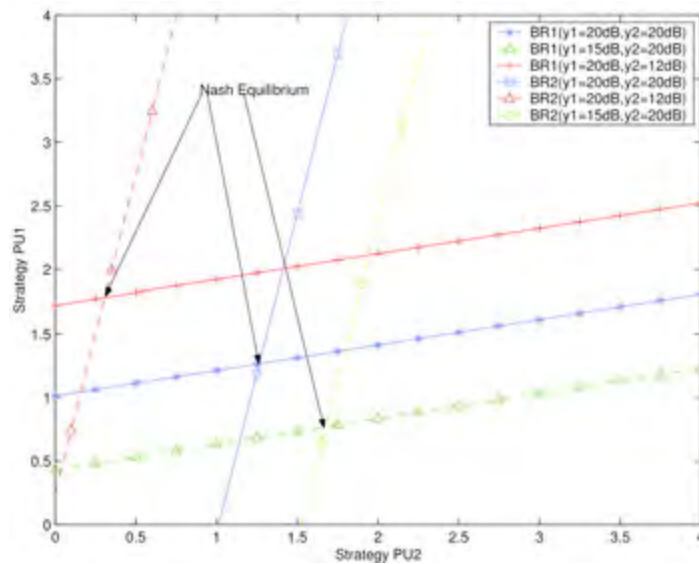


Figure 6.4: *Best Response (Delay)*

**6.7.2 Throughput Model.** In this section, in accordance with the analytic throughput model, firstly we characterize the interaction between a secondary and primary user through the following functions

- Spectrum demand of the secondary user (Equation 6.25)
- cost (Equation 6.27)

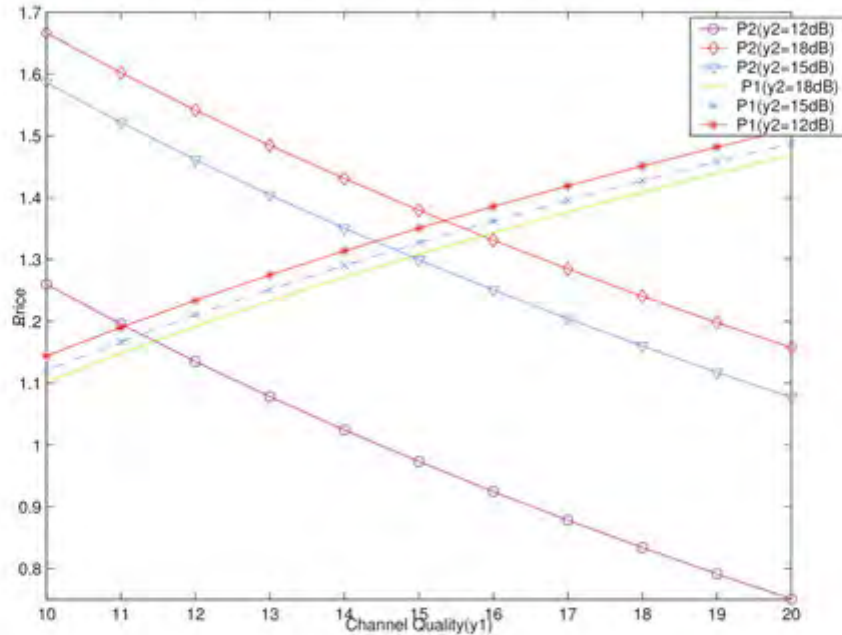


Figure 6.5: Channel Quality (Delay)

- Revenue (Equation 6.28)
- profit of the primary user (Equation 6.29)

In the second instance we characterize the interaction of two primaries in a competitive context, relative to the following criterion:

- Best response
- Channel quality

The first instance is depicted by Figure 6.6, where the spectrum demand decreases considerably as the price increases. Similar to the analytic delay model, when the primary user strategizes by increasing spectrum price, the service recipient which is the secondary user interactively responds by demanding less spectrum and this is in accordance with the predictions of equation 6.25. Unlike the analytic delay model, the cost for the primary user sharply decreases given a smaller demand for spectrum. The revenue and profit functions (Equation 6.28 and Equation 6.29) traverse parabolic paths as in the previous model. The main difference in the gap between the revenue and the profit is perhaps reflective of the differences in the cost functions.

The second instance is depicted by Figure 6.7 in which two primaries interact and attempt to achieve their best response under the market conditions.

This is a competitive scenario, which should encourage investment as the two players under cut each other in their attempt to capture the market share. To this end, the intersection of the response lines depicts point of Nash Equilibrium, which are located at higher positions than those

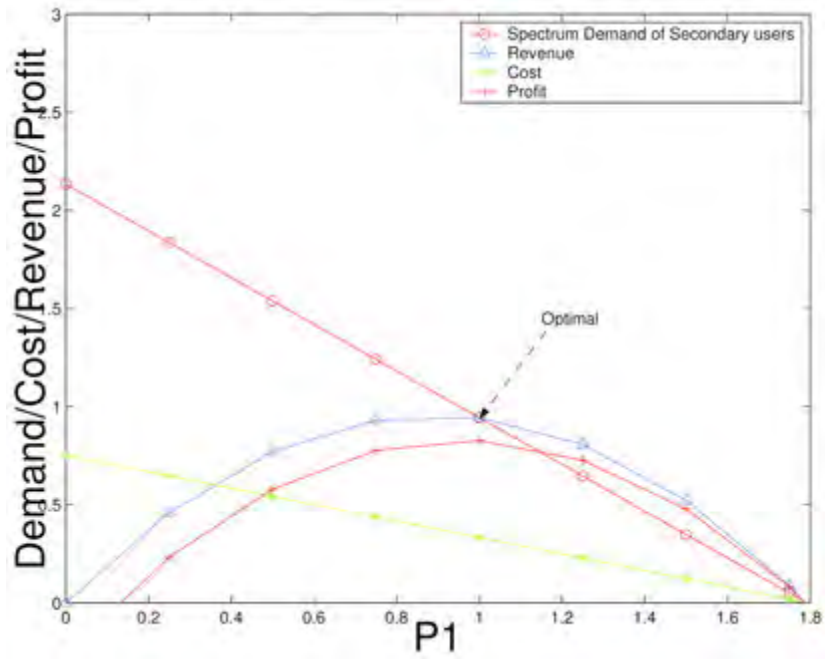


Figure 6.6: Demand-Revenue-Cost and Profit(Throughput)

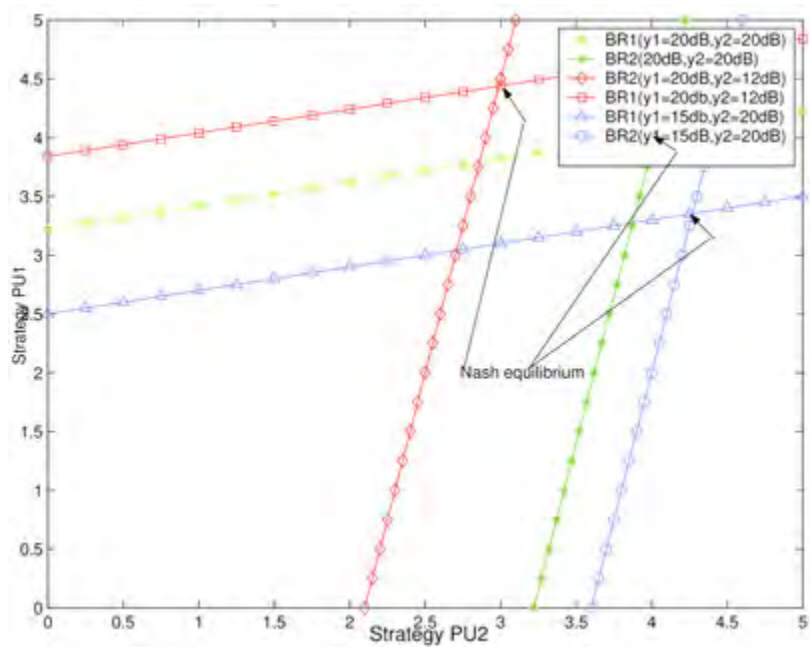


Figure 6.7: Best Response(Throughput)

in the delay model. This represents the feasibility of improving and accessing more spectrum under this model, though at a price.

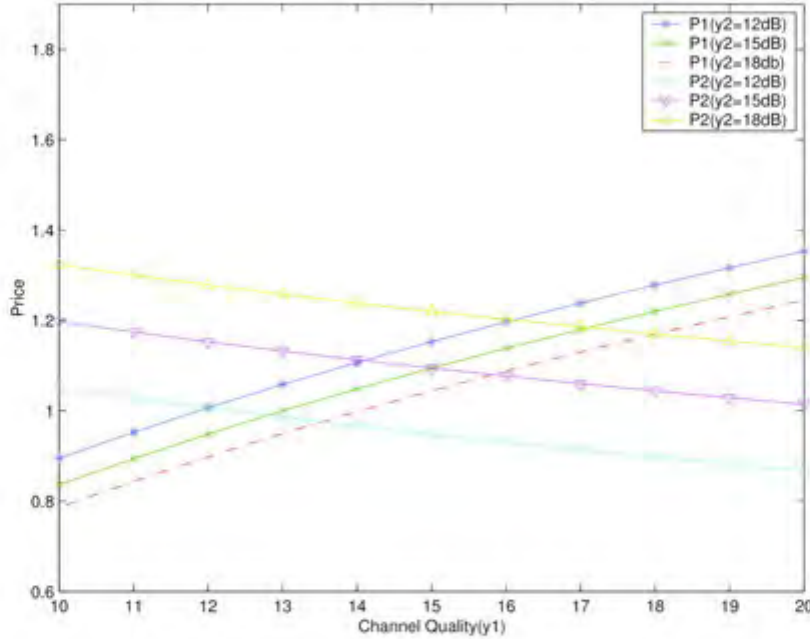


Figure 6.8: Channel Quality(Throughput)

It is clear that the price strategy is itself a function of channel quality as depicted by Figure 6.8 and predicted by the NE condition in equation 6.32. The channel quality offered by one player impacts on the strategy of another player. This is to say, when the demand offered by one player is varied, the other player has to responsively adjust its price. Compared with the delay model, the throughput model delivers the same channel quality at a decreased price thus making it a more desirable model than the delay model.

### 6.7.3 Combined Delay and Throughput.

In this subsection, we follow the same chronology as in the previous models i.e delay in subsection 6.7.1 and throughput in subsection 6.7.2. Thus we characterise the following functions

- Spectrum demand of the secondary user (Equation 6.35)
- cost (Equation 6.36)
- Revenue (Equation 6.37)
- Profit of the primary user (Equation 6.38)

in Figure 6.9. Figure 6.9 depicts the demand function of the secondary user, the revenue, cost and profit of the primary user under various pricing options. As the first primary user increases its price, the secondary user responsively demands a small amount of spectrum owing to a decrease in the utility of the allocated spectrum. This is clearly shown by the negative gradient line which represents the demand function of the secondary user. However, this demand function behaviour impacts on the cost for the primary user. This is to say, the cost for the primary user decreases with a decrease in the demand function this therefore translates to a larger amount of residual

spectrum corresponding to smaller delay. The revenue and profit functions of the primary user are all traversing a parabolic path as depicted on the same graph. Clearly both functions in question initially increase with an increase in price up to the optimal point where both functions begin to show a decline in both the revenue and profit. To this end, the primary user is able to sell a larger amount of spectrum to the secondary user at a smaller price thereby giving an increase in revenue as well as profit. Conversely when the price increases a small amount of spectrum is sold due to a decrease in the level of demand by the secondary user ultimately resulting in dwindling profit. Certainly an optimal price exists upon which the profit is maximized and this denotes an apparent best response for the corresponding primary user. This best response is further investigated wherein the best responses of the two primary users are analysed in accordance with equation 6.41 in Figure 6.11 and Figure 6.10 (channel quality).

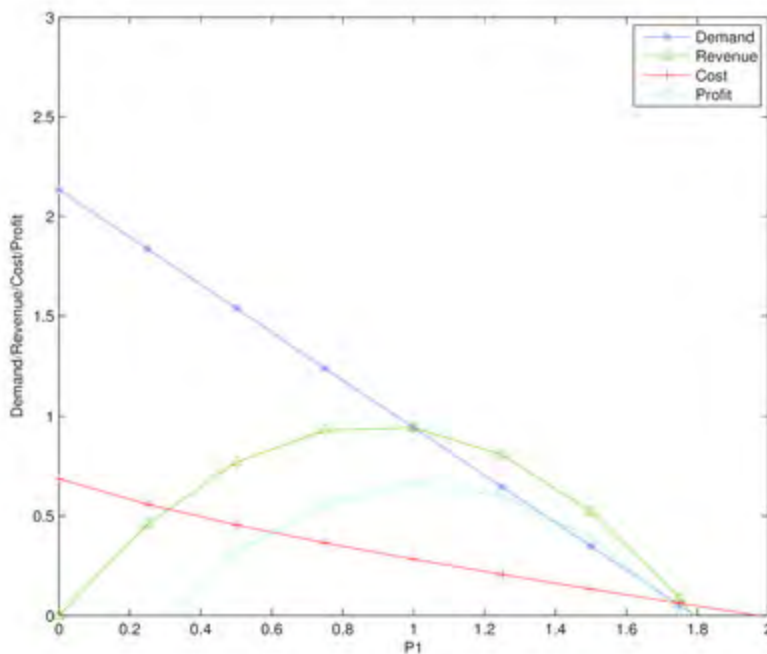


Figure 6.9: Demand-Revenue-Cost and Profit(Composite)

In Figure 6.11, we analyse the best response functions of the two primary users under variable channel quality ( $y_1, y_2$ ) for the secondary user. When the channel quality increases, the spectrum demand correspondingly increases. The individual primary user then consequently offers a higher price. However, the best response function graphs intersect at some point called Nash Equilibrium. We analyse this Nash equilibrium under varied channel quality. Figure 6.10 depicts a scenario in which the Nash equilibrium is higher for higher channel quality, this emanates from an increased demand of spectrum by the secondary user. Moreover, we notably realize that the channel quality offered by one individual primary user impacts on the other individual primary user. This is to say, channel quality offered by one primary user impacts the strategy adopted by the other primary user. Consequently when the demand for spectrum from an individual player is varied, the other player adapts the price so as to maximize profit.

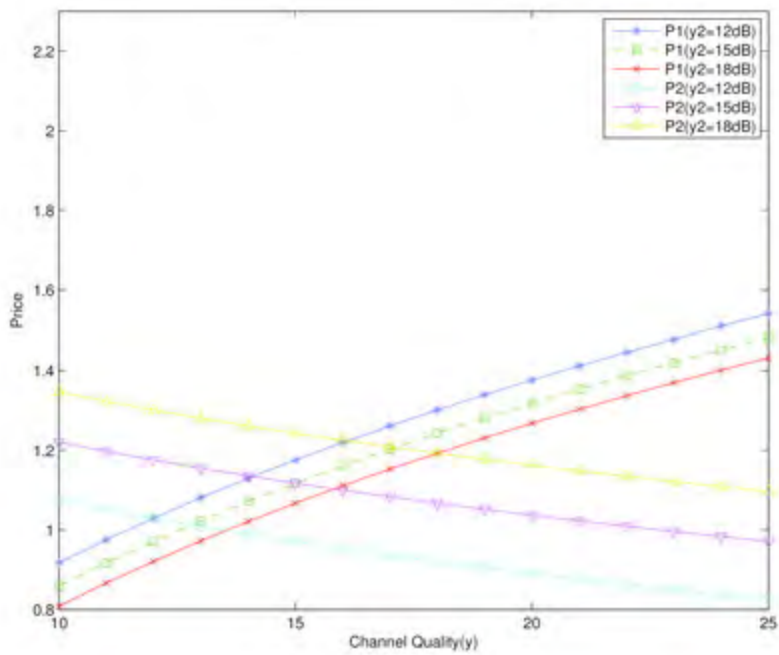


Figure 6.10: *Channel Quality(Composite)*

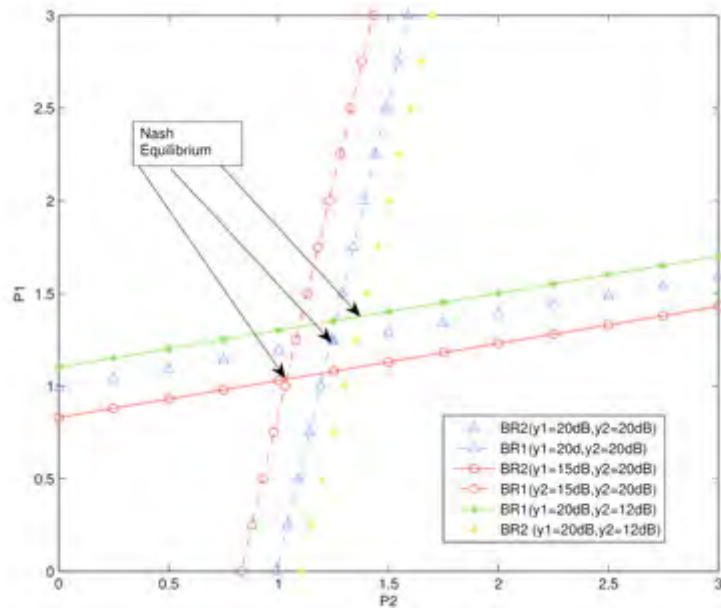


Figure 6.11: *Best Response(Composite)*

Given that profit can be realized from a Decentralized network, Figure 6.12 gives an indication of the practical uses of the internet for a community wherein, the Internet can be used in schools,

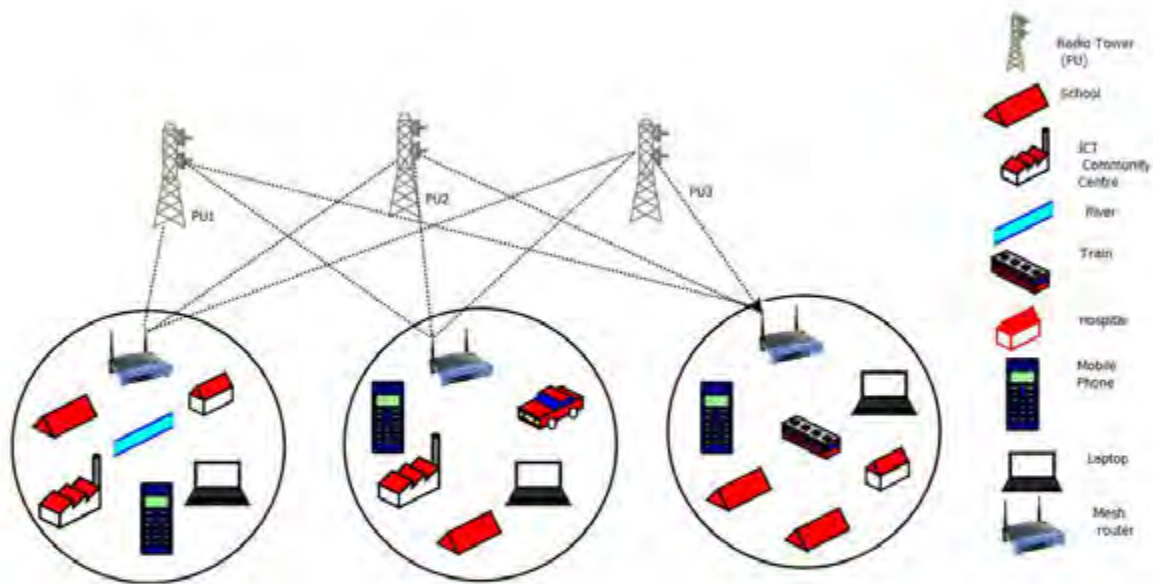


Figure 6.12: *Internet Provision*

health care (hospital) as well as intelligent transportation (i.e., trains, cars (vehicular networks)). Furthermore it is possible to configure sensors to monitor water pollution in rivers. The design of this type of network is realizable in accordance with the parameters discussed in section 4.5 of chapter 4

## 6.8 Conclusion

In this chapter, we have partly responded to the first research question where a framework for TV White Space spectrum exploitation through dynamic spectrum sharing in coexisting primary and secondary networks has been designed for next generation networks. The interactions between the primary and secondary users have been analysed using game theory and subsequently formulated as a non-cooperative game. The non-cooperative game is then viewed as a pricing problem wherein each PU strives to maximize its profit. Ultimately the problem is formulated as a Bertrand game in an oligopolistic market with PUs selling their spectrum to secondary users. The PUs strategize in terms of price adjustment such that SUs favour lower prices when buying. On the basis of inter-operator agreements of delay, throughput and a combination of delay and throughput, three tractable analytic models have been developed. The performance of these models is analyzed with respect to parameters such as cost, demand, revenue, profit, best response and channel quality. Further research efforts should explore the implication of such a framework in a routing scenario within the context of a next generation network such as a wireless mesh network.

# 7. TV White Space Management Framework: Traffic Engineering Approach

## 7.1 Introduction

The realization of a heterogeneous next generation network in which different network systems coexist with varying and sometimes conflicting QoS requirements calls for a new design metaphor. The design metaphor needs to take into account and leverage on the latest technological developments and innovations such as TV White Space, Cognitive radio as well as current standards initiatives in the quest for Cognitive networks. Intuitively, the realization of such a design goal demands a revisit of the two methods that have been widely used to achieve Quality of Service (QoS) agreements between the offered and expected traffic and the available network resources. Traffic engineering (TE) moves the traffic to where the network resources (including bandwidth) are available while Network Engineering (NE) moves bandwidth to where the traffic is offered to the network [30]. In classical network design approaches, traffic engineering represented by routing and network engineering represented by channel assignment have largely been decoupled problems. In the majority of works, network engineering has been generalized into a pricing problem [179]. To this end, and from a game theoretic perspective leveraging on the latest technological developments and regulatory frameworks, the network engineering problem is revisited in chapter 5 and chapter 6 wherein cooperative and non-cooperative TV white space spectrum sharing frameworks were designed. Furthermore in our published works [193] and [192, 191], we clearly stated our desire to further effective TV White Space management in the network. In the general case, Content Delivery Network (CDN) and traffic engineering are promising options for effective TV White Space network management. These techniques aim to distribute traffic in space dimension by adequate routing [275]. Traffic engineering (TE) can be used to reduce the whole network cost by adapting physical routing in response to varying traffic patterns. To this end, we revisit the traffic engineering problem with a view to leveraging on it to achieve an efficient Cognitive mesh network. In the classical case, traffic engineering is used to balance the traffic workload between source and destination and is very vital in addressing the pitfall of the destination based shortest path routing paradigm currently used in the Internet. Routing is a primary mechanism for load balancing and when employed in conjunction with other QoS mechanisms, scalable QoS as well as efficient resource utilization can be accomplished [245]. However, for next generation networks such as Cognitive mesh networks, routing will certainly not involve end-to-end resource reservation owing to the dynamic nature of white spaces which are in-turn influenced by the random behaviour of primary users. Reservations will most probably be available on a link by link basis. Subsequently resources for secondary traffic will have to be sought and reserved at node level. This will have to be done while maintaining QoS of the traffic being transmitted. The choice as to which node traffic should be routed will depend on how the routing algorithm predicts the utilization of a given node or network. Intuitively secondary traffic should be steered along links with least utilization and care should be taken in observing the delay

tolerances of the traffic being transported. Furthermore, owing to primary node activity, spectrum resource available to Cognitive mesh networks varies in both space and time. This creates a strong interdependence between the routing and resource allocation problems in such kind of networks. Intuitively, Mitra et al. [179] recognizes the importance of both routing and pricing as basic mechanisms for managing network resources. Furthermore the intricate nature of interaction between routing and pricing (spectrum assignment) is an unexplored NP-hard problem [299, 41]. Moreover, according to Dhananjay et.al [68], realizing the full potential of a Cognitive-radio mesh network involves two main challenges: how to assign channels to radios at each node to minimize interference and how to choose high throughput routing paths in the face of lossy links, variable channel conditions and external load. They affirm that designing a high-performance cognitive-radio protocol faces many practical constraints and challenges (small node size, highly fluctuating link qualities, external load). However, routing in Cognitive-radio mesh networks has been confirmed to provide reliable paths for efficient spectrum sharing among numerous communication devices [140]. More recent efforts in pursuit of spectrum efficient and effective networks [18] have seen the formulation of a comprehensive economic framework for routing and channel allocation in cognitive mesh networks objectively to maximize profit. The framework which is premised on Markov decision theory, perceives cognitive ability as a cost-efficient measure to increase available bandwidth but requires an adaptive bandwidth management mechanism to deal with dynamics of primary users' activities.

In this chapter, we investigate an important and yet unexplored issue, which is the interdependence between the routing and TVWS allocation in the context of a Cognitive mesh network which represents a paradigm shift in viewing the traffic engineering problem. Traffic engineering is a network management technique which involves adapting the routing of traffic to the network conditions, with the joint goals of good user performance and efficient use of network resources [87]. In our adaptation, Multi Protocol Label Switching (MPLS) is used to implement Traffic Engineering (TE). MPLS is a rapidly emerging technology which is increasingly playing a crucial role in next generation networks by delivering QoS and traffic engineering features [213]. According to [84] Label-Switched Paths (LSPs) are used in MPLS networks as a mechanism for traffic Control. Specifically in wireless mesh networks traffic engineering objectively strives to reduce blocking probability, minimizing network costs and load balancing [17]. Leveraging on the work done in both the cooperative (chapter 5) and non-cooperative TV white space allocation (chapter 6) and with cost minimization in mind, we revisit and extend the works in [27, 31, 29, 28, 30]. In particular and contrary to popular approaches, our new design metaphor proposes a Time of Day Traffic Engineering (ToD TE) framework wherein, unlike [18], we leverage on MPLS capabilities to design a routing model based on game decision theory which incorporates time of day spectrum usage for the purpose of efficient traffic engineering the heterogeneous network. The routing model is designed with the capacity to deploy three different QoS routing strategies for traffic engineering the network based on a time dependent usage and pricing policy wherein the user is charged on the basis of how much spectrum has been used and which time of day is it consumed. The three QoS routing strategies will certainly differ in their performances and the best strategy will need to be identified. Furthermore unlike [204, 78], we perform occupancy measurement studies (using the approach described in chapter 3 section 3.2) for the Ultra-High Frequency (UHF 470-850MHz) band and deploy the results in a heterogeneous network of varying sizes for the sole purpose of effective and efficient management of the Cognitive mesh network wherein

the best QoS routing strategy is deployed. Ultimately the results of this deployment points to the usefulness of TVWS. Thus our contribution as stated in subsection 7.1.1 is a response to our second research question ( *Looking at QoS routing strategies, what will be the best strategy among Traffic and Networking Engineering approaches for next generation Cognitive mesh networks?* ).

**7.1.1 Contribution.** Our main contribution in this chapter is a traffic engineering management framework based on Time of Day (ToD) and addressing the concerns of the second research question. Our contribution (response to research question 2) is categorized into two: Firstly from a theoretical perspective we:

- develop in section 7.4 a TE management framework for the management of TV white spaces based on time of day TV white space availability with differential pricing. The pricing scheme is categorized into two level and three level pricing schemes. Three QoS routing strategies are deployed in the network to provide three modes for routing traffic from source to destination.
- Evaluate the performance of the three QoS routing strategies (IOPT, MIX and CSPF) in a cooperative and non-cooperative routing setting (Section 7.6.1) so as to identify the best strategy.

Secondly, from a practical (experimental) perspective:

- An indoor spectrum occupancy measurement within the UHF TV band in the range 470 – 850MHz is carried out using a low cost RF explorer for a two week period.
- In section 7.5 an adaptive architectural framework is designed on the basis of the practical measure of TV white space occupancy in the UHF range (470-850MHz) for a two-week period.
- Simulation of Traffic engineering by setting up connection oriented tunnels in a wireless cognitive mesh network to provide QoS. This is achieved by developing a discrete event simulator and subsequently deploying it in simulating different network sizes based on the TV white space occupancy results wherein the OSPF routing strategy (best QoS routing strategy) is deployed in both a Standard Traffic Engineered (Std TE) and Time of Day Traffic Engineered (ToD TE) networks in section 7.6.3.

The rest of the chapter is organized as follows. The section 7.2 introduces the TV white Space market and tariff pricing policy. The network model and traffic engineering problem is articulated in section 7.3. Section 7.4 is a detailed analysis of the problem stated earlier in section 7.3 wherein the two routing perspectives are presented namely as cooperative and non-cooperative routing. Section 7.5 builds on the previous sections by adopting an adaptive and practical approach to the traffic engineering problem and this is subsequently followed by section 7.6 where numerical and simulation results are presented and discussed. Ultimately a conclusion is reached in section 7.7 where a summary of the work done in the chapter is presented.

## 7.2 Time of Day TV White Space Market Pricing Policy

Time dependent usage pricing policies were originally crafted in the energy sector wherein it has been specifically explored in the electricity industry [42]. In the context of the Telecommunications industry, time dependent usage pricing basically involves charging a user based on both how much bandwidth is consumed and when it is consumed, as opposed to time-independent usage pricing which may consider monthly consumption amounts [130]. Furthermore time dependent pricing can potentially even out Time-of-Day (T-o-D) fluctuations in bandwidth consumption. In implementing time day of pricing an indirect load management scheme is achieved with the following objectives:

1. reducing peak load
2. shifting a portion of the peak load to the base load
3. Utilising spectrum that is not being used by other secondary users.

In our TV White Space market policy, our pricing can be implemented in two ways:

1. two prices with day divided into two periods:
  - Day Period
  - Night Period
2. three prices with the day demarcated into three periods of eight hours duration:
  - Morning Period
  - Afternoon Period
  - Evening Period

**7.2.1 Assumptions.** The following is assumed for the market pricing schemes:

1. Two level pricing
  - Day Period the price  $p(t) = 1.1 * p^*$  where  $p^*$  is the normal price
  - Night Period the price  $p(t) = 0.7 * p^*$
2. Three level Pricing: The day is divided into three periods i.e., Morning Afternoon and Evening periods and the prices are as follows:
  - Morning Period the price  $p(t) = 0.7 * p^*$
  - Afternoon Period the price  $p(t) = 1.1 * p^*$
  - Evening Period the price  $p(t) = 0.9 * p^*$

The price factors 0, 7, 0.9 and 1.1 are assumed to be competitive and sustainable. The rationale is to shift traffic from congested peak periods to non-peak periods in the networks thereby achieving load balancing as well as ensuring that no one is turned away from getting a service as in [139]. To this end, consumers pay less for using the spectrum when there is ample unutilised capacity, rather than when demand takes up or even exceeds all the capacity. An example is when the prices are reduced during the night compared to the day, i.e,  $0,7 * p^*$  and  $1.1 * p^*$ . The prices can further be distributed in three phases as in the three level pricing scheme. This approach constitutes a more effective use of capacity.

### 7.3 Network Model and T-o-D Traffic Engineering Problem Definition

Consider a network represented by a directed graph  $(\mathcal{N}, \mathcal{L})$  where  $\mathcal{N}$  is a set of nodes and  $\mathcal{L}$  is a set of links. Let  $R_\ell(t)$  denote the maximum reservable bandwidth of link  $\ell$  at time  $t$  and let  $\mathcal{P}_{i,e}$  denote the set of feasible paths (WLSPs) connecting the ingress-egress pair  $(i, e)$ . Assume that a request to establish an WLSP of  $d_{i,e}(t)$  bandwidth units between an ingress-egress pair  $(i, e)$  is received and that future demands concerning WLSP requests are not known. Let  $\beta(t)$  denote the elasticity of the spectrum availability resulting from time-of-the-day usage by the primary user. Let  $L_p(t) = \sum_{\ell \in p} L_\ell(I_\ell, r_\ell, t)$  denote the cost of path  $p$  where  $L_\ell(I_\ell, r_\ell, t)$  is the cost of link  $\ell$  when carrying  $I_\ell$  flows and  $r_\ell$  is the total bandwidth reserved by the WLSPs traversing link  $\ell$ .

The traffic engineering problem consists of finding the best feasible path  $p^* \in \mathcal{P}_{i,e}$  where

$$L_{p^*}(t) = \min_{p \in \mathcal{P}_{i,e}} L_p(t) \quad (7.1)$$

$$R_\ell^*(t) < \min_{\ell \in p^*} (R_\ell(t) - r_\ell(t)) \quad (7.2)$$

$$R_\ell(t) = R_\ell - \beta(t)R_{ws}(t). \quad (7.3)$$

Equations (7.1), (7.2) and (7.3) express respectively the optimality of the routing process, the feasibility of the flows, and the elasticity of the reservable bandwidth based on time-of-the-day fluctuation of spectrum.

**Routing weights.** We consider routing weights that follow the TE model described in [28, 27] where the link cost is expressed by

$$L_\ell(I_\ell, r_\ell, t) = I_\ell^\alpha / S_\ell^{1-\alpha} \quad (7.4)$$

where the link interference  $I_\ell$  is the number of flows carried on the link, the link slack  $S_\ell = R_\ell(t) - r_\ell(t)$  where  $R_\ell(t)$  is the maximum reservable bandwidth of link  $\ell$ ,  $r_\ell(t)$  is the total bandwidth reserved by the WLSPs traversing the link and  $0 \leq \alpha \leq 1$  is a parameter representing a trade-off between the number and the magnitude of the LSPs traversing a link.

The link cost function (7.4) is minimized by minimizing the link interference  $I_\ell$  (IOPT routing) and maximizing the link slack  $S_\ell$  (CSPF routing). By dispersing traffic flows over the network through interference minimization, this link cost will minimize the number of LSPs blocked under

congestion and minimizes the number of LSPs which must be re-routed under a single link failure. Through link slack maximization, the link load is kept far from a congestion region where the link load approaches the link capacity. Note that

$$L_\ell(I_\ell, r_\ell, t) = \begin{cases} 1/S_\ell(t) & \alpha = 0 & \text{CSPF} \\ 1/R_\ell(t) & 0 < \alpha < 1 & \text{MIX} \\ I_\ell(t) & \alpha = 1 & \text{IOPT} \end{cases}$$

When  $0 < \alpha < 1$  the link cost function yields a mix of IOPT and CSPF routing. We consider the case where the number of flows  $I_\ell$  is a static parameter that can be precomputed based on each node's density to balance the impact of network topology and traffic demand.

**Spectrum elasticity.**  $\beta(t)$  is the elasticity parameter expressing time-of-the-day variations of the spectrum. It is expressed as follows

$$\beta(t) = \begin{cases} p(t) & O(t) < T & \text{Secondary usage} \\ 0 & O(t) \geq T & \text{Primary usage.} \end{cases}$$

Where  $O(t)$  expresses the spectrum occupancy at time  $t$  and  $T$  is a threshold usually set to  $T = -119db$  by the standardization bodies when the energy algorithm is used for spectrum sensing. We consider a white space broadband market pricing model similar to [193] where  $p(t)$  is the spectrum price which can be set low/high to encourage/discourage competition for white space spectrum usage between WSPs. As expressed above, the elasticity parameter reveals high spectrum pricing under primary usage and lower under secondary usage to encourage WSPs to buy spectrum from TVWS providers following the Leader-Follower (Stackelberg) model summarized in subsection 7.3.1.

**7.3.1 Cooperative Stackelberg White Space Allocation.** The Stackelberg equilibrium is a solution concept originally defined for the scenarios where a hierarchy of actions exists between users. To this end, the Stackelberg contextually prescribes an optimal strategy for the leader, so long as its followers always respond by playing their Nash equilibrium strategies in the smaller sub-game. Nash equilibrium is thus considered as the solution of the bandwidth sharing and pricing game which guarantees the maximization of the White Space WiMAX BS revenue. To this end, we aim to integrate the framework in chapter 5 with our model in section 7.3 thereby achieving the coupling of the spectrum sharing and routing modules. In chapter 5, section 5.7, the cooperative scenario has an optimal spectrum demand at the point where N.E. is attained, thus according to equation 5.35, which we revisit, the profit of the router is given as:

$$\phi_M^r = R_M^r - C_M^r$$

. We expand this equation by substituting the revenue and cost values to obtain:

$$\sum_{i=1}^N P_M^r (c_i - d_i P_M^r) - P_M^{BS} \sum_{i=1}^N (c_i - d_i P_M^r) - F_M^r$$

, this equation explicitly shows the relationship between the profit and price parameter. The optimal price charged to a Wi-Fi node is obtainable by way of computing the derivative of the profit function and and setting it to zero.

$$P_M^r = \frac{d_i P^{BS} - c_i}{2d_i}$$

the optimal price is thus

$$P^* = \frac{d_i P^{BS} - c_i}{2d_i}$$

$$(P_M^r) = c_i - d_j P_M^r$$

at this point  $P_M^r = P^*$ , the price at N.E. Thus the ultimate demand is equivalent to

$$= c_i - d_j P^*$$

The routing contextual demand is then

$$R_{i,e} = c_i - d_j P^*$$

$$P(P_M^r) = \frac{d_i P^{BS} - c_i}{2d_i} P_M^r = \frac{d_i P^{BS} - c_i}{2d_i} = \frac{d_i P^{BS} - c_i}{2d_i}$$

According to chapter 5, section 5.7, the profit of the BS is given by equation 5.37 which is expressed as:

$$\phi^{BS} = \sum (a_i - e_i T(n, b_i^s)) + \sum_{M=1}^N P_M^{BS} b_M^r$$

From the profit of the BS

$$\phi^{BS} = \sum (a_i - e_i T(n, b_i^s)) + \sum_{M=1}^N P_M^{BS} b_M^r$$

Previously we abandoned the derivative route for this particular case of limited information availability and instead opted for a Darwinian approach. Thus the ultimate demand is equivalent to:

$$c_i - d_j P^* \tag{7.5}$$

The routing contextual demand is then

$$R_\ell^*(t) = c_i - d_j P^* \tag{7.6}$$

where

$$P^* = P_M^r = \frac{d_i P^{BS} - c_i}{2d_i} P_M^r = \frac{d_i P^{BS} - c_i}{2d_i} = \frac{d_i P^{BS} - c_i}{2d_i} \tag{7.7}$$

**7.3.2 Non-Cooperative White Space allocation.** This section is largely based on the work done in chapter 6. We leverage on this work to formulate from a non-cooperative perspective, a TVWS allocation mechanism that will be integrated onto our ToD TE routing model in section 7.3 so as to achieve a coupling of the spectrum assignment and routing engine. To ascertain the demand, which is an important function in analysing the network dynamics we start from the quadratic utility function (equation 6.23), in section 6.3, subsection 6.3.2, as follows:

$$\psi(Q) = \sum_{i=1}^M Q_i k_i^s - \frac{1}{2} \left( \sum_{i=1}^M Q_i^2 + 2\Delta \sum_{i=1}^M Q_i Q_j \right) + J$$

where  $\mathbb{Q} = Q_1, \dots, Q_i, \dots, Q_M$  and  $J$  is given by:

$$J = - \sum_{i=1}^M P_i Q_i$$

The demand is obtained by taking the derivative of the utility function with respect to  $Q_i$ . The demand function is therefore:

$$Q_i^* = \frac{k_i^{(s)} - P_i^* - \Delta(k_j^{(s)} - P_j^*)}{1 - \Delta^2} \quad (7.8)$$

With reference to section 7.3 and equation 7.2 the ToD TE routing demand is computed as follows:

$$R_\ell^{*c} = \frac{k_i^{(s)} - P_i^* - \Delta(k_j^{(s)} - P_j^*)}{1 - \Delta^2} \quad (7.9)$$

After establishing an expression for the ToD TE demand, the next task is to ascertain the optimal price through an analysis of the profit.

The profit due to a delay QoS performance

$$\phi(\mathbb{P})_i^{(D)} = Q_i P_i - C_i^{(D)} \quad (7.10)$$

While the throughput based profit is

$$\phi(\mathbb{P})_i^{(T)} = Q_i P_i - C_i^{(T)} \quad (7.11)$$

The  $NE$  value in the context of delay QoS measure is obtainable by differentiating as follows:

$$\frac{d\phi(\mathbb{Q})}{dP_i} = 0$$

for all  $i$  where

$$\phi(\mathbb{P}) = P_i \frac{k_i^s - P_i - \nabla(k_j^{(s)} - P_j)}{1 - \nabla^2} - \frac{d\lambda_i}{2(W_i - Q_i)^2 - 2\lambda_i(W_i - Q_i)}$$

The derivative of this profit function is equated to zero as follows

$$0 = \frac{k_i^{(s)} - 2P_i - \Delta(k_i^{(s)} - P_j)}{1 - \Delta^2} + \frac{d \frac{\lambda_i}{1 - \Delta^2 (4Q_i - \lambda_i)}}{(2Q_i^2 - 2Q_i \lambda_i)^2}$$

$$\psi(\mathbb{P}) = P_i \frac{k_i^s - P_i - \nabla(k_j^{(s)} - P_j)}{1 - \Delta^2}$$

$$Q_i = W_i - \frac{k_i^{(s)} - P_i - \Delta(k_j^{(s)} - P_j)}{1 - \Delta^2}$$

$$\frac{k_i - 2P_i^* - \Delta k_j + \Delta P_j}{1 - \Delta^2} = 0$$

The optimal price is thus expressed as:

$$P_i^* = \frac{k_i - \Delta k_j}{1.6} + 0.64 \quad (7.12)$$

The optimal price depends on the spectral efficiency of transmission as shown on equation 7.12. At N.E  $P_i^* = P_i^*$ . In summary, in our non-cooperative WS allocation, we have established some important functions to be used in the ToD TE routing model. The first function is the demand which is crucial in analysing the dynamics due to the SUs and its expression is given in equation 7.9. The level of demand is influenced by the optimal price as well as the spectral transmission efficiency. The optimal price depends only on the spectral efficiency and has been established in equation 7.12.

## 7.4 Cooperative and Non-Cooperative Routing

**7.4.1 Cooperative routing.** The cooperative routing scenario within our context is a Stackelberg inspired one wherein the routing process comprises a leader and a follower. The leader also called the primary network is the service provider and the follower also called the secondary network is the service recipient (user). The service provider sets the prices and each price defines a sub-game among the users. With each user having a fixed amount of data to transmit, we are particularly interested in the routing choices of individual users. In the system we are analysing, when the service provider sets prices, the users should practically have the option of not routing any traffic if the prices are too high, otherwise the service provider may charge infinite prices on the links. Our overall objective in this context is that of minimizing the cost in conditions of cooperative routing scenario. Prior to optimizing the overall cost objective function; we perform some analysis of other important parameters such as the demand and reserved bandwidth for the three different routing strategies (i.e., CSPF, MIX and IOPT). In terms of the reserved bandwidth, we note that If our channels have fixed bandwidth it means each channel (data and control) has a fixed bandwidth. Thus with more channels, the network can potentially use more bandwidth. If the bandwidth is reserved it implies channels are reserved. As more bandwidth is reserved, this will translate to more channels. The reserved bandwidth is the free spectrum which has been called white space. It thus suffices to say, more reserved bandwidth translates to more channels.

1. Link Cost and Demand: The link cost  $L_\ell = \frac{I^\alpha}{(R_\ell(t) - r_\ell(t))^{1-\alpha}}$

The demand function from a cooperative perspective is substituted into the link cost equation and a relationship between the link cost and demand is established for the three routing strategies as follows

$$L_\ell = \frac{I^\alpha}{(R_\ell(t) - r_\ell(t))^{1-\alpha}} \quad (7.13)$$

Our goal of relating the link cost and demand is achieved as follows, we initially invoke equation 7.3 and subsequently combine it with the equation 7.6 for the demand function which relates the optimal price and bandwidth demand. Furthermore the optimal spectrum price is given by equation 7.7. These efforts culminate in a general link cost relation in equation 7.14

$$L_\ell = \frac{I^\alpha}{(R_\ell(t) + r_\ell \frac{R_{ws}}{d_i} - R_\ell^* \frac{R_{ws}}{d_i} - r_\ell(t))^{1-\alpha}} \quad (7.14)$$

Having reached our goal of establishing a general relationship between the link cost and bandwidth demand, we extend our efforts to analysing the impact of the different routing strategies on this general relationship by varying the routing weights. The routing weights are set at 0, 0.5 and 1 to equitably ascertain routing strategies performance on the entire range of the weight parameter.

- **CSPF** when  $\alpha = 0$ : The link cost-bandwidth demand relation is depicted by equation 7.15

$$L_\ell = \frac{1}{(R_\ell(t) + r_\ell(t) \frac{R_{ws}}{d_i} - R_\ell^* \frac{R_{ws}}{d_i} - r_\ell(t))} \quad (7.15)$$

The link cost and bandwidth demand have an inverse relationship.

- **MIX** when  $\alpha = 0.5$  : The link cost- bandwidth demand equation transforms to

$$L_\ell = \sqrt{\frac{I}{(R_\ell(t) + r_\ell(t) \frac{R_{ws}}{d_i} - R_\ell^* \frac{R_{ws}}{d_i} - r_\ell(t))}} \quad (7.16)$$

The relation is an inverse square relationship between the link cost and the bandwidth demand.

- **IOPT** when  $\alpha = 1$ : The link cost-bandwidth demand relation reduces to just the flow as shown in equation 7.17

$$L_\ell = I \quad (7.17)$$

The relation is independent of the bandwidth demand for this routing strategy. This has consequences for TV White space exploitation for the Cognitive mesh network under scrutiny.

2. **Reserved bandwidth and Price**: The general relationship between the reserved bandwidth and price can be ascertained during the course of the general cost minimization process. In the general case, cost minimization is a necessary (but not sufficient) condition for profit maximization. However, from a purely economic perspective even when a producer is not a price taker in the output market, or when the solution to the profit maximization problem is not well defined, the producer must still minimize costs. In the case of our, Cognitive Mesh network our main concern is the link cost. We however recognize that the problem at hand generally resembles the optimization problems that arise in economics, computer science, network economics and other related areas wherein there are restrictions on the values that the independent variables may take. This kind of problem is termed a constrained optimisation problem and can be tackled using the Lagrangian approach in chapter 3, section 3.1, subsection 3.1.1. Two common approaches to this kind of problem are

- (a) Substitution Method: An approach to solving a constrained optimization problem is to use the constraint to reduce the number of variables, and subsequently transform the problem to an unconstrained optimization problem in fewer variables.
- (b) Lagrangian Method: An approach for solving constrained optimization problem is premised on considerations from vector calculus, and is named after the mathematician Joseph Louis Lagrange. This approach is more complex, and as a consequence yields more information. For concreteness, if we are required to ascertain the optimal value of an objective function  $f(x, y, z)$  subject to the constraint  $g(x, y, z) = c$ . Then the path to determining the optimal value will involve the deployment of a Lagrangian multiplier  $\lambda$

$$F(x, y, z, \lambda) = f(x, y, z) + \lambda.(g(x, y, z) - c) \quad (7.18)$$

**Principle:** Under suitable conditions, the optimal value(s) of the objective function,  $f(x, y, z)$ , subject to the constraint,  $g(x, y, z) = c$ , is (are) obtained at the  $(x, y, z)$ -components of stationary point(s)  $(x^*, y^*, z^*, \lambda^*)$  of the Lagrangian  $F(x, y, z, \lambda)$ .

In summary, we opt for the Lagrangian approach owing to the stated advantage of consequently yielding more information. As a starting point to solving the problem at hand, we express the problem using the Lagrangian approach as in equation 7.19

$$\psi(r_\ell(t), \lambda) = \sum_{m=1}^M \sum \frac{I_\ell^\alpha r_\ell(t)}{(R_\ell(t) - r_\ell(t))^{1-\alpha}} + \lambda(R_\ell^*(t) - R_\ell(t) + r_\ell(t)) \quad (7.19)$$

Our objective function now contains the Lagrangian multiplier and the constraints. We take another step by determining the derivative of the objective function with respect to the reserved bandwidth  $r_\ell(t)$  and the Lagrangian multiplier.

$$\frac{d\psi(r_\ell(t), \lambda)}{dr_\ell(t)} = 0 \quad (7.20)$$

The derivative is given as :

$$\frac{d\psi(r_\ell(t), \lambda)}{dr_\ell(t)} = \frac{I_\ell^\alpha}{(R_\ell(t) - r_\ell(t))^{1-\alpha}} - \frac{I_\ell^\alpha r_\ell(-1 + \alpha)}{(R_\ell(t) - r_\ell)^{2-\alpha}} + \lambda = 0 \quad (7.21)$$

On the basis of equation 7.21, the multiplier is given by

$$\lambda = -\left(\frac{I_\ell^\alpha}{(R_\ell(t) - r_\ell(t))^{1-\alpha}} - \frac{I_\ell^\alpha r_\ell(-1 + \alpha)}{(R_\ell(t) - r_\ell)^{2-\alpha}}\right) \quad (7.22)$$

We further take an additional step by reformulating the objective function as in equation 7.23

$$\psi(r_\ell(t)) = \sum_{m=1}^M \sum \frac{I_\ell^\alpha r}{(R_\ell(t) - r_\ell(t))^{1-\alpha}} - \left(\frac{I_\ell^\alpha}{(R_\ell(t) - r_\ell(t))^{1-\alpha}} - \frac{I_\ell^\alpha r_\ell(-1 + \alpha)}{(R_\ell(t) - r_\ell)^{2-\alpha}}\right)(R_\ell^*(t) - R_\ell(t) + r_\ell(t)) \quad (7.23)$$

The critical point is obtainable by way of differentiating the objective function with respect to  $r_\ell(t)$  as follows:

$$\begin{aligned} \frac{d\psi(r_\ell(t))}{dr_\ell(t)} = & -\left(\frac{r_\ell - R_\ell + R_\ell^*}{(R_\ell(t) - r_\ell(t))^{2-\alpha}}\right)(-I^\alpha)(-1 + \alpha) + \frac{I_\ell^\alpha r_\ell(t)(-1 + \alpha)}{(R_\ell(t) - r_\ell(t))^{3-\alpha}} + \\ & \frac{I_\ell^\alpha(-1 + \alpha)}{(R_\ell(t) - r_\ell(t))^{2-\alpha}} - \frac{I_\ell^\alpha r(-1 + \alpha)}{(R_\ell(t) - r_\ell(t))^{2-\alpha}} \end{aligned} \quad (7.24)$$

Equation 7.24 clearly constitutes, in our view, the general case for the routing scenario in regard to the reserved bandwidth and the price parameter. Next, we investigate within a purely cooperative setting the relationship between the reserved bandwidth and the price charged by the Primary user which is the base station. For concreteness, we actively investigate this relationship in the context of the three routing strategies by purposely varying the values of  $\alpha$  parameter

- **IOPT:** When the parameter  $\alpha = 1$ , the relation resembles the cost-demand relationship which was established to be a constant; the general equation in this particular context yields a constant upon substitution of  $\alpha = 1$  and other variables for the reserved bandwidth and price.
- **CSPF:** When the parameter  $\alpha = 0$ , the CSPF strategy has the relationship between the reserved bandwidth and price deduced from solving the equation

$$\begin{aligned} & \frac{-(r_\ell(t) - R_\ell(t) + R_\ell^*(-1))}{(R_\ell(t) - r_\ell)^2} + \frac{(2)(-1)}{(R_\ell(t) - r_\ell)^3} \\ & + \frac{(-1)}{(R_\ell(t) - r_\ell(t))^2} - \frac{(-1)r_\ell(t)}{(R_\ell(t) - r_\ell(t))^2} = 0 \end{aligned} \quad (7.25)$$

The roots of the equation are obtainable by substituting the equation for the demand  $R_\ell^*(t)$ , the value of  $R_\ell(t)$  and the value of the price into equation 7.25.

- **MIX:** The value of the  $\alpha$  parameter is set at  $\alpha = 0.5$  and consequently the general case reduces to:

$$\begin{aligned} & \frac{-(r_\ell(t) - R_\ell(t) + R_\ell(t)^*)(-\sqrt{I_\ell})(-0.5)}{(R_\ell(t) - r_\ell(t))^{1.5}} + \frac{(-1.5)(-0.5)\sqrt{I_\ell}}{(R_\ell(t) - r_\ell(t))^{2.5}} \\ & + \frac{(-0.5)\sqrt{I_\ell}}{(R_\ell(t) - r_\ell(t))^{1.5}} - \frac{(-0.5)r_\ell(t)\sqrt{I_\ell}}{(R_\ell(t) - r_\ell(t))^{1.5}} = 0 \end{aligned} \quad (7.26)$$

An expression for the reserved bandwidth is obtained by substituting the respective demand  $R_\ell^*(t)$ , price and the value of  $R_\ell(t)$  into the equation 7.26

### 3. Link Cost-Exact solution and Link Cost- Genetic Algorithmic Approach Solution

The link cost is determined in the cooperative routing scenario using the Lagrangian approach and also the link cost is ascertained by way of a genetic algorithm. The rationale behind the use of the GA is that compared to other optimization approaches discussed in chapter 2, section 2.5, the GA has the ability to optimise both continuous and discrete variables, it does not require derivative information and also has the capacity to deal with a large number of variables. Furthermore this optimisation technique achieves both local exploration and global exploration to provide a robust and efficient methodology in searching for a near-optimal solution. They provide near-optimal results in a relatively small computation time. The genetic algorithm denotes a Darwinian approach achievable through the following steps:

- Initial population: As a first step we begin by creating an initial population of chromosome. The population is usually randomly generated and can be any desired size, from only a few individuals to thousands individuals. The population consists of individuals, and these individuals consist of genes.
- Fitness level: This step comes immediately after the formation and initialisation of population of chromosomes and objectively computes fitness. The fitness measure indicates the capability of chromosome to solve the given problem. Practically the fitness level is denoted by either a 1 or 0 with 1 denoting the best fitness level. Within our context the fitness is the value of our objective function. The objective function in our case is denoted by the link cost whose value as we have already indicated will vary depending on the strategy as discussed in earlier in this section. For Convenience we formally restate equation 7.23

$$\psi(r_\ell(t)) = \sum_{m=1}^M \sum \frac{I_\ell^\alpha r}{(R_\ell(t) - r_\ell(t))^{1-\alpha}} - \left( \frac{I_\ell^\alpha}{(R_\ell(t) - r_\ell(t))^{1-\alpha}} - \frac{I_\ell^\alpha r_\ell(-1 + \alpha)}{(R_\ell(t) - r_\ell)^{2-\alpha}} \right) (R_\ell^*(t) - R_\ell(t) + r_\ell(t)) \quad (7.27)$$

Furthermore we remind the reader that by varying the  $\alpha$  value equation will evolve into three different cost functions denoting the different strategies. To this end, we reiterate that when  $\alpha = 0$  the cost objective function denotes the CSPF routing strategy,

$$\psi(r_\ell(t)) = \frac{r}{(R_\ell(t) - r_\ell(t))} - \left( \frac{1}{(R_\ell(t) - r_\ell(t))} + \left( \frac{r_\ell}{(R_\ell(t) - r_\ell)} \right)^2 \right) (R_\ell^*(t) - R_\ell(t) + r_\ell(t)) \quad (7.28)$$

Equation 7.28 thus denotes the relationship between link cost, reserved bandwidth and price. However when the same equation is substituted with the value of the optimal price, then it denotes the objective function. The value of  $\alpha = 0.5$  denotes MIX strategy cost function as shown in equation 7.29

$$\psi(r_\ell(t)) = \frac{I_\ell^{0.5} r}{(R_\ell(t) - r_\ell(t))^{0.5}} - \left( \frac{I_\ell^{0.5}}{(R_\ell(t) - r_\ell(t))^{0.5}} + \frac{0.5 I_\ell^{0.5} r_\ell}{(R_\ell(t) - r_\ell)^{1.5}} \right) (R_\ell^*(t) - R_\ell(t) + r_\ell(t)) \quad (7.29)$$

Equation 7.28, thus achieves two aims, firstly it denotes the relationship between link cost, reserved bandwidth and price. In the second instance when a value for optimal price is provided the equation 7.29 constitutes the objective function to be used in the Genetic algorithm. A third value of  $\alpha = 1$  denotes IOPT cost function and its equation is

$$\psi(r_\ell(t)) = (I(R_\ell(t) - r_\ell(t))^2)(R_\ell^*(t) - R_\ell(t) + r_\ell(t)) \quad (7.30)$$

- **Selection:** The main objective of the selection phase is to select more copies of the chromosomes whose fitness values are higher. To this end, our GA like any other GA leverages on the law of natural selection where the fittest survive. A number of selection schemes are available and these range from Roulette wheel, Rank based selection, Elitism and Tournament selection [196]. In our work we adopt the roulette wheel selection algorithm for the selection as it is the simplest and widely used scheme. The roulette wheel algorithm basically determines the survival probability of each chromosome with regards to its fitness value. Intuitively individuals are first mapped to roulette wheel slices to such that each individual's value is proportional to its fitness. Ultimately, the selection process is based on the spinning wheel for the number of times equal to the actual population size, each time selecting a single chromosome for crossover and mutation [261].
- **Crossover** Crossover is the most important element within a genetic algorithm. It involves combining two chromosomes (parents) and produces entirely new chromosomes consisting of attributes of both parent chromosomes. A variety of techniques exist for crossover [249]. In our our work, we opt for the two point crossover technique. An advantage of using the two point crossover is that more crossover points may be searched more thoroughly. Intuitively this technique involves selecting two crossover points with the contents between these points exchanged between two mating parents as shown in Figure 7.1.

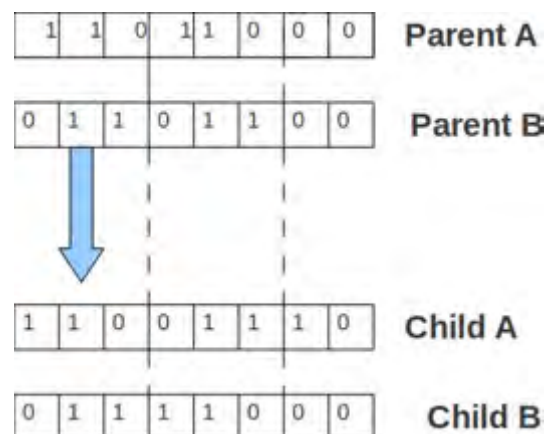


Figure 7.1: Two Point Crossover

The dotted lines illustrate the crossover points and these points are exchanged between the parents to produce new children for mating in next generation.

- **Mutation:** This is genetic operation that alters the state of one or more genes of a chromosome. This change will introduce a genetic modified equation into the population.

Mutation can be perceived as an operator that occasionally break one or more members of a population towards a local minimum or maximum space as well as potentially discover a better minimum or maximum space. During the evolutionary process mutation is guided by the mutation probability. In our work we opted for the Gauss mutation operation mainly because it is highly flexible and supports both fine tuning of solutions and searching the domain. In principle, the Gaussian mutation operator adds a Gaussian distributed random value to the chosen gene. In the event that the new gene falls outside the upper or lower bound of the chosen value it is clipped. This mutation operator is however best suited for use with integer or float genes.

- **Search Termination:** In this algorithm the search terminates when either the specified number of generations has evolved or when the fitness function (Cost function) remains the same. This implies the genetic process will end if there is no change to the populations' best fitness for a specified number of generations.

**7.4.2 Non-Cooperative routing.** The proposed model allows us to solve a joint problem of non-cooperative QoS routing and dynamic capacity allocation over a network of parallel links. This problem is solved by playing a Nash game taking place among players belonging to two categories: (i) the category of individual users, whose objectives are to ship their macro-flows from the source node to the destination node, by suitably splitting them over the parallel links and (ii) the category of capacity players, whose task is to partition and to assign to the classes of traffic upon which the macro flows are mapped, the dynamic portion of capacity over each link. A unique and innovative aspect of our model is that the allocation of the dynamic portion of capacity to each class of traffic over each link is realized during the actual operation of the network, i.e., in conjunction with the QoS routing.

1. **Link cost variation with Demand :** An approach similar to the cooperative routing scenario is adopted and the three routing strategies are analyzed as follows: **CSPF** when  $\alpha = 0$

The link cost demand relation is obtained by combining equation 7.3, equation 7.12 and the optimal price equation 7.2

$$L_\ell = \frac{1}{(R_\ell - \beta(t)p(t) - r_\ell(t))} = \frac{1}{(R_\ell + 12.8 - R_\ell^{*c} - r_\ell(t))} \quad (7.31)$$

**MIX** when  $\alpha = 0.5$  The link cost equation transforms to

$$L_\ell = \frac{1}{\sqrt{(R_\ell + 12.8 - R_\ell^{*c} - r_\ell(t))}} \quad (7.32)$$

**IOPT** when  $\alpha = 1$  , The link cost is

$$L_\ell = I \quad (7.33)$$

- **CSPF** when  $\alpha = 0$

$$\begin{aligned} & \frac{-(r_\ell(t) - R_\ell(t) + R_\ell^{*c}(-1))}{(R_\ell(t) - r_\ell(t))^2} + \frac{(2)(-1)}{(R_\ell(t) - r_\ell(t))^3} \\ & + \frac{(-1)}{(R_\ell(t) - r_\ell(t))^2} - \frac{(-1)r_\ell(t)}{(R_\ell(t) - r_\ell(t))^2} = 0 \end{aligned} \quad (7.34)$$

Next we perform substitution as follows:

$$\begin{aligned} & \frac{r_\ell(t) - R_\ell + p^*(t)R_{ws}(t) + R_\ell^{*c}(-1)}{(R_\ell - p^*(t)R_{ws} - r_\ell)^2} - \frac{2}{(R_\ell - p^*(t)R_{ws} - r_\ell(t))^3} \\ & - \frac{1}{(R_\ell - p^*(t)R_{ws} - r_\ell(t))^2} - \frac{(1)r_\ell(t)}{(R_\ell - p^*(t)R_{ws} - r_\ell(t))^2} = 0 \end{aligned} \quad (7.35)$$

The demand in a competitive setting is given by

$$R_\ell^{*c} = \frac{k_1 - p_1 - \Delta(k_2 - p_2)}{1 - \Delta^2} \quad (7.36)$$

- MIX when  $\alpha = 0.5$

$$\begin{aligned} & \frac{-(r_\ell(t) - R_\ell(t) + R_\ell^{*c}(t))(-\sqrt{I_\ell})(-0.5)}{(R_\ell(t) - r_\ell(t))^{1.5}} + \frac{(-1.5)(-0.5)\sqrt{I_\ell}}{(R_\ell(t) - r_\ell(t))^{2.5}} \\ & + \frac{(-0.5)\sqrt{I_\ell}}{(R_\ell(t) - r_\ell(t))^{1.5}} - \frac{(-0.5)r_\ell(t)\sqrt{I_\ell}}{(R_\ell(t) - r_\ell(t))^{1.5}} = 0 \end{aligned} \quad (7.37)$$

We further simplify equation 7.37 by inserting the expression for  $R_\ell(t) = R_\ell - p(t)R_{ws}$  in both the numerator and denominator to obtain equation 7.38

$$\begin{aligned} & \frac{-(r_\ell(t) - R_\ell + p^*(t)R_{ws} + R_\ell^{*c}(t))(-\sqrt{I_\ell})(-0.5)}{(R_\ell - p^*(t)R_{ws} - r_\ell(t))^{1.5}} + \frac{(-1.5)(-0.5)\sqrt{I_\ell}}{(R_\ell - p^*(t)R_{ws} - r_\ell(t))^{2.5}} \\ & + \frac{(-0.5)\sqrt{I_\ell}}{(R_\ell - p^*(t)R_{ws} - r_\ell(t))^{1.5}} - \frac{(-0.5)r_\ell(t)\sqrt{I_\ell}}{(R_\ell - p^*(t)R_{ws} - r_\ell(t))^{1.5}} = 0 \end{aligned} \quad (7.38)$$

- IOPT when  $\alpha = 1$ . The model predicts a constant for this particular strategy.

2. Link Cost: The link cost is now determined from the equation when the Lagrangian multiplier's value is known. A genetic algorithm is used to optimize the link cost. We begin by restating equation 7.23 which we now present as equation 7.39 has been previously transformed to equation 7.24 as follows:

$$\begin{aligned} \psi(r_\ell(t)) &= \sum_{m=1}^M \sum \frac{I_\ell^\alpha r}{(R_\ell(t) - r_\ell(t))^{1-\alpha}} - \\ & \left( \frac{I_\ell^\alpha}{(R_\ell(t) - r_\ell(t))^{1-\alpha}} - \frac{I_\ell^\alpha r_\ell(-1 + \alpha)}{(R_\ell(t) - r_\ell)^{2-\alpha}} \right) (R_\ell^*(t) - R_\ell(t) + r_\ell(t)) \end{aligned} \quad (7.39)$$

The general case equation now differs when it comes to the demand function as well as the optimal price. We analyse the routing for the cases when  $\alpha = 0$ ,  $\alpha = 0.5$  and  $\alpha = 1$

- CSPF when  $\alpha = 0$

$$\begin{aligned} \psi(r_\ell(t)) &= \sum_{m=1}^M \sum \frac{r_\ell}{(R_\ell(t) - r_\ell(t))} - \\ & \left( \frac{1}{(R_\ell(t) - r_\ell(t))} + \frac{r_\ell}{(R_\ell(t) - r_\ell)^2} \right) (R_\ell^*(t) - R_\ell(t) + r_\ell(t)) \end{aligned} \quad (7.40)$$

- MIX when  $\alpha = 0.5$

$$\psi(r_\ell(t)) = \sum_{m=1}^M \sum \frac{I_\ell^{0.5} r}{(R_\ell(t) - r_\ell(t))^{0.5}} - \left( \frac{I_\ell^{0.5}}{(R_\ell(t) - r_\ell(t))^{0.5}} - \frac{I_\ell^\alpha r_\ell(-10.5)}{(R_\ell(t) - r_\ell)^{1.5}} \right) (R_\ell^*(t) - R_\ell(t) + r_\ell(t)) \quad (7.41)$$

- IOPT when  $\alpha = 1$

$$\psi(r_\ell(t)) = r I_\ell - (I_\ell)(R_\ell^*(t) - R_\ell(t) + r_\ell(t)) \quad (7.42)$$

According to [52] the setting up of quality routes in dynamic variable environment is highly influenced by PU activity or behaviour. As an example, if the PU activity is moderate- to-low, the topology of the secondary users' network is almost static, and classical routing metrics adopted for wireless mesh networks could be leveraged. However, if PUs become active very frequently, routing techniques for disconnected networks must be adopted. In our context of non-cooperative routing the link cost in each routing strategy is optimised by way of a genetic algorithmic approach as shown in Figure 7.2

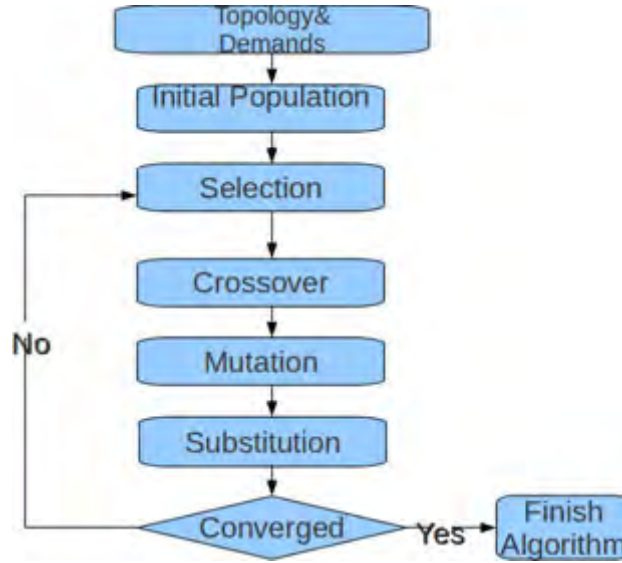


Figure 7.2: Genetic Algorithmic approach to link cost optimisation

An advantage of the genetic algorithmic approach is that while it can optimise both continuous and discrete variables, its choice in our case is motivated by the fact that it does not require derivative information and can also deal with a large number of variables. Furthermore this optimisation technique achieves both local exploration and global exploration to provide a robust and efficient methodology in searching a near-optimal solution [158]. The genetic algorithmic approach in Figure 7.2 has five steps. In the first step the population is initialised, wherein candidate solutions are generated. It is however important to recognise that the size of the population has an effect on both the performance and efficiency of the algorithm. The population

size must be selected on the basis of the size of the solution space. Step 2 involves selection wherein a new population is generated without elite members. The selection criteria are based on the individual's fitness, this translates to individuals with higher fitness being highly likely to survive. For concreteness in our context, we consider a scenario wherein the selection of a quality route, there are two variables involved in the learning process, spectrum requested from a PU and price charged to an SU, a possible new strategy will involve choosing the price of one good candidate and the spectrum of another one good candidate. A variety of selection methods exist and these range from random selection, roulette-wheel and tournament selection. Using a Fitness function, the best individuals are selected to compound the population to crossover. Step 3 involves a crossover mechanism wherein two parents in the population of solutions are chosen to create new solutions by mating the two parents. The mating of these parents can be done using any of the three techniques:

- Single point crossover
- Multipoint crossover
- Uniform crossover.

The next important technique in step 4 called mutation is used by the GA to explore the solution space. In the general case, mutation will change some attribute in an element or individual of the population, selected randomly and it has the ultimate goal of enlarging the variety of the solutions. Ultimately, step 5 is the substitution which performs a selection in the new elements generated in crossover mutation processes to substitute some elements in the original population. The steps 2 - 5 are repeated until the convergence.

## 7.5 Adaptive Routing: A Practical Perspective

Classically, routing of traffic has been achieved by routing along minimum hop paths in IP networks. Practically this has translated to minimal usage of link resources subsequently leading to congestion of some links and under-utilization of others. Adaptive routing has been proposed as a way of improving network performance by providing multiple paths between a source and destination. Adaptive routing allows paths to be chosen dynamically distributing traffic over the links more evenly thereby enhancing network performance. In the context of Cognitive Mesh networks, the biggest challenge is that of dynamic spectrum availability to secondary users which potentially could cause the breaking of routes and ultimately the entire communications process. As a way of mitigating this challenge, an adaptive joint spectrum allocation and routing scheme is proposed. A cognition process entails the adaptation to changes in various dynamic factors present in the network system. The adaptation is achieved by initially detecting and then reacting to changes in these factors. Clearly, detection encompasses collecting information about a dynamic factor and subsequently reacting wherein action is taken by the system to improve performance or alternatively maintain the communication after a change has been detected. In the context of Cognitive Mesh networks, the sources of these changes or dynamic factors come from various sections of the environment. The dynamic factors can range from spectrum, policy

enforcements, changes in network topology, or changes in application requirements. Needless to say, detecting these changes is critical to the cognition function given that the network's ability to respond is highly dependent on the information collected during detection. Moreover, the accuracy of the detected data determines the correctness of the action to be taken by the system which is described in subsection 7.5.1.

**7.5.1 Adaptive Routing System Architecture and Design.** The Centralized system architecture for our cognitive radio mesh network is as shown in Figure 7.3 and comprises the Primary user, Secondary user, Whitespace Broker and Mesh Network manager. We assume the Primary

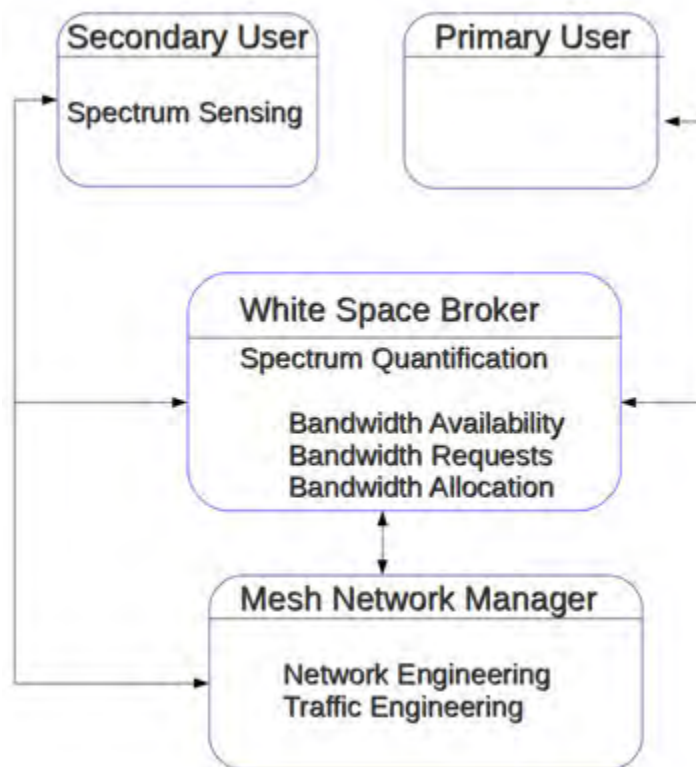


Figure 7.3: System Architecture for adaptive Traffic Engineering

user is licensed to operate in the Ultra High Frequency band (UHF-470-850MHz) and the Secondary user is unlicensed to operate and must thus rely on the primary system for the necessary spectrum resource to provision services to its clients. The secondary user gets the spectrum from the primary user via the White Space broker entity. The Cognitive Mesh Manager then performs network and traffic engineering on the combined primary and secondary networks in conjunction with the WS broker. Next we give a detailed explanation of each of the cognitive Mesh network entities as follows:

1. **Primary User network** The primary user uses the classical communication system with static spectrum allocation. It is the licensed user of the spectrum. Normally a number of primaries are licensed to operate on the Ultra high frequency band. Within the band certain frequency channels are licensed to be operated by particular primaries. For example in our case for adaptive routing, South African Broadcasting Corporation (SABC1-3) as well as ETV services are some of the known and licensed users of the UHF band. These primaries have different activity patterns within the band, these patterns are variable with regards to time, space and geographical location. From a time perspective, this translates to primaries being active at some times and non active in the other times. Depending on its activities it is able to avail variable capacities with time. Contextually we will be more interested in the aggregate spectrum, i.e., the combined unused spectrum from the entire primary user network. Practically, this translates to spectrum from say Tx1 to Txn. On the basis of this, the primary network is able to influence the network state in multi-hop Cognitive mesh network.

## 2. **Secondary User Network**

The life and survival of the unlicensed network is intertwined with that of the primary or licensed network. Clearly in the DSA paradigm employed in this context, the most critical piece of information for the SU is the presence of the PU. The DSA paradigm proposes to allow secondary users (SUs), also called Cognitive users, access to the licensed spectrum subject to the condition that SUs do not interfere with the operations of the primary network of incumbents.

In the system architecture considered in this context, the secondary network whose nodes are equipped with Cognitive radios have basically two functions to perform:

- sensing of the primary user
- Traffic Demands from clients that need to be satisfied.
- Secondary User, Spectrum sensing and Occupancy measurement

Equipped with a low cost device, called an RF explorer, an indoor measurement campaign was carried out in the UHF band in the range 470 MHz to 850MHz. The setup comprised an RF explorer, a laptop loaded with firmware v1.11 which includes 3D waterfall.

The RF explorer utilizes the energy detection spectrum sensing algorithm discussed in chapter 2, section 2.4 for the sensing. The algorithm senses the presence or absence of primary users.

- Traffic Demands: According to [127] the heterogeneity of both spectrum availability and traffic demand in secondary users has brought significant challenge for efficient spectrum allocation in cognitive radio mesh networks. However, when the traffic demand and spectrum resource availability are largely mismatched, these existing works cannot fully utilize spectrum resource and fulfil secondary users' demands. Thus, an important issue is how to handle the unbalanced spectrum usage within the secondary network to fulfil the heterogeneous traffic demand from secondary users, which has not drawn much attention before.

3. **WS Broker and its role in our scenario:** The white Space broker is tasked with buying (reserving) bandwidth from spectrum licensees in advance and then reselling the reserved bandwidth to unlicensed White Space Devices (WSDs) in real-time. A major challenge for the Broker is to make the proper bandwidth reservation under WSDs demand uncertainty [163]. Clearly, a higher reservation may translate to larger revenue in the event of a higher demand, conversely it may also lead to a higher loss when the market demand is low. In our context, several secondary users share a common band i.e., the UHF band and their spectrum usage is coordinated by the spectrum broker. Fundamentally, the inter-operator spectrum sharing scenario involves at least one network user being involved with the new market entity, which is the spectrum broker. Essentially, the WS broker does not have its own resources, but pools unused spectrum from operators. The WS broker takes the investment risk related to the purchase of spectral resources. The broker is distributing spectrum resources grants from the owned spectrum bands using appropriate trading and charging mechanism for the spectrum usage. The feasibility of such a scheme is made possible by a trading mechanism building on the capacity auctioning on a short time basis. The role of the broker is to act as an intermediary between the market players in radio resource acquisition namely buyers who are the network operators. This scenario is premised on the fact that spectrum sharing is done in real-time and the spectrum grants are assigned to the operators by the spectrum trading entity which is tasked with selling the spectrum chunks in a location specific, time and demand based manner [258, 184, 40]. The Spectrum broker collects operation information from each secondary user network and allocates the resources in a manner which promote efficient and effective spectrum sharing

#### 4. **Mesh Network manager**

Manages the heterogeneous network where different networking technologies with different service levels and QoS requirements are integrated.

- Network engineering
- Traffic Engineering

One of the main objectives of traffic engineering is to avoid congestion by controlling and optimizing the routing function, or in short, to put the traffic where the capacity is.

The main challenge for traffic engineering in ambient networks is to cope with the dynamics of both topology and traffic demands.

From a traffic engineering perspective, for a network operator it is important to analyse and tune the performance of the network in order to make the best use of it. The process of performance evaluation and optimization of operational IP-networks is often referred to as traffic engineering. One of the major objectives is to avoid congestion by controlling and optimizing the routing function.

## 7.6 Performance Evaluation

In this section we respond to the second research question stated as:

**Research Question: (“QoS Strategy:”):** Looking at QoS routing strategies, what will be the best strategy among Traffic and Networking Engineering approaches for next generation Cognitive mesh networks?. Our QoS routing strategies are the CSPF, MIX and IOPT and our performance evaluation of the model will advise on the best strategy. Furthermore we will carry out a simulation study of the best strategy to compare its performance on a Standard Traffic Engineered (Std TE) network and on a Time of day Traffic Engineered (ToD TE) Network. For convenience in a realistic cognitive radio mesh networking setting the following parameters are set for numerical analysis as follows  $R = 10$ ,  $R_{ws}$ ,  $d = 1$ ,  $k_1 = 18$ ,  $k_2 = 15$ ,  $\Delta = 0.4$ ,  $p_2 = 1$ .

### 7.6.1 Numerical Results.

1. **Cooperative Routing:** Centralized Cooperative routing is characterised by cooperation between and among nodes of wireless multihop networks. The cooperation between the nodes increases communication reliability, reduces energy consumption and decreases delay. The stackelberg game theoretic inspired cooperative routing has the PU network nodes cooperating with the SU nodes wherein the PU nodes assume a leadership role and the SU nodes assume a follower status. Cooperative multi-hop routing thus extends the coverage by allowing nodes to establish multi-hop routes to communicate with other nodes that would have otherwise have been outside the transmission range. In this section within the cooperative routing context of a centralized cognitive radio mesh network, we optimise the objective function which is the global link cost of the network. Furthermore, cognisant of the interdependence of the spectrum and routing module, we investigate the dependence of the link cost with demand for spectrum from the SU nodes in the cognitive radio mesh network. The demand for spectrum is a function of the pricing scheme and as such we interrogate the relationship between the reserved spectrum and the pricing scheme. Ultimately we optimise the link cost using the Lagrangian and genetic algorithm approaches.

- **Link cost dependence on Demand:**

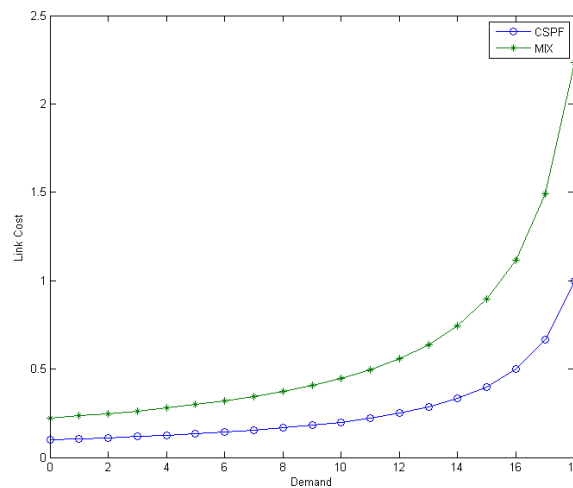
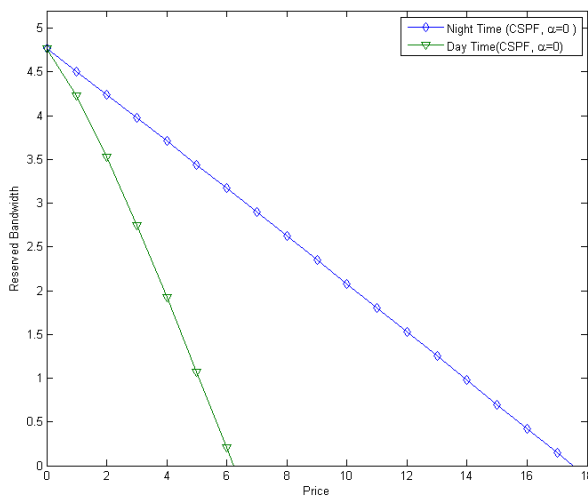


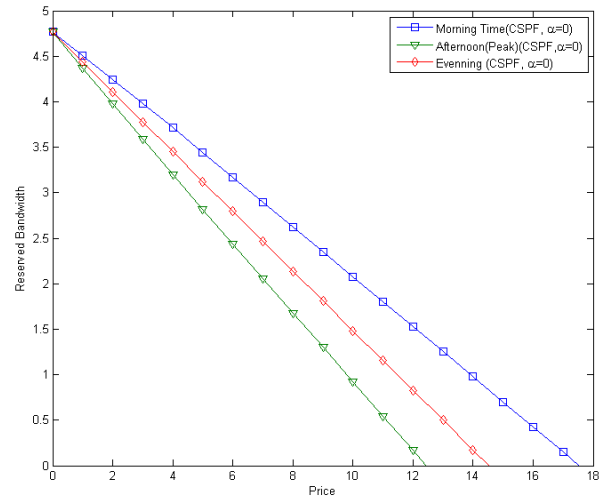
Figure 7.4: Cooperative Routing: LinkCost Against Demand

From a cooperative routing perspective, we analyse the relationship between link cost against the demand to route macro flows along the link in Figure 7.4 as predicted by equations 7.15 and equations 7.16 for the CSPF and MIX strategies respectively. For some particular range in demand (0 – 10), the increase in demand triggers a slight rise in link cost. Practically this implies that a secondary with a demand in this range will incur nearly the same delay. However for both routing strategies (CSPF and MIX) in a cooperative setting there is a rapid increase in link cost beyond the 0 – 10 range in demand. As the demand becomes larger the differences in the link cost incurred is clearly noticeable. Ultimately the CSPF routing strategy has a demand associated with a much higher cost as compared to the MIX strategy. The IOPT strategy has already been proved to have a link cost which remains constant irrespective of the demand as predicted by equation 7.17. However our analysis is further expanded to the relationship between the reserved bandwidth and the price for each of the routing strategies.

- Reserved bandwidth and Pricing Scheme:** The reserved bandwidth-price relationship is initially analysed for the CSPF routing strategy (Figure 7.5a wherein the white space market pricing regime is dual (when charged for day and night ) and when the prices are pegged at three levels, morning, afternoon and evening as predicted by equation 7.25. Figure 7.5a depicts the variation of price and reserved bandwidth in a cooperative routing setting, with the time of day divided between day and night periods.



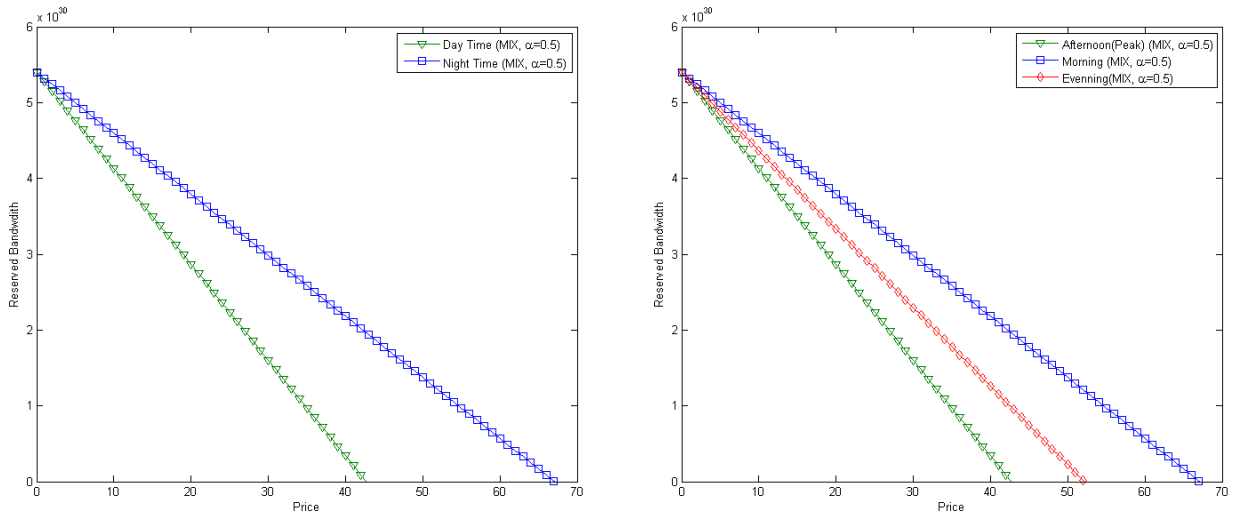
(a) Reserved Bandwidth and Price variation for Day and Night Pricing



(b) Reserved Bandwidth and Price variation

Figure 7.5: Cooperative Routing (CSPF)

In general, it is possible to reserve a higher amount of bandwidth under a lower price. This implies that as the price increases the amount of reserved bandwidth decreases. In the given tariff regime, the prices are higher during the day and slightly lower during

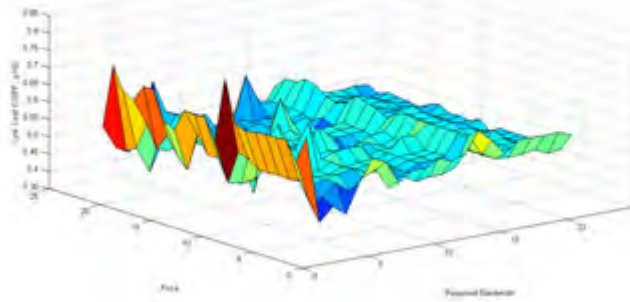


(a) Reserved Bandwidth and Price variation (Two-level Pricing scheme) (b) Reserved Bandwidth and Price variation (Three-level Pricing Scheme)

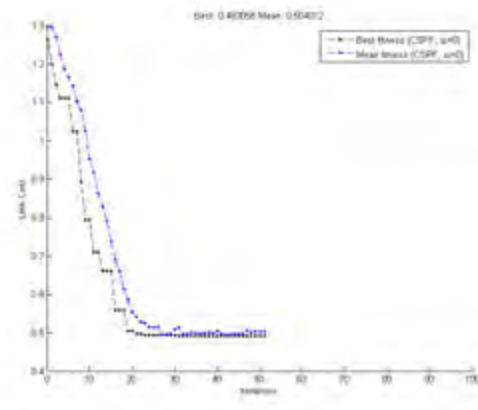
Figure 7.6: Cooperative Routing (MIX)

the night. Subsequently it is possible to reserve more bandwidth at night due to a lower cost. The implication of Figure 7.5a is that it is possible to manage the network load by shifting some of the load to the night time period in which a lower tariff is designed so as to entice SUs to make use of the network during the night period. This scheme can however be refined by dividing the time of day into three eight hour periods during which different prices are charged. Figure 7.5b shows the variation of reserved bandwidth with price for different periods of the day in the market. The period 0900–5pm is the peak period and has a higher price about  $1.1p$  the equilibrium price, while the period 6–12 midnight has the second highest price and the finally the period 12–8am has the least price. We infer from the graph that it is generally possible to acquire larger chunks of spectrum at lower cost. Comparing the three periods of the day, the period 12–8am has higher bandwidth reservation followed by the period 6–1200 and finally 9–1700hrs. The implication of this is a much more refined scheme with a capacity to effectively manage secondary network traffic with three available options. Some of the traffic can be shifted from the peak period and further shared between the other two periods. In the second part of this analysis, a MIX strategy is used when  $\alpha = 0.5$  and the following observations are made from Figure 7.6a as in accordance with the predictions of equation 7.26 there is generally more bandwidth reserved when the prices are lower, as in Figure 7.6b.

However this strategy tends to avail substantially higher amounts of bandwidth for the same price than the CSPF strategy under both pricing mechanisms. The three-level pricing regime also avails much more bandwidth (Figure 7.5a) than the CSPF strategy under the same pricing mechanism. The practical implication of this observation is similar to that of the CSPF strategy. However on the basis of the amount of bandwidth availed real-time applications and other more resource-hungry applications



(a) Cooperative Routing: Link Cost, Reserved Bandwidth and Price (CSPF)



(b) Cooperative Routing: Link Cost, Reserved Bandwidth and Price (CSPF)-Genetic Algorithm

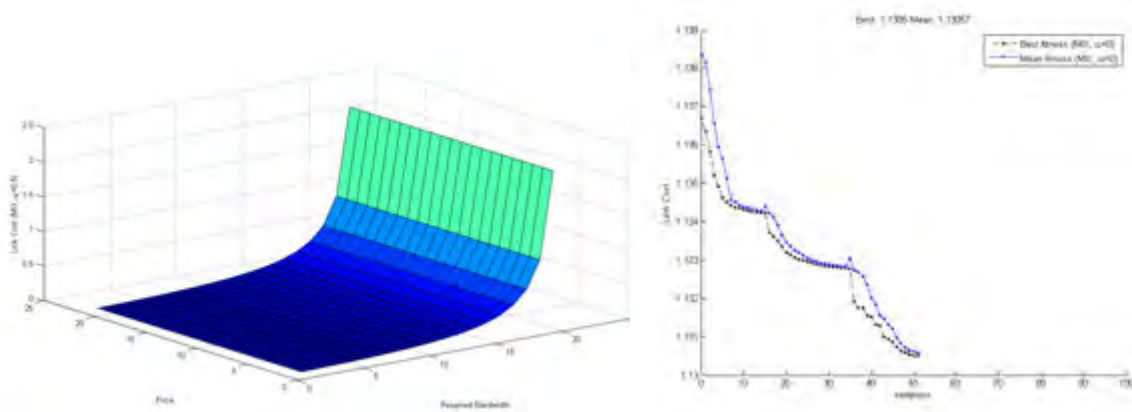
Figure 7.7: Cooperative Routing (CSPF)

as well devices can benefit from deploying this routing strategy under this pricing regime. Furthermore this provides excellent potential opportunities for new entrants or entrepreneurs into the industry. The model is not able to ascertain the relationship for  $\alpha = 1$ . Subsequently we further expand our analysis for the link cost, reserved bandwidth and price under the different strategies for a single period pricing and at the same time simultaneously compare the link cost achievable by way of a genetic algorithm.

- **Lagrangian and Genetic Algorithm** The Lagrangian technique as described in chapter 3 is a traditional optimisation method that is applicable to constrained optimisation problem. The performance of this technique is compared to the GA introduced in chapter 2, detailed in chapter 3 and applied in this chapter. Furthermore, our comparison leverages on table 7.1 wherein GA parameters are specified for both cooperative and non-cooperative routing.

Table 7.1: GA parameter setting

Parameter	Value
Initialisation method	Random
Selection method	roulette
Crossover operation	two point
Mutation operation	gaussian
Fitness Function	Eqn 7.27 link cost
Elitism	4
Population size (N)	100
Mating pool size	0.8*N
Crossover probability	0.01
Number of iterations	50



(a) Cooperative Routing: Link Cost, Reserved Bandwidth and Price (MIX)

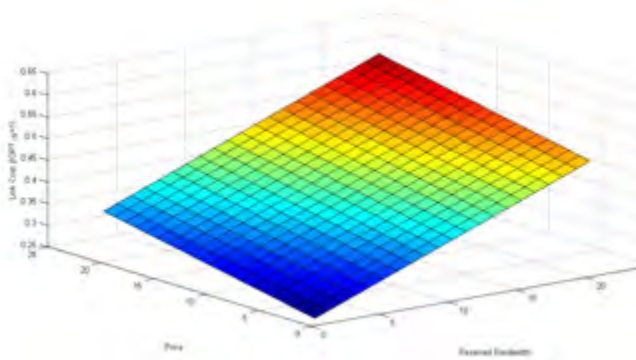
(b) Cooperative Routing: Link Cost (MIX) using Genetic Algorithm

Figure 7.8: Cooperative Routing (MIX)

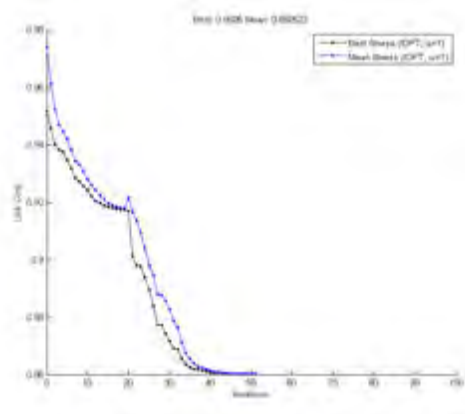
The performance of the Lagrangian and genetic algorithm is compared by way of the solutions delivered in Figure 7.7a and Figure 7.7b for a CSPF QoS routing strategy as predicted by equation 7.28. In genetic algorithms a proper selection of GA parameter configuration is of paramount importance in achieving better performances. To this end, several significant parameters are presented in table 7.1. As for the Lagrangian solution, the link cost, price and reserved bandwidth are the plotted parameters. For the GA link cost is plotted against the number of iterations. In Figure 7.7a, for the CSPF strategy the relationship between Link cost, reserved Bandwidth and price is depicted as seemingly a series of epochs and resembles the Schwefel Function for constrained optimization. Schwefel's function is often used as a benchmark problem for minimization problems. This to some extent could possibly be an indication of the dynamic variations of the three quantities with time. However there is a strong correlation between the theoretically predicted link cost due to the Lagrangian approach and the one obtained through a genetic algorithm optimization in Figure 7.7b. When the routing strategy is changed to a MIX strategy, predicted by equation 7.29, a different kind of pattern with regards to the relationship, as shown in Figure 7.8a and is obtained and is called a Quadric surface. A quadric surface is the graph of a second-degree equation in (exactly) three variables and in this case the link cost function, the price and reserved bandwidth. As a consequence, according to [262], two main challenges are associated with this sort of pattern or class of problems.

- The feasibility region is non-convex and multiple local minima abound. This makes conventional numerical search techniques unattractive as they are unable to locate the global optimum consistently (unless a finite search area is specified).
- The large optimization space makes the use of decision-method algorithms for the theory of the reals unattractive. This is because these algorithms involve the solution of the roots of univariate polynomials of order to the square of the optimization space.

The MIX strategy seems to be associated with generally higher link costs. However



(a) Cooperative Routing: Link Cost, Reserved Bandwidth and Price (IOPT)



(b) Cooperative Routing: Link Cost (IOPT) Using Genetic Algorithm

Figure 7.9: Cooperative Routing (IOPT)

the genetic approach for cooperative routing in Figure 7.8b uses equation 7.29 as the objective function and gives a lower value of the link cost after 50 iterations as compared to the one predicted by the Lagrangian approach. Clearly the difference between the two predictions warrants further investigations using other algorithms based on Newtonian type iterations. Finally for the cooperative setting, Figure 7.9a reports the relationship between link cost, price and reserved bandwidth according to our model with regard to the IOPT routing strategy. The three variables are in this instance represented by a nearly tilted plane which is possibly indicative of the near static relationship between some variables involved.

Using the equation 7.30 as the objective function for the Genetic algorithm, Figure 7.9b points to an interesting behaviour of the link cost between 15 and 25 iterations where the link cost appears to be showing signs of stabilising and then continues to iterate until the optimal value is obtained. In practical terms this may give a false sense of stability. The algorithm performance is such that after 50 iterations an optimal value is obtained as shown in the Figure 7.9b. There is a departure from the pattern of the other previous cases where the genetic algorithm had lower values. Next we embark on an analysis of the non-cooperative routing where competition is the order of the day.

2. **Non-Cooperative Routing** In this section, we chronological follow the same procedure as in the previous section, wherein we evaluate the link cost's dependence on variables such as demand, price and reserved bandwidth. Furthermore we comparatively deploy the Lagrangian and the genetic algorithm approaches to determine link cost. For the genetic algorithm the parameters are as set in table 7.1 with the objective functions varying in accordance with the routing strategy.

- **Link cost dependence on Demand:**

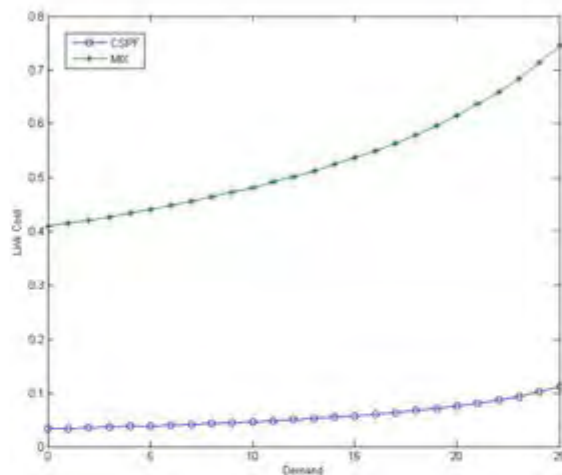
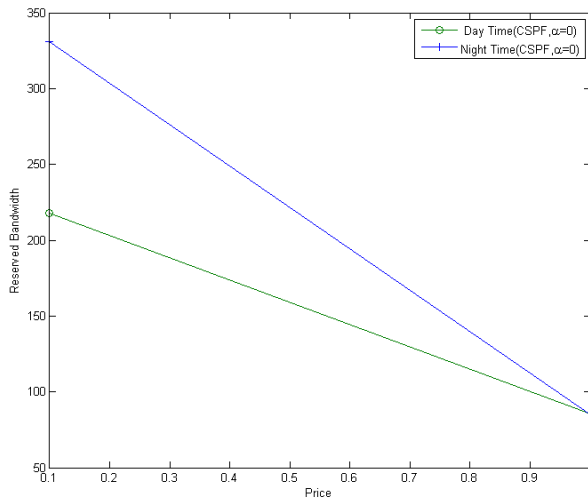


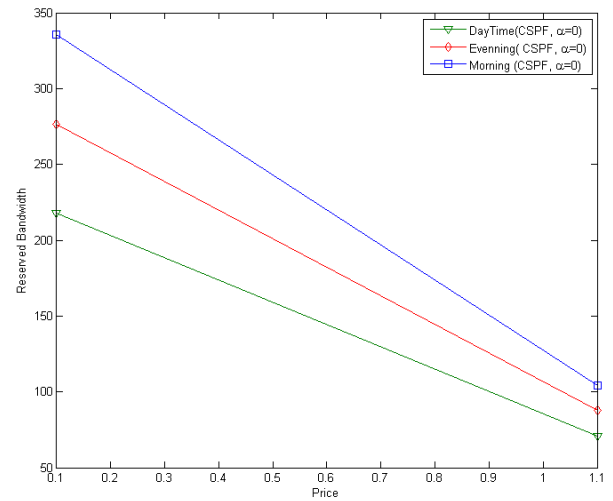
Figure 7.10: *Non-Cooperative Routing: Link Cost variation with Demand*

In the non-cooperative scenario, we follow the same procedure as in the cooperative scenario where we initially analyse the link cost relative to the demand of routing macro flows when different routing strategies are deployed as shown in Figure 7.10. Similar to the cooperative scenario, the link cost increases with an increase in demand. However the competitive routing scenario is less rapid than the cooperative routing. In terms of the strategies, the MIX strategy (equation 7.32) records a higher cost as compared to the CSPF routing strategy predicted by equation 7.31. The competitive routing on average incurs a lower cost than the cooperative scenario. The IOPT strategy produces no variation as predicted by equation 7.33.

- **Reserved Bandwidth and Pricing Scheme:** The reserved bandwidth's behaviour is studied under the two different pricing schemes i.e., the two level and three level pricing schemes under a non-cooperative setting.

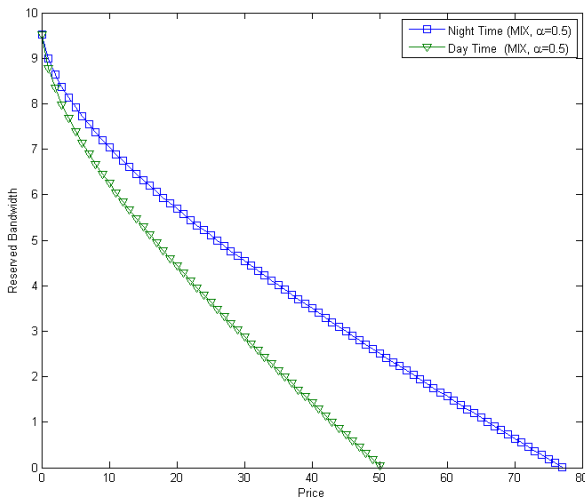


(a) Reserved Bandwidth and Price variation (Two-level Pricing scheme)

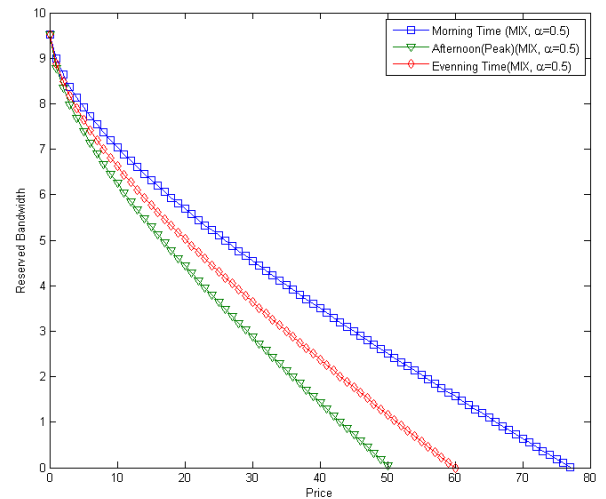


(b) Reserved Bandwidth and Price variation (Three-level Pricing Scheme)

Figure 7.11: Non-Cooperative Routing (CSPF)



(a) Reserved Bandwidth and Price variation (Two-level Pricing scheme)



(b) Reserved Bandwidth and Price variation (Three-level Pricing Scheme)

Figure 7.12: Non-Cooperative Routing (MIX)

The general interdependence between reserved bandwidth and price for a CSPF routing strategy in a non-cooperative for day and night pricing scheme is shown in Figure 7.11a is predicted by equation 7.35. There is more bandwidth reservable at night than during the day. However as the price increases like in the cooperative setting, less bandwidth is reserved. Interestingly, the graph indicates that at the edge of the

graph the bandwidth reserved is the same. This is indicative of a Nash Equilibrium (N.E) price. However when the scenario is changed to a three level pricing regime in Figure 7.11b, then more bandwidth is obtainable in the morning followed by the evening period and finally the peak period during the day. For the CSPF routing strategy this interdependence is represented by a straight line graph with negative gradient indicating a drop in reservable bandwidth as price increases. When the analysis is extended to a MIX routing strategy, the predictions of equation 7.38 are depicted by Figure 7.12a and Figure 7.12b for the two level and three level pricing schemes respectively. Figure 7.12a shows a quadratic interdependence between the reserved bandwidth and the associated bandwidth price for the MIX routing strategy. This is however a significantly different pattern as compared to the previous CSPF routing strategy. We observe that as the bandwidth price increases, less bandwidth is obtainable. The same trend applies to the three level pricing scheme in Figure 7.12b.

- Link cost, Lagrangian and Genetic Algorithm:** The link cost is also further investigated in terms of the other two variables namely, the price and reserved bandwidth. Furthermore genetic algorithmic approach is also employed to determine the link cost using the Darwinian principles with the parameters as set in table 7.1. More importantly we also reiterate the fact that the objective functions will change in accordance with the routing strategies in our analysis. Figures 7.13-Figure 7.18 all indicate the three being related by a surface plane and the results of employing a genetic algorithm. The respective different routing strategies are distinguished by the orientation of the planes.

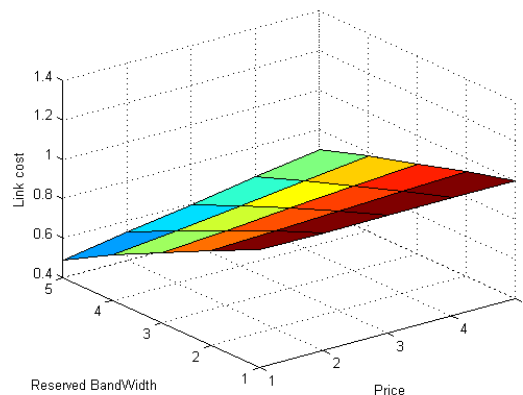


Figure 7.13: *Non-Cooperative Routing (CSPF): Link cost, Reserved Bandwidth and Price variation*

The CSPF strategy link cost is predicted by equation 7.40. The predicted value of the link cost is generally much higher in the Lagrangian approach (Figure 7.13) than in the genetic algorithmic approach as shown in Figure 7.14. The implication is that the CSPF routing strategy is associated with a higher cost in the Lagrangian approach compared to the genetic algorithm. The difference may emanate from the genetic algorithm's ability to uncover some hidden patterns through a learning process. Figure 7.15 shows the link cost when the MIX strategy is deployed in the routing of traffic

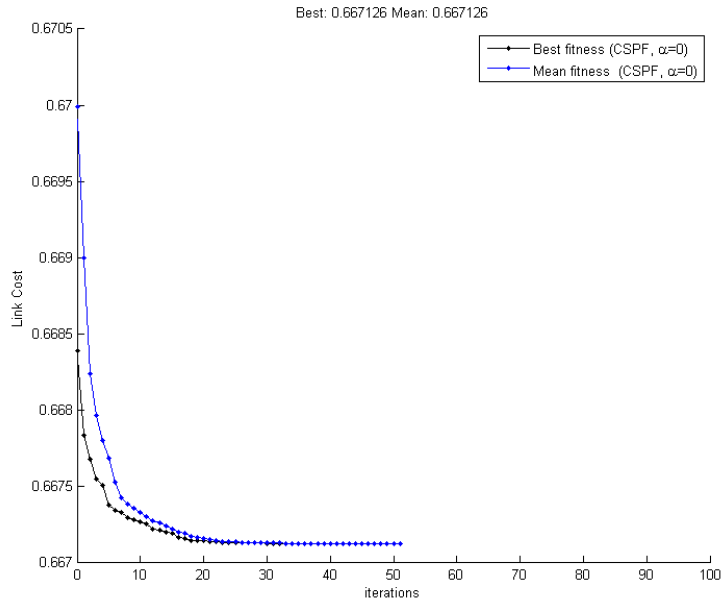


Figure 7.14: *Non-Cooperative Routing (CSPF): Link Cost*

from the source to the destination in a given wireless link of the Cognitive mesh network. The link cost equation is predicted by equation 7.41 Similar to the cooperative

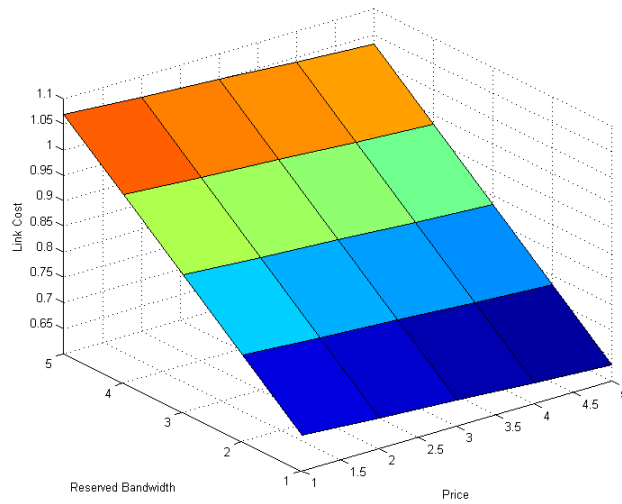


Figure 7.15: *Non-Cooperative Routing (MIX): Link Cost, Reserved Bandwidth and Price*

scenario, this strategy is generally associated with a higher link cost compared to the other two strategies. However it is also able to secure lots of bandwidth compared to the other strategies i.e., high bandwidth reservations. The same applies to the genetic algorithm approach in Figure 7.16

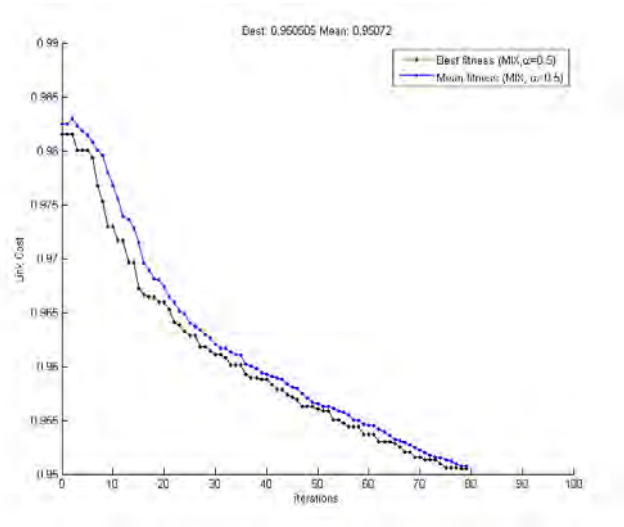


Figure 7.16: Non-Cooperative Routing (MIX): Link Cost

Finally from a non-cooperative routing perspective, Figure 7.17, depicts the link cost performance relative to the price and reserved bandwidth. The generally equation for the IOPT routing strategy in a non cooperative setting is predicted by equation 7.42. The link cost is less than the MIX strategy but more than that of the CSPF strategy.

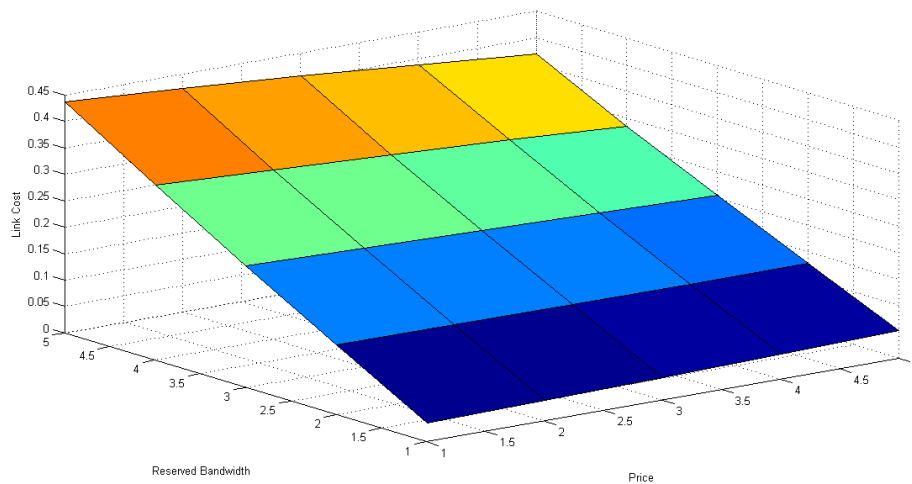


Figure 7.17: Non-Cooperative Routing (IOPT): Link Cost, Reserved Bandwidth and Price

A genetic algorithm optimization is presented in Figure 7.18 and the link cost is higher than that of the Lagrangian.

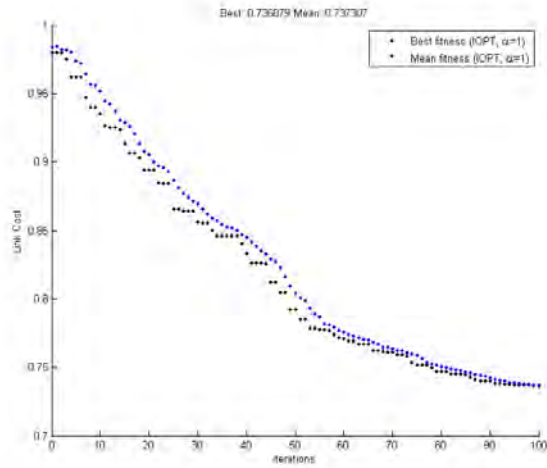


Figure 7.18: *Non-Cooperative Routing (IOPT): Link Cost*

**7.6.2 TV White Space Occupancy Measurement.** A practical spectrum occupancy measurement experiment was carried out in accordance with the methodology in chapter 3, section 3.2 so to fulfil the spectrum sensing portion of our adaptive routing approaching in section 7.5 of this chapter, wherein the objective is to ascertain the spectrum occupancy within the UHF band.

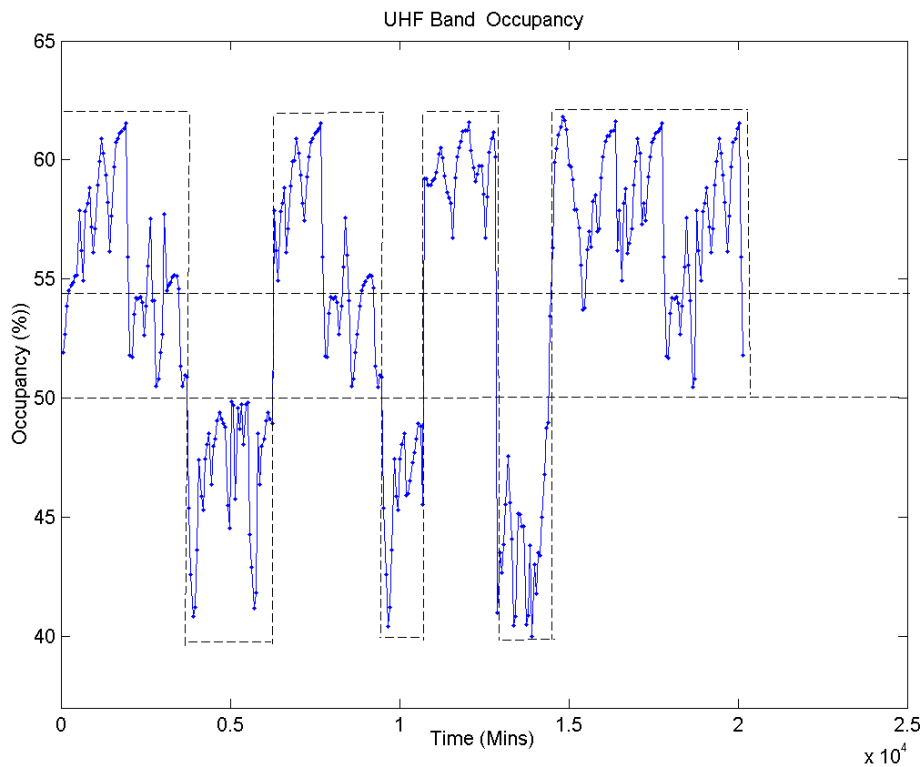


Figure 7.19: *Spectrum Occupancy*

Using an RF Explorer-handheld RF spectrum Analyser, an Antenna (Nagoya NA-773 wide-band telescopic ) and a laptop we performed a series of indoor measurements within the University of Cape Town campus. The laptop was loaded with RF software client for windows (based on Graphical User Interface) for easy interface with the RF explorer. The RF Explorer is an affordable device based on highly integrated frequency synthesizer and double balanced mixer which offers high performance, compact, low power consumption and low cost. The measurement parameters were set as follows: threshold was set at  $-95$  dBm, start frequency 470 MHz and step Frequency 3428.568 kHz. Figure 7.19 shows the spectrum occupancy measured for a two week period for use with the proposed adaptive routing system (Figure 7.3). The occupancy shows a periodic variation wherein the occupancy varies with time within the UHF band. The percentage occupancy varies between 40% and 65% with the 50% mark used as the reference wherein occupancy is categorized as high when above 50% and low when below the reference mark as shown in Figure 7.19.

**7.6.3 Simulation experiments.** Several simulation experiments were conducted to analyse the performance of a Time of Day Traffic Engineered (ToD TE) network for different network sizes ranging from 20 nodes, 50 nodes, and 90 nodes. Using a discrete event simulator developed in C++ for adaptive routing architecture in subsection 7.5.1, the ToD traffic engineered network is compared with a Standard Traffic Engineered (Std TE) network wherein the occupancy measurement results in subsection 7.6.2 are fed into the discrete event simulator. Furthermore, the simulation of the architecture makes use of the best routing strategy and this happens to be the CSPF ( $\alpha = 0$ ) according to our analytic investigations in section 7.4. The CSPF has the lowest link cost and as well as more reserved bandwidth. The CSPF routing algorithm is widely used in MultiProtocol Label Switching (MPLS) in Traffic Engineering. Furthermore, the path computed using CSPF could be exactly same as that computed from Open Shortest Path First (OSPF). The performance evaluation parameters are the acceptance ratio, utilisation, delay, interference (average and maximum for both network and node).

#### 1. Experiment 1: Impact of Acceptance ratio

The first simulation experiment investigates and compares the acceptance ratio in Std TE OSPF network and ToD TE OSPF network so as to ascertain which of the networks performs better.

Figure 7.20 shows the acceptance ratio for three different network sizes. When the network comprises of 20 nodes the ToD TE network has an improved acceptance ratio of 11% relative to the Std TE network. Increasing the number of network nodes to 50 nodes results in the ToD TE network experiencing an increased acceptance ratio of about 20% compared to the Std TE network. As the network scales to 90 nodes, the acceptance ratio improves only by about 8% for the ToD TE network. The low acceptance could perhaps be attributed to the use of an inferior low cost RF explorer used for the measurements.

#### 2. Experiment 2: Utilisation

The next performance parameter is the network utilisation which generally indicates the bandwidth use in the network. The results of the network utilisation performance for the Std TE and ToD TE of networks are shown in Figure 7.21. For all the network sizes

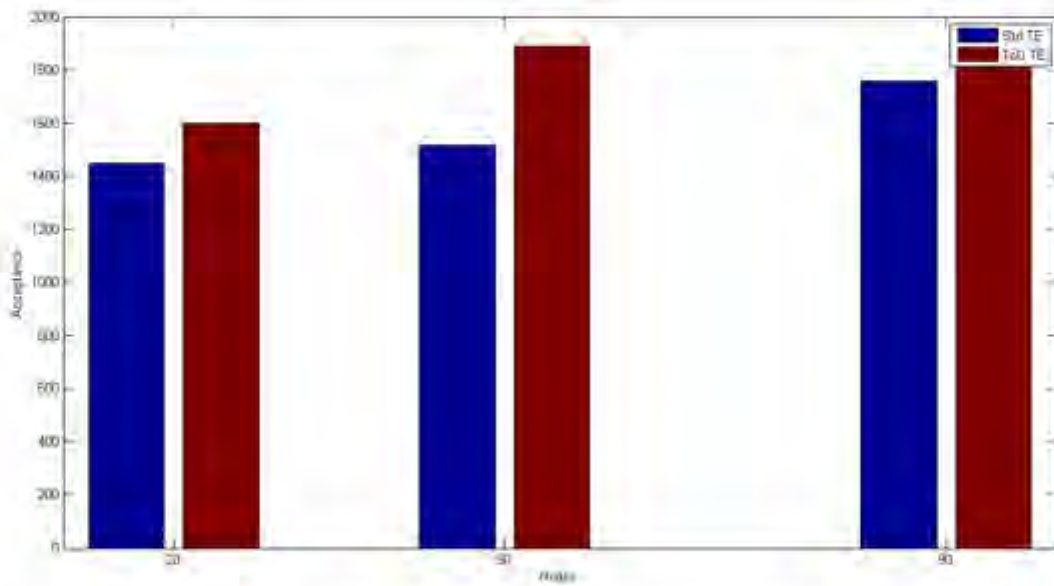


Figure 7.20: *Acceptance Ratio*

(20, 50, 90 nodes) the bar graph indicates a low network utilisation for the ToD TE network compared to the Std TE. The low utilisation is indicative of an idle network (ToD TE) and a high network utilisation is indicative of a busy network (Std TE). The low network utilisation for the ToD TE is a desirable effect as it makes it feasible to accommodate more applications and services in this kind of network. The delay parameter is also considered in the next experiment.

### 3. Experiment 3: Delay

The delay parameter is also considered in the experiment and its impact on the network is indicated in Figure 7.22. We observe that, for a 20 node network, the ToD TE network experiences a delay of 2.3% as compared to the Std TE network. As the nodes are increased to 50 nodes, the ToD TE experiences a significant drop in delay by about 89% as compared to the Std TE. As the number of nodes are increased to 90 nodes in the network, the delay experienced by the ToD TE is still less as compared to the Std TE network. A lower delay is an improvement in terms of the QoS offered by the network. Another key performance characteristic of network performance is that of interference.

### 4. Experiment 4: Interference

In the case of Figure 7.23, the average network interference is seen to be increasing by 2.2% for the 20 node network to 6% for the 50 node network. The average interferences for the 90 network nodes network is nearly the same for both the Std TE and ToD TE. The ToD TE is just about 0.63% above the Std TE network. When the maximum interference is considered for all network sizes, it is observed that the ToD TE is generally higher than that of the Std TE as shown in Figure 7.24. At the node level, the average node interference is shown in Figure 7.25, it is observed that the average node interference is initially higher

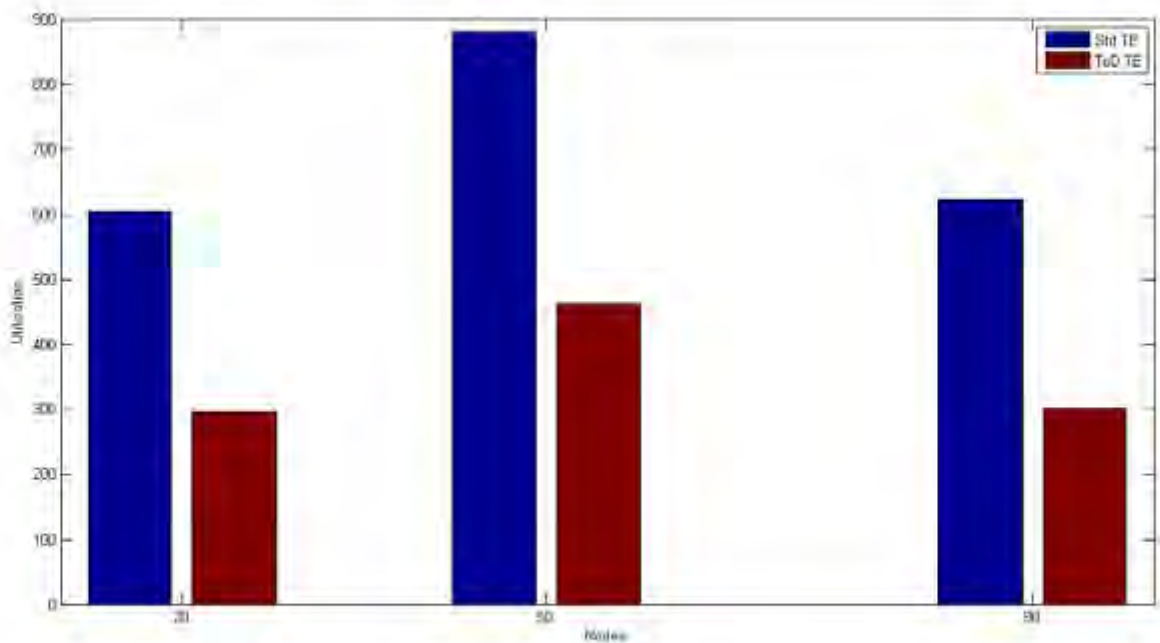


Figure 7.21: *Utilisation*

for the 20 node network wherein the ToD TE has a value 4% higher than that of the Std TE Network.

As the network is scaled to 50 nodes, the average node interference increases to about 8% for the ToD TE relative to the Std TE. Furthermore when the network size is increased to 90 nodes the ToD TE network has a 2% higher average node interference as compared to the Std TE network. When the maximum node interference is considered as a performance parameter, the variation of the interference for the different network sizes is shown in Figure 7.26. The general observation is that the maximum node interference is higher for the ToD TE network relative to the Std TE. This could possibly be due to narrowband interferences which may emanate from either spurious or unintentional transmissions.

However, despite the interference which can be dealt with, the simulation experiment reveals the usefulness of the TVWS. Intuitively, the availability of TVWS implies UHF is underutilized and it's on the basis of its propagation characteristics, it is suitable for non-line of sight connectivity. According to [151], TVWS base stations operating in the UHF band can be utilized to provide a backhaul network to rural, remote and underserved areas. A cognitive mesh network, comprising of nodes operating in the UHF band as well as wireless access points using the 2.4GHz Wi-Fi can be leveraged upon to bring not only broadband, but other services as well such as telemedicine in Figure 7.27. Practically, a UHF band node is provisioned at each access point. Depending on the factors involved, TV base stations can connect in different topologies such point-to-point as well as multi-hop mesh network. Telemedicine services can be provisioned by deploying MPLS and TV white

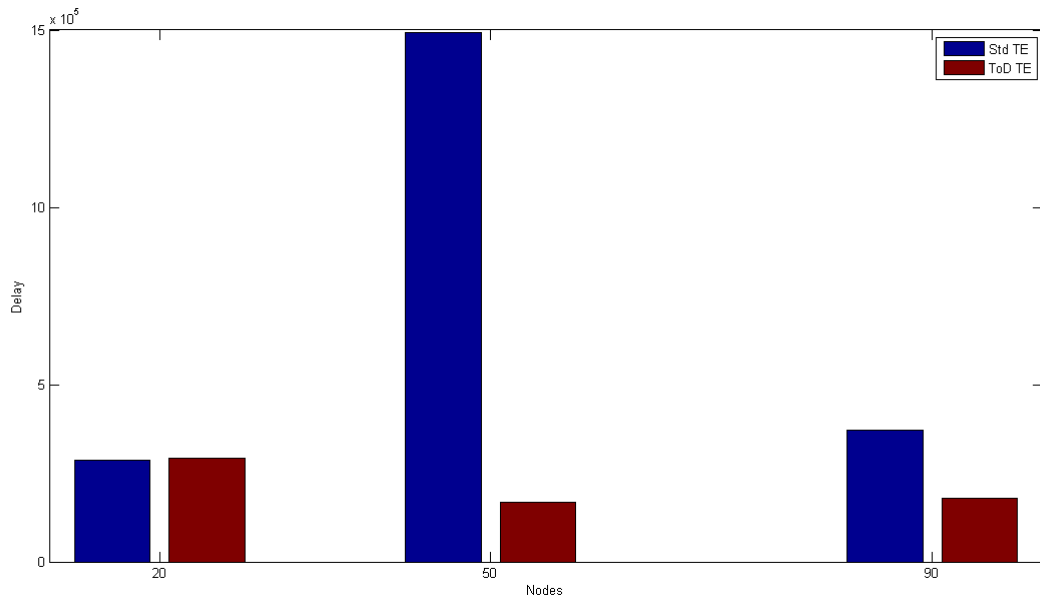


Figure 7.22: *Delay*

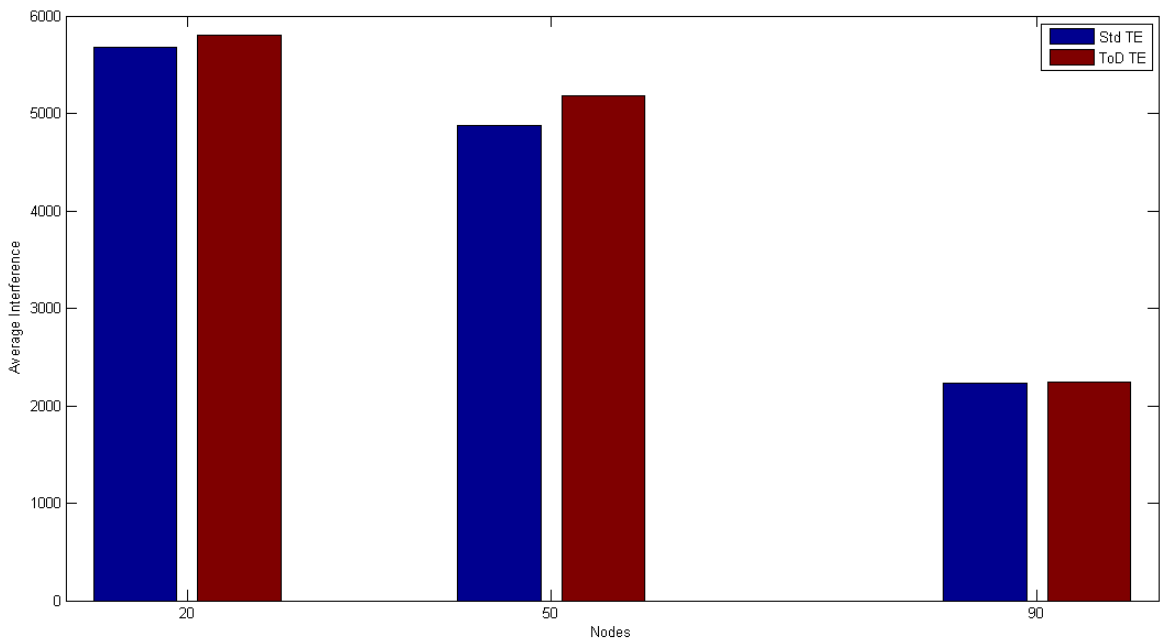


Figure 7.23: *Average Interference*

space technologies. For example the clinics in the surrounding villages (C, D, E, F) can be

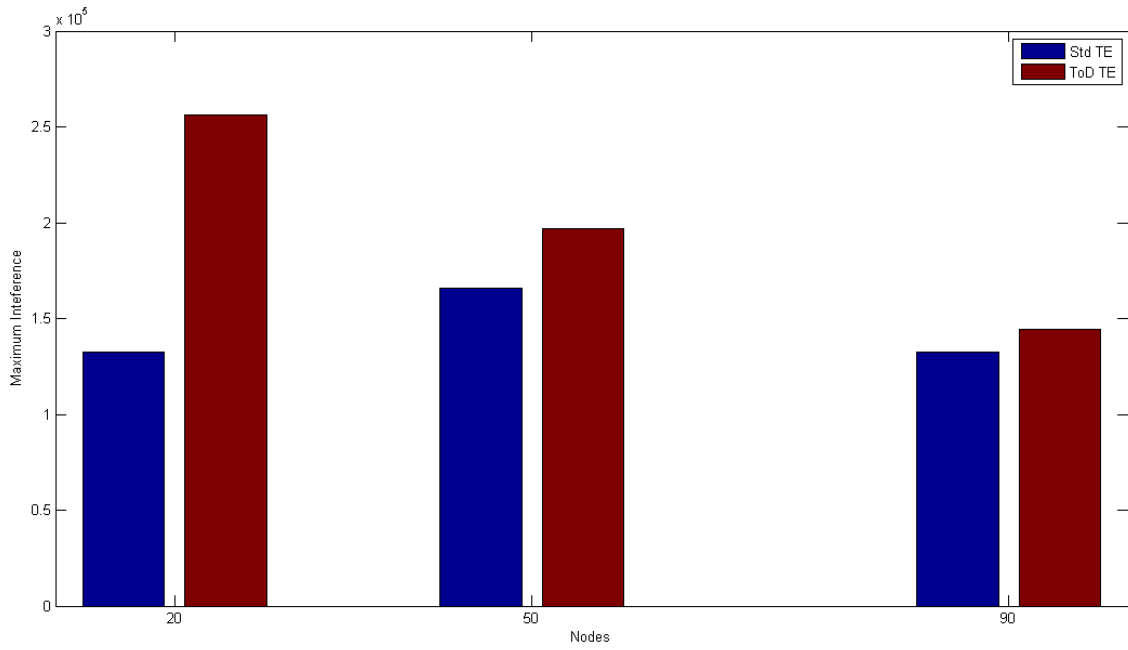


Figure 7.24: *Maximum Interference*

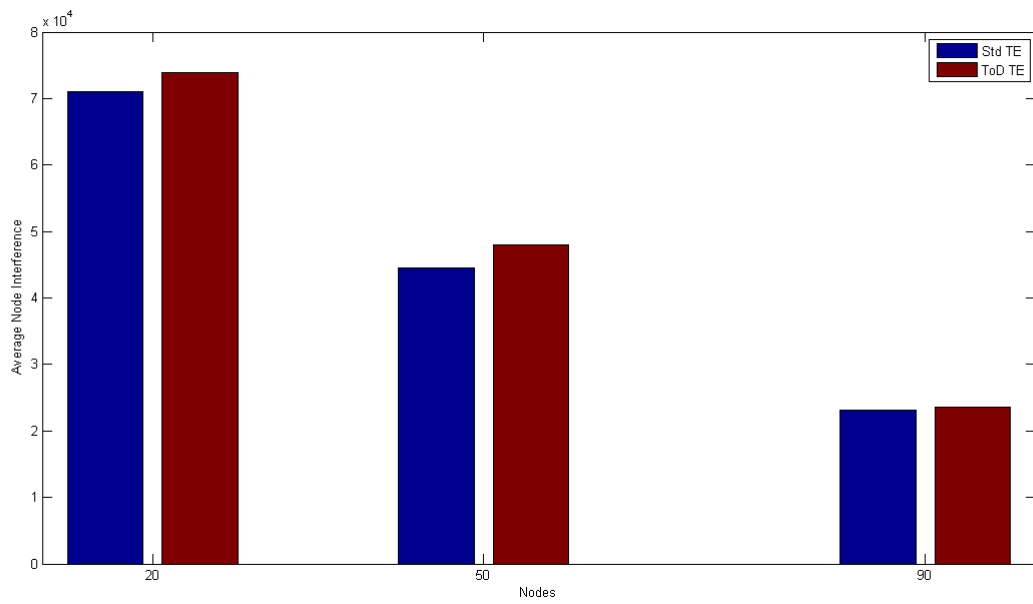


Figure 7.25: *Average Node Interference*

linked to a main district hospital in Village B.

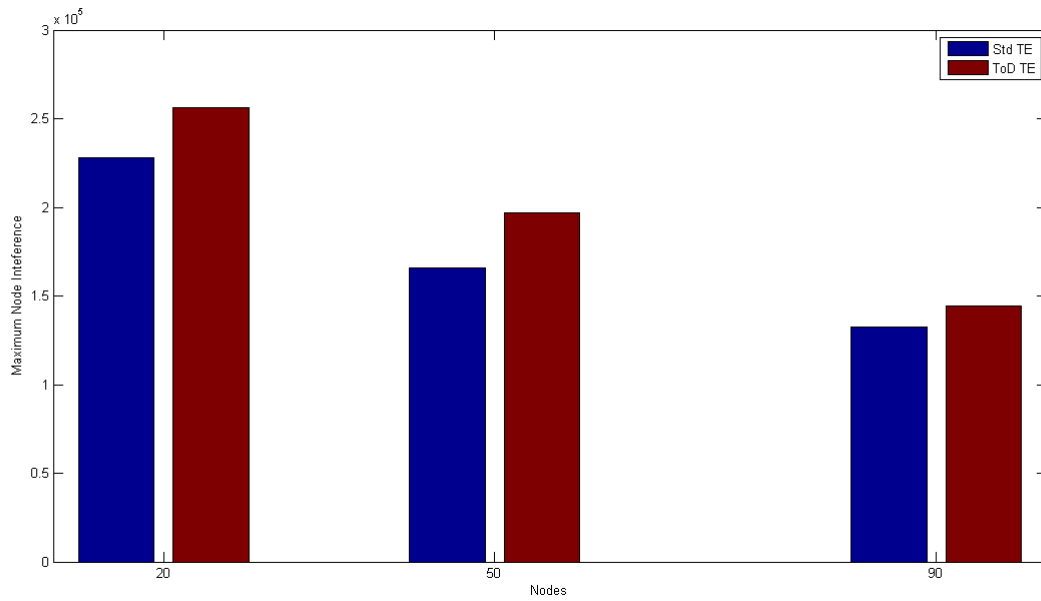


Figure 7.26: *Maximum Node Interference*

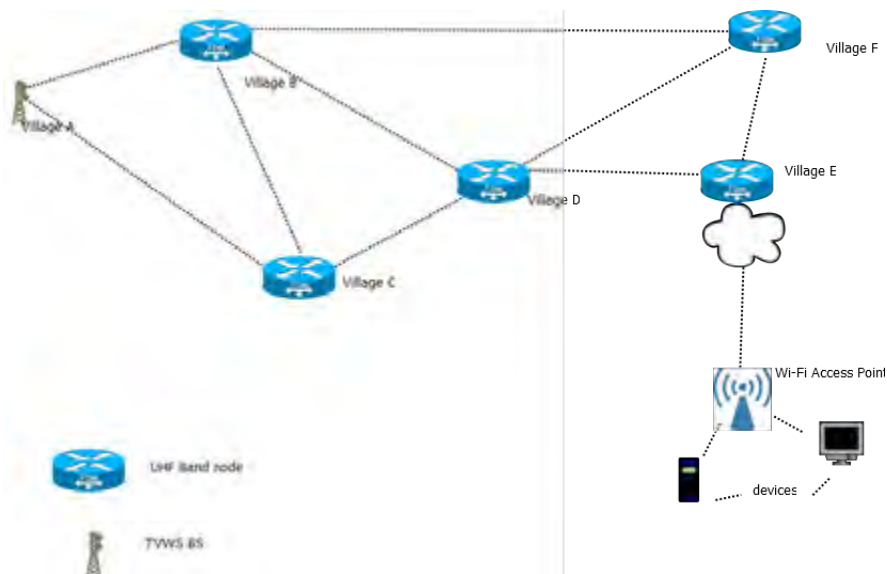


Figure 7.27: *UHF Nodes on Mesh Network*

## 7.7 Conclusion

In this chapter, the classical traffic engineering problem was revisited and subsequently used to design a ToD Traffic engineering framework for the management of TV White Spaces in a Cognitive mesh network by way of shifting traffic flows. Using the TE framework for the

management of TV white Space, we have addressed the research question pertaining to the QoS Routing strategy. The QoS Routing strategy Research question looks at three QoS routing strategies, namely, CSPF, MIX and IOPT and seeks to establish which of these routing strategies is the best for next generation Cognitive mesh networks. Under a time of day (ToD) traffic engineering scheme, the three QoS routing strategies were evaluated in both a cooperative and non-cooperative setting with regards to the following parameters:

- Link cost under varying demand
- Reserved bandwidth under varying prices
- link cost under joint price and reserved bandwidth variation
- link cost using a genetic algorithm

Numerical analysis results indicate that in terms of the link cost performance parameter, CSPF is the best strategy in both a cooperative and non-cooperative setting. Furthermore practically measured occupancy results were deployed in simulation experiments conducted on three networks of different sizes to investigate the performance of the OSPF routing strategy with regards to acceptance ratio, utilisation, delay and interference wherein a Std TE network and ToD TE network were compared. Simulation results point to an increased acceptance ratio, reduction in delay and utilisation for the ToD TE OSPF network as compared to the Std TE.

## 8. Conclusion

In this thesis, we have revisited the classical network engineering and traffic engineering problems with a view to leveraging on these approaches in designing a low cost Cognitive mesh network for the purpose of Internet provision. The network engineering problem involves providing resources to the traffic and is thus a resource allocation problem. The resource allocated in this case is the spectrum called white space, in which we leveraged on the technological developments in Cognitive radio for its harnessing. We developed appropriate frameworks for the more efficient and effective allocation and use of the TVWS spectrum. The second problem revisited is the traffic engineering problem or approach wherein the traffic is taken to where resources are, and is subsequently done through the routing process. A time of day based routing model is proposed as the crux of a traffic engineering framework, responsible for efficient management of TVWS and is subsequently evaluated. We provide a detailed summary of our contributions in section 8.1 emanating from a reconsideration of the two classical problems based on our two fundamental research questions. Ultimately we discuss the practical implications of the results of our work wherein we highlight that solving the spectrum scarcity problem enables us to effectively and efficiently use TVWS. Subsequently upon recognition of TVWS as an enabler of Internet of Things (IoT) which pertains to the connecting of physical things to the Internet and subsequently making it feasible to access remote sensor data as well as controlling the physical world from a distance [70]. However at device level, individual devices tend to communicate with each other and we consider Machine-to-Machine (M2M) comprising technologies that permit both wireless and wired systems to communicate with other devices of the same ability. Practically, M2M involves a device (such as a sensor or meter) capturing an event (such as temperature, inventory level, etc.) and relaying via network (wireless, wired or hybrid) to an application (software program), that translates the captured event into meaningful information.

### 8.1 Summary of Contributions

Our contributions are categorised into the Network Engineering and Traffic Engineering sections. The NE section is further subdivided into the cooperative and non-cooperative subsections when answering the first research question.

**8.1.1 Network Engineering: Cooperative Spectrum Sharing Framework (Research Question 1).** The first part of the network engineering problem involves tackling spectrum allocation by designing a cooperative spectrum sharing framework for a heterogeneous network using a cooperative Stackelberg game. The rationale behind formulating the problem as a centralized cooperative Stackelberg game is to allow for individual nodes to cooperate with each other to form coalitions. For concreteness, a centralized Cognitive mesh network was considered to be a heterogeneous network as it comprised WiMAX Base Station (BS) and Wi-Fi Access points (APs) that belong to different operators engaged in the trading of TVWS. The interaction of the BS and APs was subsequently generalized to a pricing problem wherein the BS strives to maximize its profit by selling secondary spectrum and the Wi-Fi APs strive to satisfy clients' demands by acquiring as much spectrum as possible to meet the demand. The pricing problem is ultimately

generalized into a Stackelberg game in an oligopolistic market setting where the BS attains a leader role and the APs attain a follower role engage in a game with Nash Equilibrium (N.E) as the solution. Our centralized cooperative spectrum sharing framework comprises three tractable models as follows:

1. Delay QoS based model which analytically attempts to characterize how spectrum can be dynamically shared to simultaneously satisfy QoS of the SU traffic which carries different classes of traffic while protecting the PU.
2. Throughput QoS model which strives to characterize a scenario of maximizing overall network throughput for SU in the heterogeneous network while protecting the QoS of the PU.
3. Composite Metric model, this model is formulated from a combination of the throughput and delay QoS parameters. All the models were evaluated based on performance parameters such as arrival rate, price, revenue generated and scalability.

**8.1.2 Network Engineering: Non-Cooperative Spectrum Sharing Framework (Research Question 1).** The second part of the network engineering problem is the formulation of a decentralized Non-cooperative TVWS spectrum sharing framework for heterogeneous networks. The problem is also approached from a game theoretic perspective in which the interaction between different competing technologies viewed as a non-cooperative game with Nash Equilibrium as the solution. The non-cooperative game is competitive game in which PUs strive to maximize profits and SUs strive to maximize the amount of bandwidth. Subsequently the game is generalized into a Bertrand game in an oligopolistic market with the PUs and SUs as the game players with different strategies. The PUs own the spectrum and thus perform the role of selling the spectrum and the SUs perform the role of buying spectrum. The PUs strategy is by way of price adjustment, with a general trend that SUs tend to favour the lowest prices when buying. Three tractable analytic models are used in the framework as follows:

1. Delay based model
2. Throughput based model
3. Combination of delay and throughput metrics model.

The results of our revisit of the network engineering problem has implications on the routing of traffic in a network wherein either existing routing protocols are adapted to cognitive routing or new ones created. We substantiate this claim as follows:

1. routing: Routing is the backbone of communication for transferring data from one machine to another in a multi-hop fashion. A good routing protocol is required for efficient communication and a good routing protocol is based on channel selection strategy. Therefore, a good channel selection strategy is required for efficient routing protocol so that routes should be stable and exist for longer time [222].

2. on demand routing: AODV and DSR are used as two representative routing protocols for the on demand class of routing protocols. Whenever the need to communicate data arises, the source will in the general case, find a route to the destination and this is called route discovery. Route discovery is initiated when the source node broadcasts route request (RREQ) packets whose travel towards the destination node are aided by intermediate or relay nodes. The destination node or intermediate node knows the route to the destination node and responds by sending route reply packet (RREP) to the source node. Upon receipt of the RREP packet, the source node is assured of the existence the route. AODV uses sequence number as freshness indicator and loop free- guarantee. The use of classic on-demand routing protocols on cognitive mesh networks is not feasible due to the dynamic spectrum environment. To this end, make available spectrum related information onto the routing control packets from the spectrum sharing framework. In the route discovery, this spectrum related information is piggybacked onto the control packets (RREQ, RREP, and RERR). If the source node inserts its spectrum related information on RREQ packets, the intermediate nodes forward the RREQ packets they also append their own spectrum related information. Thus when a cooperative spectrum sharing framework is coupled to the routing module, all active routing nodes will periodically broadcast routing information packets, exchange routing information and proactively discover routing. Simultaneously nodes must maintain the routing destined for the whole network of all nodes. To this end, when a node needs to transmit packets, there will be plenty route options to the destination for the packets and this will result in low delay. The drawback in this particular case will be that of overhead. The ever changing topology triggered by PU activity will also pose challenges to the routing protocol [270]. Some routing protocols are however based on the throughput metric. Throughput is defined as average rate of successful delivery of packets per second. This is the basic metric of routing protocols and is used extensively. Throughput based routing protocols work on maximizing network throughput and measures their performance by successful delivery of packets [2]. On demand routing protocols can also be adapted for throughput maximization by sending AODV style route discovery message to its neighbours which accumulates information about each node's available channels and their quality. The approach integrates spectrum discovery, route discovery and spectrum heterogeneity [2].

Reduction of delay and the maximization of the throughput should be satisfied which possess a challenge to the proposed cognitive mesh network. A collaborative routing and spectrum utilization with minimal interference with the use of on demand routing protocol finds a reliable solution of optimization.

3. Competitive routing: Classical Optimized Link State Routing (OLSR) protocols are proactive and are mainly aimed at delay sensitive applications. In terms of operation, routing information is in general maintained in each node with routing updates being continuously propagated to every other node within the network by way of control hello packets (hello and TC messages). OLSR is adapted for cognitive mesh routing by employing two control messages namely, PU-aware Hello (P-Hello) and PU aware TC. Each SU is thus permitted to transmit data packets in licensed channels by CR without interfering with the PU activities. Consequently the challenge of OLSR failing to efficiently utilize link state information such as channel and spectrum condition is dynamically resolved so as to estimate alternative paths resulting in reduced delay [254], [17].

4. Throughput: The Link state routing protocol can also be adapted for multi-radio, multi-channel networks to enhance throughput and perform load balancing. This is achievable by distributing data among diverse multiple paths to avoid congestion and appreciably improve throughput. Our throughput metric is such that the number of hops has an influence on the level of the throughput. The higher the number of hops or nodes the more likely the packet losses and a subsequent reduction in throughput. The composite metric enables the routing protocol to achieve a tradeoff between delay and throughput by adjusting the adjustable parameters.

**8.1.3 Traffic Engineering: Routing (Research Question 2).** A reconsideration of this problem subsequently led to the design of an adaptive traffic engineering framework based on a Time of Day (ToD) theoretical routing model and a TVWS occupancy measurement campaign. The objective of the model is to minimize the network cost. The routing model comprises three strategies, namely the CSPF, MIX and IOPT. These routing strategies are deployed in the network and allow for the performance evaluation of the framework based on such parameters as link cost, demand, reserved bandwidth and price. Using the Lagrangian and the genetic algorithmic approach, the CSPF is found to be a better strategy in terms of network cost. We leverage on our results from the theoretical model, to build an adaptive framework based on daily occupancy measurements for a two week period. Three different networks with nodes ranging from 20 nodes 50 nodes and 90 nodes are configured and the CSPF strategy deployed in both a standard network and ToD network. Simulation results indicate a higher acceptance rate, lower utilisation, and lower delay for the ToD TE Cognitive mesh network as compared to the Std TE network.

## 8.2 Implications of contribution on Rural and Urban Areas

The contribution of this thesis has a huge impact on the future or Next Generation Networks (NGN), wherein from a rural and urban perspective the infrastructure can be improved by leverage on TV white space standards such as those discussed in chapter 5. Some examples of such standards include weightless which involves Machine-to-Machine Communications, IEEE 802.22 which species a point-to multipoint architecture, etc.

1. Internet of Things in Rural and Remote areas-M2M: Wireless Mesh technology (WMN) is a first step toward providing high-bandwidth network over a specific coverage area. Thus, WMNs are predicted to be a key technology that provides ubiquitous connectivity to the end user. The integration of Wireless Mesh technology with Cognitive radio mitigates the spectrum scarcity problem and subsequently gives rise to a cognitive radio mesh network. In this thesis, a cognitive radio mesh network that has been designed for internet provision. Currently the main communication form on the internet is human-human. However, it is envisaged in the near future that any object will have a unique way of identification and can thus be subsequently connected to every other object. To this end, an important implication of Internet provision emanating from the design of cognitive radio mesh network is the feasibility of Internet of Things (IoT). The IoT is a novel paradigm that strives to integrate several technologies such as wired and wireless sensor and actuator networks, en-

hanced communication protocols, distributed intelligence for smart objects, mobile phones and undoubtedly the internet. The basic idea of IoT is to connect things to enhance several aspects of everyday life and behaviour of potential users. In rural environments, for example, a cooperative cognitive mesh network can be utilised to bring health services to the community [221], wherein the wireless node entities can increase their effective QoS via cooperation. In most rural and remote communities in developing countries, this can reduce the death rate by making available medical treatments on time and subsequent quality care. This can be achieved by leveraging on cooperative IoT to avail improved health monitoring and control of rural and poor human being's health parameters such as blood pressure (BP), haemoglobin (HB), blood sugar, abnormal cellular growth in any part of the body etc. Furthermore, given that most patients in rural areas do not have access to specialists [23], it is possible to offer remote consulting services in rural villages by leveraging on media rich network capabilities. The doctors can see and interact with patients in remote telemedicine centres, with the case history and medical data automatically transmitted to the doctor for analysis. In the Agricultural domain, cognitive radio mesh networks can potentially aid IoT to bring about poverty reduction in rural and remote areas [70]. A case in point is that of drip irrigation in environments where the advent of climatic change has given rise to erratic rainfall. The IoT inspired drip irrigation facilitated through white space availability involves watering only the soil closest to the plant's roots. Numerous sensors are placed in the field to sense such parameters as temperature, humidity, radiation and soil water content with the data being relayed to a central node which then makes a decision on how much water is released and where. IoT can further be utilised in the provision of branchless banking services wherein farmers and villagers are able to withdraw and transfer money, and pay bills from a network of agents that may include retails outlets. This mainly benefits the rural and remote communities who main not have access to banks within a reasonable distance. For governments and other relevant authorities, public agriculture surveillance programmes enable decision makers to guide agricultural interventions such as preventing the spread of plant eating pests or other plant diseases. The systems leverage on IoT technologies as well as TVWS standards such as IEEE 802.22, IEEE 802.11af, IEEE 802.15.4, weightlessness, etc. to track and monitor farm animals subsequently detecting potential signs of diseases. Furthermore for rural communities with small populations, the IEEE 802.22 standard which specifies a point-to-multipoint (centralized -discussed in chapter 4) architecture as in chapter 5 can be leveraged upon to provision broadband internet to the schools, hospitals and other relevant community centres. Practically this may translate to a central base station managing its own cell and all associated consumer nodes. Consequently, the Base station (Bs) controls the medium access in its cell and transmits in the downstream direction to the different nodes, which respond back to the base station in the upstream direction.

## 2. Internet of Things in Urban areas-Smart Cities:

From the modern urban environment perspective where congested networks exists as a consequence of a high density of devices competing to access the scarce radio spectrum, the implication of the cognitive mesh network design is that plenty white space can be harvested using TVWS technology. The use of TVWS technology brings in tremendous benefits ranging from supporting smart city infrastructure, extending connectivity into previously challenging environments as well as enabling ubiquitous and reliable wireless con-

nectivity aimed at enhancing the lives of the resident populations. Specifically powering the data needs of mobile workers as well as enabling Machine-to-Machine (M2M) communications in a Smart city, wireless connectivity can improve the socio-economic status of urban societies. A smart sustainable city is an innovative city that uses information and communication technologies (ICTs) and other means to improve quality of life, efficiency of urban operation and services, and competitiveness, while ensuring that it meets the needs of present and future generations with respect to economic, social, environmental as well as cultural aspects (ITU). Thus, the smart city leverages on the use of Internet of Things (IoT) paradigm and technologies for the purpose of improving efficiency of city infra-structures. At the level of the Municipalities, TVWS based networks such as the designed cognitive mesh networks will likely have an impact in numerous domains including for example, transportation, traffic control, building management, energy monitoring and pollution. As for traffic control, traffic sensor technologies such as magnetic sensors and Wi-Fi scanners can be deployed to assist in traffic management. In the city water supply domain, the monitoring of main water supply is also a benefit to be accrued from an improved infrastructure. The current labour intensive approach characterized by frequent testing which is uneconomic as well as long delayed response to problems can be mitigated by installing sensors in the water supply sources thereby enabling the simultaneous monitoring of both level and quality. Moreover this also allows the city water departments to receive real time reports of both water levels and associated quality. Cameras can be installed for surveillance to improve security as well as for the purpose of traffic management. Video surveillance of highways keeps does not only ensure smooth traffic movement but also reduces pollution as well as wear and tear on the highways.

In the energy domain, the Smart Grid transforms the way power is generated, delivered, consumed and billed. From an architectural view, the Smart grid comprises three layers

- (a) Physical Power layer (generation and distribution)
- (b) Communication networking layer
- (c) Application layer (Application services e.g. Advanced Metering, demand response and grid management)

The Smart Grid is a vision by the utility where their smart consumer loads will be able to interact by themselves in real time with many different components in the grid from transmission, distribution to energy sources such as traditional fossil based to sustainable but unstable sources of power such as solar and wind energy efficiency of the electrical network [198]. In the applications layer, the IEEE 802.22 standard discussed in section 2.6 is used in smart grid applications such as remote Smart metering, Advanced Meter Infra-structure (AMI) or Field Area networks that carry information between premises. Good coverage and reliable communication links are a requisite for the remote control and automation of electricity distribution entities [113]. The basis for offering the smart grid is that reliable broadband communications are readily available and cost effective, giving rise to the need to develop TVWS as an obvious choice as current RF Mesh and Power line communications (PLC) are either limited by range or speed.

However from the Service Provider (SP) perspective, the implication of our work is as follows:

- The spectrum owners and users are able to express the value they are willing to pay for a service.
- Pricing will enable the owners to realize profits.
- Pricing of spectrum can also be a way of limiting the spectrum usage by users. The prices will tend to deter the hoarding or abuse of spectrum.
- Control of prices is essential to the efficient use of spectrum

## 8.3 Further Work

In the thesis the cooperative setting involved a single BS and multiple APs.

- In future work it will be prudent to model the Stackelberg game sharing with multiple leaders. This is to say, the number of BS should be increased in the model so as to bring in issues of fairness.
- Both the cooperative and non-cooperative spectrum frameworks can be extended to incorporate the impact of dynamic interference.
- Further investigations can continue with the use of realistic usage statistics for both the cooperative and non-cooperative setting.
- A more superior set of measurement equipment can be used to get a much clearer picture of the impact of traffic engineering in the TVWS context.
- Routing: A series of different algorithms can be implemented within the designed framework.

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