White Space Network Management: Spectrum Quantification, Spectrum Allocation and Network Design

by

Hope Rabson Mauwa

a thesis submitted in fulfillment of the
requirements for the degree of
Doctor of Philosophy
in
Computer Science

October 2017

Declaration of Authorship

I, Hope Rabson Mauwa, declare that this thesis *White Space Network Management: Spectrum Quantification, Spectrum Allocation and Network Design* is my own work, that it has not been submitted for any degree or assessment at any other University, and that all the sources I have used or quoted have been indicated and acknowledged by means of complete reference.

Signed: _____

HOPE RABSON MAUWA

Date: _____

Abstract

Faculty of Science

Department of Computer Science

Doctor of Philosophy

by Hope Rabson Mauwa

The unused spectrum in the television broadcasting frequency bands (so-called TV white spaces) can alleviate the spectrum crunch, and have potential to provide broadband connection to rural areas of countries in the developing world. Current research on TV white spaces focuses on how to detect them accurately, and how they can be shared or allocated to secondary devices. Therefore, the focus of this research is three-fold: to investigate a novel distributed framework, which does not use propagation models in detecting TV white spaces, and suitable for use in countries of the developing world; to investigate a suitable spectrum sharing mechanism for short-time leasing of the TV white spaces to secondary devices; and extend the research to investigate the design of a TV white space-ware network in TV white space frequencies.

The investigation of a novel distributed framework, which does not use propagation models in detecting TV white spaces, and suitable for use in countries of the developing world is necessitated by the existing conditions in the countries of the developing word, which do not favour the use of the geo-location database as a method for detecting TV white spaces. Based on the protocols and standards that have been developed so far on TV white space access in counties of the developed world, such as the US and UK, the geo-location database approach, is the preferred method of detecting TV white spaces, as it guarantees high protection to the TV broadcasters (spectrum incumbents) from interference. Conditions required by the geo-location database approach to detect the white spaces accurately are lacking in most countries of the developing world, especially in the rural areas.

The investigation of a suitable spectrum sharing mechanism for short-time leasing of the TV white spaces to secondary devices is necessitated by the limitations of the existing proposals on sharing/trading secondary spectrum such as TV white spaces. Many spectrum sharing methods have been suggested in the literature for sharing the TV white space spectrum such as oligopoly competition, Cournot competition, Bertrand competition, and auction. Due to their perceived fairness and allocation efficiency, an auction stands out as the best approach. Auction mechanism design for secondary spectrum market, such as TV white spaces, has to meet many complementary requirements because of the many diverse network players, in addition to meeting the usual economic properties that any auction mechanism designed for selling general merchandise, should meet. Existing auction mechanism design attempts for secondary spectrum markets from researchers result in spectrum auctions that do not meet all the requirements.

The investigation of the design of a TV white space-ware network in TV white space frequencies is necessitated by the anticipated new challenges that will be met by network planners and designers in designing communication networks, such as mesh networks, in TV white space frequencies. Dense network topology is one of the major challenges that will be faced by network planners and designers, because of better

signal propagation and penetration properties of TV white space frequencies. This part proposes topology control mechanism that takes both traditional network parameters and white space parameters into consideration during the network design phase. The relevance of this work is to guide the network engineers during network feasibility studies done in white space frequencies to select the most relevant performance metrics during the actual implementation process.

Supervisor: Prof. Antoine Bagula
Co-supervisors: Dr. Marco Zennaro and Prof. Timothy Brown

UNIVERSITY *of the*
WESTERN CAPE

Acknowledgment

List of Publications

Journal articles

Mauwa H, Bagula BA, Zennaro M, Pietrosemoli E, Lysko A, and Brown TX. "Systematic Analysis of Geo-Location and Spectrum Sensing as Access Methods to TV White Space". *Journal of ICT Standardization*, Vol. 4, 147-176, 2016.

Mauwa H, Bagula BA, and Zennaro M. "Improving Spectrum Sensing as a Method for White Space Identification Through Design Principles". *Journal of ICT Standardization*, Vol. 3, 177-200, 2016.

Refereed conference publications

Mauwa H, Bagula BA, Zennaro M, Pietrocemoli E, Lysko A, and Brown T. "Systematic Analysis of Geo-location and Spectrum Sensing as Access Methods to TV White Space". *Proceedings of International Telecommunications Union (ITU) Kaleidoscope 2016*, Bangkok, Thailand, November, 14-16, 2016.

Mauwa H, Bagula BA, and Zennaro M. "Exploring TV White Spaces for Use in Campus Network". *Proceedings of 7th EAI International Conference on e-Infrastructure and e-Services for Developing Countries (AFRICOMM 2015)*, Cotonou, Benin, December, 15-16, 2015.

Mauwa H, Bagula BA, and Zennaro M. "WhiteNet: A White Space Network for Campus Connectivity Using Spectrum Sensing Design Principles". *Proceedings of International Telecommunications Union (ITU) Kaleidoscope 2015*, Barcelona, Spain, December, 9-11, 2015.

Mauwa H, Bagula BA, Zennaro M, and Zodi GL. "On the Impact of Propagation Models on TV White Space Measurements in Africa". *Proceedings of 2015 International Conference on Emerging Trends in Networks and Computer Communications 2015 (ET-NCC 2015)*, Windhoek, Namibia, May, 17-20, 2015.

Brown TX, Pietrosemoli E, Zennaro M, Bagula BA, **Mauwa H**, and Nleya SM. "A Survey of TV White Space Measurements". *Proceedings of 6th International Conference on e- Infrastructure and e-Services for Developing Countries (AFRICOMM 2014)*, Kampala, Uganda, November, 24-26, 2014.

Contents

UNIVERSITY *of the* WESTERN CAPE

List of Figures

UNIVERSITY *of the* WESTERN CAPE

List of Tables

Abbreviations

ATSC	**A**dvanced **T**elevision **S**ystems **C**ommittee
ATT	**A**nalog **T**errestrial **T**elevision
CR	**C**ognitive **R**adio
CEPT	**C**onference of **E**uropean **P**ostal and **T**elecommunications
CDS	**C**onnected **D**ominating **S**et
dBm	Decibel
DRC	**D**emocratic **R**epublic of **C**ongo
DTV	**D**igital Television
DTT	**D**igital **T**errestrial **T**elevision
DSA	**D**ynamic **S**pectrum **A**ccess
ECC	**E**lectronic **C**ommunications **C**ommittee
FCC	**F**ederal **C**ommunications **C**ommission
GA	**G**enetic **A**lgorithm
GHz	Gigahertz
GPS	**G**lobal **P**ositioning **S**ystem
HAAT	**H**eight **A**bove **A**verage **T**errain
ICASA	**I**ndependent **C**ommunications **A**uthority of **S**outh **A**frica
ISM	**I**ndusrial, **S**cientific and **M**edical
IEEE	**I**nstitute of **E**lectrical and **E**lectronics **E**ngineers
IETF	**I**nternet **E**ngineering **T**ask **F**orce
IoT	**I**nternet-**o**f-**T**hings
KP	**K**napsack **P**roblem
K-SP	**K**-**S**hortest **P**ath
LTR	**L**ink-Based **T**opology **R**eduction
LAN	**L**ocal **A**rea **N**etwork

LTE	**L**ong-**T**erm **E**volution
MAC	**M**edia **A**ccess **C**ontrol
MHz	Megahertz
MANET	**M**obile **A**d-Hoc **Net**work
OFDM	**O**rthogonal **F**requency **D**ivision **M**Multiplexing
PU	**Primary User**
PMSE	**P**rogramme-**M**aking and **S**pecial **E**vents
PAWS	**P**rotocol to **A**ccess **W**hite **S**pace
QoS	**Q**uality of **S**ervice
RF	**R**adio **F**requency
SU	**Secondary User**
SNR	**S**ignal-to-**N**oice **R**atio
TV	**T**elevision
TVBD	**T**elevision **B**and **D**evices
TVWS	**T**elevision **W**hite **S**pace
TR	**T**ransmission **R**ange
UHF	**U**ltra **H**igh **F**requency
UK	**U**nited **K**ingdom
US	**U**nited **S**tates of America
UMTS	**U**niversal **M**obile **T**elecommunications **S**ystem
UWC	**U**niversity of the **W**estern **C**ape
VHF	**V**ery **H**igh **F**requency
WLAN	**W**ireless **L**ocal **A**rea **N**etwork
WMNb	**W**ireless **M**esh **N**etwork
WRAN	**W**ireless **R**egional **A**rea **N**etwork
WSP	**W**ireless **S**ervice **P**rovider
WSD	**W**hite **S**pace **D**evice

This piece of work is dedicated to my family, which has been a pillar of strength before and during the study. These are my wife Veronica, and my two sons, Malango and Upile.
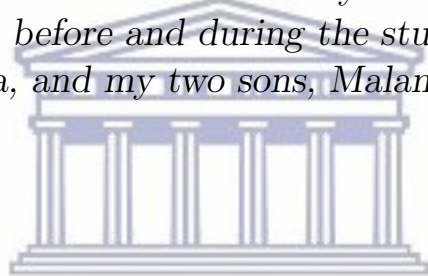
Chapter 1

Introduction

1.1 Introduction

Imagine the current generation without any wireless communication. In recent years, the fundamental importance that the radio frequency (RF) spectrum is playing in wireless communication systems cannot be over-emphasized. A multitude of wireless applications and services are using the RF spectrum for data transmission, e.g., data-centric smartphones, Bluetooth devices, broadband Wi-Fi Internet connections, satellite radios, navigation systems, just to mention a few. Mobile broadband services are undergoing a period of dramatic growth, causing a tremendous increase in data traffic as a result of the transition from voice communications to multimedia applications [17]. To circumvent this rising tide of data traffic, mobile operators are continuously upgrading their networks in an effort to make them more efficient by investing in new generations of mobile technology and rolling out increasing numbers of cellular base stations [17]. However, these network upgrades are not sufficient to meet the growing demand. Hence mobile services need access to more spectrum [17]. At the same time, the unlicensed bands such as the Industrial, Scientific and Medical (ISM) bands, have become extremely crowded with a proliferation of wireless technologies, such as Wi-Fi, Bluetooth, and wireless mesh networks [18]. These two factors have translated into a need for increased spectrum bandwidth. However, the RF spectrum is a limited resource and most of the useful part is already allocated to different wireless communication systems. As a result, it is now becoming difficult to find useful vacant bands to either deploy new wireless services or enhance the existing ones [19]. This RF spectrum scarcity has the potential to hinder the development of future wireless communication systems [20, 21] if alternative means of sharing the already allocated useful part of the RF spectrum is not found. Faced with the limitation of the natural RF spectrum and the increase

1

in demand for it, more research is being carried out by research institutions to find
new and innovative techniques that can offer ways of sharing the already allocated RF
spectrum. The research is focussing on how existing wireless network services are using
the already allocated RF spectrum. In a quest to find alternative ways of sharing the
already allocated RF spectrum, government institutions, research institutions, and other
stakeholders around the world have performed measurements and studied the occupancy
of the already allocated part of the RF spectrum. The measurements have revealed that
most of the allocated RF spectrum is heavily underutilized except for the RF spectrum
allocated to cellular technologies, and the ISM bands [22]. Although the measurements
have revealed that the already allocated RF spectrum is heavily underutilized, current
license spectrum allocation policies followed by governments do not allow unlicensed
users to use the spectrum even if it is not being used by the licensed users because the
licensed users are given exclusive rights to use particular parts of the RF spectrum on a
long-term basis. This static license spectrum allocation policy to license holders is now
being challenged as it has been shown to be inefficient [23] based on the results of the
measurements. The inefficiency is more apparent in the television (TV) broadcasting
frequency bands (Very High-Frequency band and Ultra High-Frequency band) as huge
portions of the assigned spectra in the bands have been shown to be unused [11, 23–25]
most of the time. It has been suggested that using these unused parts of the RF spec-
trum in the Very High-Frequency (VHF) and Ultra High Frequency (UHF) TV radio
frequency bands (so-called TV white spaces) could prove to be a means for meeting the
growing demand for increased wireless data transmission. An efficient long-term solu-
tion that has been proposed is dynamic spectrum access (DSA) [26], in which wireless
devices are able to make a real-time adjustment of spectrum utilization in response to a
changing environment using cognitive radio (CR) technology. Currently, CR technology
has not been adopted yet, as the technical details for its implementation have not been
solved completely.

The spectral measurement results have encouraged some governments to carry out re-
forms in their spectrum allocation policies to allow the legal operation of unlicensed
devices in the portions of the licensed TV bands that are not in active use by spec-
trum incumbent users [26], and also in the spectrum that has been freed up due to
analog-to-digital television transition. For example, the telecommunications regulatory
body in the USA, the Federal Communications Commission (FCC), has adjusted the
spectrum allocation policies to allow temporary broadcasting rights to secondary users
on these TV white spaces (TVWSs). As the digital television (DTV) transition begins
to roll out worldwide, regulatory agencies of several countries are also exploring similar
possibilities of allowing unlicense devices to communicate over TVWSs [27]. The FCC
ruling permits unlicensed devices to transmit in TVWSs as long as they do not interfere

with the primary licensed users of the spectrum [28]. In order to meet that requirement, secondary devices have to detect or identify the unused RF spectrum (vacant channels) accurately, which is difficult as the vacant channels vary according to location and time of the day. Consequently, utilizing these channels comes with a major drawback that any secondary access service can potentially cause harmful interference to the primary terrestrial TV broadcasting incumbents or users already broadcasting in the band, unless the vacant channels are detected accurately. This places a $'must\ do'$ requirement on any secondary user device (so-called white space device) to check if a primary user signal is present or absent in a channel before it goes ahead using it. Two techniques have been suggested in the literature to help white space devices (WSDs) do this: geo-location spectrum database and spectrum sensing. The next two sections discuss these approaches in detail.

1.2   Geo-location database approach

This approach requires a white space device (WSD) to send a query to a geo-location database of known TV transmitters in order to determine the available spectral opportunities at a given location. Before the WSD can query a geo-location database for available channels and associated transmission powers, it needs to be authenticated by registering with the database. After registering with the database, the WSD can now query the database for available channels by sending its location, demand, and other optional information such as device type and location accuracy [29], to the database. The WSD determines its location through a global positioning system (GPS) or via a base station that it is associated with [30]. The database responds to the WSD query with details of available white spaces (e.g., frequencies and transmission power limits) at the WSD's location [29]. The WSD selects a channel for its operation (or it decides not to select any channel) and informs the database about its selection by sending the number of the selected channel and information about itself such as the device type and number and the transmitting power. [31]. The database then registers the WSD (if necessary) and indicates that the selected channel is used by the particular WSD [32]. All this communication happens over the Internet. Figure 1.1 shows a simple implementation of the geo-location database approach.

To identify white spaces over the TV frequency bands, the geo-location database stores a set of transmission parameters of known TV transmitters and translates that information into a list of allowed frequencies and associated transmit powers to the WSD [32] by using sophisticated propagation models that include high-resolution terrain-data [30]. Some of the primary TV transmitter operational characteristics stored by the database
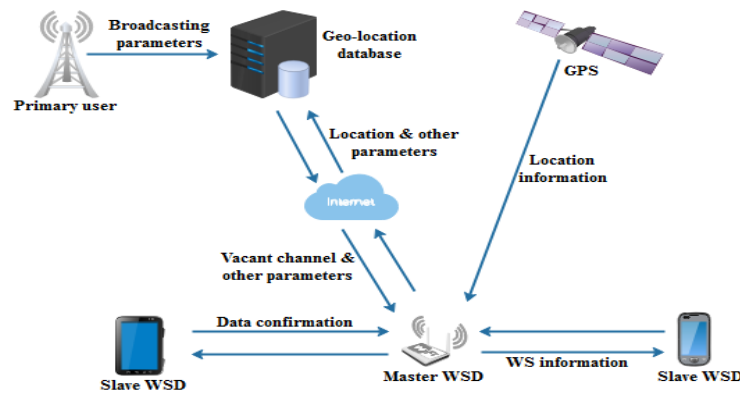
FIGURE 1.1: Geo-location database implementation

include location, antenna parameters (radiation pattern, height), transmit power, times of operation, protection requirements, the RF of operation and other related parameters. The database is dynamically updated over the Internet with the spectrum incumbents' information so that the information it contains remains valid. Primary users either provide their parameters to the geo-location database or the geo-location database pulls this information from them. Guided by the rate at which the primary users' transmission parameters change, the regulator determines the appropriate update frequency.

As already mentioned previously, propagation models play a very important role in translating transmission parameters of known TV transmitters stored in a geo-location database into a list of allowed frequencies for use by WSDs. In wireless radio communication systems, propagation models can be classified into deterministic (also called site-specific models) or empirical (also called statistical models). These propagation model types are discussed in the next two subsections to gain an understanding of the nature of the propagation models proposed for use in the geo-location databases.

1.2.1 Empirical propagation models

Empirical models (statistical models) are based on extensive measurements and mainly give a prediction of path loss as a function of various input parameters, which are usually qualitative and not very specific [8, 9]. Examples of input parameters can be dense urban area, rural area, suburban, indoor/outdoor, transmitter antenna height, receiver antenna height, link distance between transmitter and receiver and frequency range. Empirical models add environmental-dependent loss variables to the free-space loss to compute the net path-loss in the corresponding environment [9]. The models have output parameters that are primarily range-specific, not site specific [10]. Each model is useful for some specific environment and the accuracy of a model depends on the fit between the parameters available for the area concerned and the parameters required by the

model [7]. The advantages of empirical models include ease of implementation, reduced computational cost and reduced sensitivity to the environmental geometry [8]. The main drawback of empirical models is that they cannot be used for different environments other than the ones for which they were built without modification [10]. Table 1.1 shows some examples of empirical models and their corresponding operating parameters.

TABLE 1.1: Examples of empiricals models [7–10]

Model name	Application area	Frequency range (MHz)	Link distance (Km)	Transmitter antenna height (m)	Receiver antenna height (m)
Longley-Rice	Urban, suburban, rural	20 - 40000	1 - 2000	0.5 - 3000	0.5 - 3000
Hata	Urban, suburban, rural	150 - 1500	1 - 20	30 - 200	1 - 10
Egli	Urban	30 - 3000	< 60	30 - 200	< 10
Ericsson 9999	Urban, suburban, rural	150 - 1900	1 - 20	30 - 200	1 - 10
FSPL	Open area above any clutter	Any	Far field region	High	High

1.2.2 Deterministic propagation models

Deterministic models predict signal path transmission losses by mathematical analysis of the path geometry of the terrain between the transmitter and the receiver and the refractivity of the troposphere [33]. These models require detailed input parameters such as geometric information on terrain profile, location, and dimensions of buildings [8], and as such, their accuracy is usually very high. The main disadvantage of deterministic models is the computational overhead incurred during the signal path loss calculation that may be prohibitive for some complex environments [10]. Examples of deterministic models included Epstein-Petersen model, Deygout model and Bullington model.

Although deterministic models have the potential to be far more accurate than empirical models for a specific location and set of circumstances, they are less frequently used in practice because of their computational overhead. Consequently, empirical models are the ones mostly recommended for use in geo-location databases. For example, the FCC's in the USA approved geo-location databases that use F-curves [34], which are statistical models derived from empirical measurements.

1.3 Spectrum sensing approach

Sensing the spectrum using a detector is another method of detecting the presence or absence of the primary system signal in a spectrum. This spectrum access method is known as the detection-based spectrum access or spectrum sensing-based access. In this approach, the detector does not know any information about the locations of TV transmitters and their transmission powers. The protection of the TV tranmitters is estimated from the measurements; if the measured signal level is low enough, the spectrum is assumed to be free and can be used for transmission. The secondary user uses the primary user's signal level it measured as a proxy for its distance to the primary user [35]. It is possible to do that since signal attenuation is a function of distance, and as such, the signal level implicitly reflects the distance to the primary user [36]. A target signal level called detection threshold is defined to decide whether the secondary user is located far away enough from the primary user or not and the secondary user is granted the primary users spectrum provided that the signal level at its location is below the detection threshold. With the appropriately selected detection threshold, the secondary user is able to identify TVWSs accurately and transmit in those bands without causing interference to the primary user.

Technically, two conclusions are drawn from the signal measured by a spectrum sensing device: either the primary user's signal is present or absent. Traditional signal detection frameworks define two hypotheses [37] that assist in knowing which condition is present; hypothesis H_0 models the presence of pure noise, i.e., an idle channel not being use by a primary user, while hypothesis H_1 models a primary signal embedded in the noise, i.e., channel is busy and is being used by a primary user. These two hypotheses are modeled as shown in equation 1.1 and equation 1.2 respectively [37].

$$H_0 : y(n) = w(n) \tag{1.1}$$

$$H_1 : y(n) = s(n) + w(n) \tag{1.2}$$

where $y(n)$ is the n-th received signal sample, $s(n)$ is the n-th transmitted signal sample, $w(n)$ is the ambient noise sample and n is the signal sample number.

The optimal decision test for the binary hypothesis testing is a likelihood ratio test both in a Bayesian and Neyman-Pearson sense [37, 38]. Accordingly, to know which hypothesis is present, the user constructs the likelihood ratio, $\Lambda(y)$, of the hypotheses and compares it with a detection threshold, η [37].

$$\Lambda(y) = \frac{p(y|H_1)}{p(y|H_0)} \underset{H_1}{\overset{H_0}{\lessgtr}} \eta \tag{1.3}$$

where $p(y|H_i), i \in \{0, 1\}$ is the joint probability distribution function of the measured samples, y, conditioned on each hypothesis.

After replacing the probability distribution functions $p(y|H_i), i \in \{0, 1\}$ in equation 1.3, the likelihood ratio can be written as a function of the measured samples $F(y)$ [39].

$$F(y) = \underset{H_1}{\overset{H_0}{\lessgtr}} \eta' \qquad (1.4)$$

The function, $F(y)$, is called the test statistic. Upon receiving the measured samples, the detector evaluates the statistic, $F(y)$, and compares it with a detection threshold, η'. From the decision rule (1.4), preference is given to hypothesis H_1 if $F(y) > \eta'$ and hypothesis H_0 otherwise. The evaluation of the decision rule leads to four possible outcomes, of which two are erroneous [36]:

1. The detector detects correctly that there is no primary signal in the measured signal sample.

2. The detector detects correctly that there is a primary signal in the measured signal sample.

3. The detector detects incorrectly that there is no primary signal in the measured signal. This situation is known as the mis-detection.

4. The detector detects incorrectly that there is a primary signal in the measured signal sample. This situation is known as the false alarm.

Mis-detection leads the secondary user into thinking that the spectrum is free: hence starts broadcasting and cause harmful interference to the primary user of the spectrum. While false alarm leads the secondary user into thinking that the spectrum is occupied: hence the secondary user avoids broadcasting on it thereby missing a potential opportunity for secondary transmission on the spectrum. The reliability of the spectrum sensing-based model for a certain signal level is usually described in terms of these two erroneous metrics. These metrics can be evaluated provided that the probability distribution function of the measured samples conditioned on each hypothesis is known and that the detection threshold of the detector is set [39]. Normally, the design of a detector centres on minimizing these errors, which can be varied by adjusting the detection threshold. Unfortunately, the minimization of them contains two contradictory requirements; by reducing one error the other error increases [36].

In general, sensing methods can be divided into two categories: energy detection and feature detection. These categories are discussed in the next two subsections.

1.3.1 Energy detection

Energy detection based sensing, also known as radiometer or periodogram, works by measuring the energy contained in a spectrum band and comparing it with a certain pre-defined value called threshold to detect the presence or absence of a primary user's signal in an RF spectrum band. The signal is detected by comparing the output of the energy detector with a set detection threshold, which acts as the determinant of the hypothesis test outcome in equations 1.1 and 1.2. The energy detector computes the decision statistic by summing the powers of the measured samples, as in equation 1.5 [40].

$$M = \sum_{n=1}^{N} |y(n)|^2 \tag{1.5}$$

where N is the size of the observation vector.

The decision on the occupancy of a band is obtained by comparing the decision statistic M against a fixed detection threshold η. If the signal is absent, the computed statistic contains only the noise power such that $M \leq \eta$, otherwise the measured samples contain noise and signal power, i.e., $M > \eta$.

Energy detection using a spectrum analyser such as an RF Explorer in Figure 1.2 provides the simplest method to implement the hypothesis test.

FIGURE 1.2: RF-Explorer

The detection performance of energy detectors depends on the knowledge of the noise power. Knowledge of the noise power level is especially important in detecting very low signal levels of primary users. If the uncertainty of the noise power level is of the order of the primary user's signal power, then the energy detector cannot detect it and becomes unusable [41].

1.3.2 Feature detection

In feature detection, certain known characteristics of the primary user's signal that is to be detected are used in order to detect its presence such as pilot carrier signal, preamble,

continual or scattered pilots in an orthogonal frequency division multiplexing (OFDM) signal, cyclo-stationarity of a signal in the time or frequency domain [32, 42]. The fundamental hypothesis in feature detection remains as given in Section 1.3, equation 1.1 and 1.2. Using these features in the signal detection process results in a processing gain, which enables primary signal detection below the noise floor thus decreasing the possibilities of false alarms, i.e., this detection process gives much better performance in low signal-to-noise ratio (SNR) situation than energy detection. The challenges of this detection process include high computational complexity and long sensing time [43]. The dependency of this feature detection process on the specific features of the primary user's signal may limit its ability to adapt later to any new radio system introduced by the spectrum incumbents in the band [32].

Several spectrum-sensing methods based on feature detection exist in the literature. Table 1.2 provides some examples of feature detection methods. The table also provides a summary of the advantages and disadvantages of the energy detection and each feature detection method.

TABLE 1.2: Summary of advantages and disadvantages of non cooperative sensing techniques [11–15]

Spectrum Sensing Approach	Advantages	Disadvantages
Energy Detection	• Does not need any prior information of the user • Low computational cost	• Cannot work in low signal to noise ratio environment • Cannot distinguish users sharing the same channel
Matched Filter Detection	• Optimal Detection Performance • Low computational cost	• Requires a prior knowledge of the primary user
Cyclostationary Detection	• Robust in low signal-to-noise ratio • Robust to interference	• Requires partial information of the primary user • High computational cost
Wave Detection	• Effective for wideband signal	• Does not work for spread spectrum signals • High computational cost

The energy detection method is the commonly proposed method for TV white space (TVWS) detection because of its many advantages over the feature detection. As high-lighted in Table A.1, its advantages include: it is simple as it has low computational and

implementation complexities [11, 18, 44–48]; it has good performance [49–51]; it is more generic as detectors do not need any knowledge of the primary user signal [11, 40, 48] and as such, it is capable of adapting to any new system introduced into the band [32].

1.4 Performance-enabling factors

The review of the two approaches for detecting TVWSs shows that the performance of each approach is dependent on the presence or absence of certain factors. These performance-enabling factors have not been discussed clearly in the present literature. The literature discussion has placed much emphasis on the limitations of the spectrum sensing-based approach, which is mainly based on the developed world environment. This may have been the case because the idea to use TVWS originated from the developed world and the initial experiments were conducted there. The presence or absence of these performance-enabling factors affects the performance of each approach. Therefore, this section is dedicated to discussing these performance-enabling factors in details.

1.4.1 Performance-enabling factors for the geo-location database approach

An overview of the geo-location database-based approach is provided in Figure 1.3. The overview diagram includes factors that affect its performance and the financial implication for its implementation, maintenance and administration.
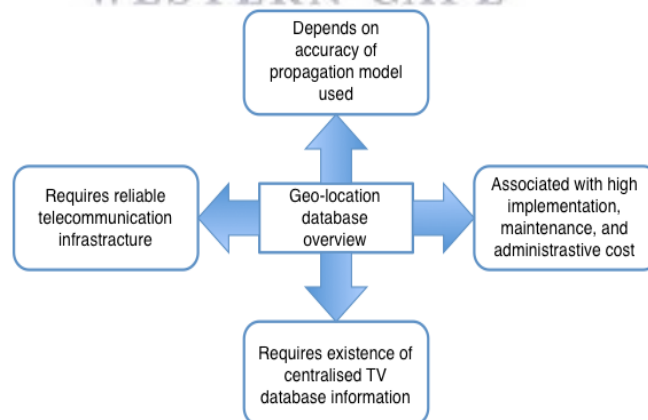
FIGURE 1.3: Overview of geo-location database approach

1.4.1.1 Propagation models

Statistical propagation models, which are being suggested for use in geo-location databases, are based on extensive measurements taken in real environments [52, 53] as already discussed. Their prediction results are most reliable if they are used in the environments for which they were developed or in other similar environments. In these environments, the prediction results are close to ground truth data obtained after extensive measurements. However, any propagation model is affected by terrain and environmental factors, for example, terrain elevation, terrain shapes, and environment changes [54], and as such, their efficiency in predicting signal attenuation over distance suffers greatly when they are used in environments other than the ones for which they were initially built [47, 55]. So a ray-tracing propagation model that uses elevation information and local terrain environment can be a better choice in arbitrary locations [54].

1.4.1.2 Internet backbone infrastructure

Efficient and frequent communication among WSDs and between WSDs and the geo-location database is required if harmful interference to spectrum incumbents is to be avoided. For example, there must be efficient communication between a master WSD and a slave WSD and a master WSD and a geo-location database. The master WSD must be able to determine its geographical position, which is often obtained by fitting it with a GPS receiver. The primary spectrum incumbent must also be able to send updated information about their broadcasting requirements to the database. This means that the WSD must have a way to communicate to the database server before being able to use the TV frequencies. This implies the requirement of an alternate communication system, which adds complexity and cost to the device. Data connectivity is an issue in most developing world countries, especially in the rural areas.

1.4.1.3 Existence of detailed TV database information

The fidelity of TV database information also plays a role in the correct identification of the presence or absence of a TV signal at a given location. Unavailability of nationwide transmitter information such as location, output power, antenna height and radiation pattern, can limit the use of a geo-location database approach. Spectrum regulators in many countries, especially in developing regions, often lack this detailed information.

1.4.2 Performance-enabling factors for the spectrum sensing approach

An overview of the spectrum sensing approach is provided in Figure 1.4. This figure summarizes the factors that affect the performance of this approach and also includes the financial implication for its implementation, maintenance and administration.
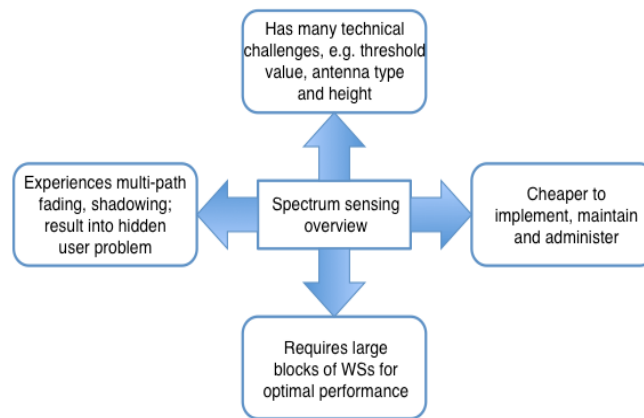
FIGURE 1.4: Overview of spectrum sensing

1.4.2.1 Multi-path fading and shadowing

Signals experience multi-path fading and shadowing due to obstacles in their path such as buildings, as they propagate through the wireless medium. Such effects may lead to a scenario called the *hidden user problem*, or *hidden terminal problem* [11], where a WSD is unable to detect the presence of a primary user in a channel, as depicted in Figure 1.5. This could lead to misinterpretation of measured data by the WSD where it would think the channel is available and start to transmit, causing interference to the primary user. These effects can be severe in places where there are a lot of obstacles, such as tall buildings or hills.

1.4.2.2 Detection threshold

The value chosen as the detection threshold has a major impact on the performance of spectrum sensing equipment. If the value is too high, the technique fails to detect the presence of a TV signal in a channel thereby causing harmful interference to the incumbent, and if the value is too low, it results in false detection due to the ever present electromagnetic noise, when actually there is no TV signal in the channel. The challenge is to come up with a threshold value that is optimal, such that there is no harmful interference to the primary users nor any missed opportunities by secondary users. Often there is no threshold that simultaneously gives low false positives and low
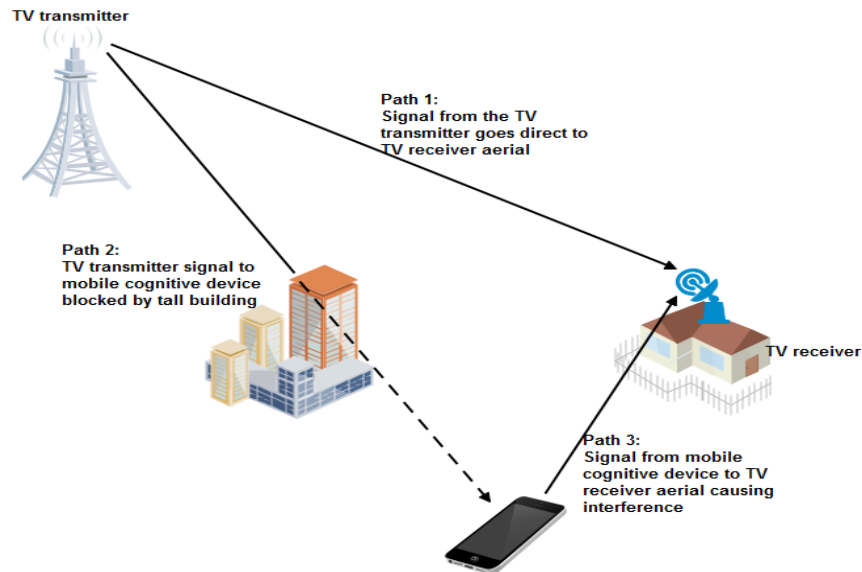
FIGURE 1.5: Hidden terminal problem [1]

false negatives. The FCC, the US regulator, mandates a sensing sensitivity threshold of -114 dBm by WSDs, which is considered as being way too conservative by many in the literature and which leads not only to significant waste of TVWS but also to increased complexity in the sensing device [22, 54, 56, 57]. In terms of protecting primary TV services from interference, higher threshold values may lead to interference while lower threshold values may result in inefficient spectrum utilization.

1.4.2.3   Absence of primary users in a spectrum chunk

The number of white spaces available in the TV broadcasting band can also contribute to the performance of the spectrum sensing approach. The many factors that affect the performance of spectrum sensing make it more vulnerable to errors in detecting primary users' signals if the primary users' signals are present in the band. On the other hand, if there are no primary users' services in the band or if there are vast tracts of unused spectrum in the band, it means that WSDs can be deployed in the band without concerns of interference to the primary users' signals.

1.5   So, what is the best approach to detecting TVWS?

Since optimal performance of each approach is dependent on some factors that may not be present in some regions, neither approach can produce superior performance in all possible regions. For example, in regions or countries where propagation models have been tried and tested extensively, such that their prediction results are close to ground

truth data, there is already reliable Internet backbone infrastructure and centralized detailed TV database information is also available. In these regions, the geo-location database approach is expected to perform better than spectrum sensing. On the other hand, in regions where the Internet backbone infrastructure is poor and unreliable, propagation models have rarely been tested so that their behaviour is unclear, spectrum usage information is scattered and stored in many formats and the regulators have not collected it into a useful centralized database that is publicly available, then the geo-location spectrum database approach may not produce optimal results.

1.6 Motivation

Currently, the use of a geo-location database approach is the preferred method of detecting the TVWSs in the USA and Europe [29, 58–61] as it guarantees high protection of the spectrum incumbents from interference. As mentioned in Section 1.2, geo-location databases use sophisticated propagation models on transmission parameters of known TV transmitters that it stores to predict the presence or absence of a TV signal at a given location. Empirical propagation models, which are recommended for use in geo-location databases, are each designed for a specific type of environment and a particular terrain profile classified as urban, suburban or rural. Consequently, each propagation model is useful for a specific environment and the accuracy of any propagation model depends on the fit between the parameters available for the area concerned and the parameters required by the model [7]. Most of the propagation models have been developed in the developed regions of the world based on the specific environment and terrain profile definition of such regions. The challenge with applying the propagation models directly in regions of the developing world is that the same terrain category definitions used in the developed world cannot be applied with the same accuracy [62] in regions of the developing world. The models have been tried and tested extensively in regions of the developed world such that their prediction results are close to ground truth data but have been rarely tested in the regions of the developing world where white space is assumed to provide broadband connectivity. Therefore, the probability of these propagation models having high prediction errors in a developing region, is high, if they are used based only on the similarities between the terrain type for which that model was built. Moreover, the behaviour of these models is not very well known in the developing world. Consequently, it is unclear how accurate the geo-location database approach will be in detecting TVWSs in developing regions at the moment.

As mentioned in Section 1.2, transmission parameters of known TV transmitters that the geo-location database stores are used to predict the presence or absence of a TV

signal at a given location. Consequently, the correct detection of the presence or absence of a TV signal at a given location also depends on the fidelity of the TV database information stored [26]. Unavailability of such information concerning a country's nationwide transmitters, such as location, output power, height and antenna type, can limit the use of the geo-location approach. In many countries of the developing regions, spectrum usage information is scattered and stored in many formats, electronic and paper and the spectrum regulators have not collected these into useful centralized databases, which can be used for TVWS access.

Efficient communication between WSDs, the geo-location database and the primary users in a geo-location database network system is very vital, if harmful interference to the spectrum incumbent is to be avoided. For example, there must be efficient communication between a master WSD and a slave WSD, a master WSD and a geo-location database and a master WSD or a slave WSD. The primary incumbent must also be able to send updated information about their broadcasting requirements to the database. Most of these communications require the Internet, which makes the Internet an integral part of the whole system for reliable performance. However, in most countries of the developing world, especially the rural areas, where white space spectrum is expected to provide broadband access, the telecommunication infrastructure is poor, which does not favour the use of geo-location database as a means to access the white space spectrum. Also, the geo-location database approach requires a complex centralized structure and even more complex logistics. Most countries in the developing world may not have the necessary infrastructures at present and so these would have to be built for DSA, which is expensive.

Fading, shadowing and the *hidden user problem*, relevant to spectrum sensing, can be severe in the developed world because of many tall buildings, especially if they are also close together. Consequently, primary TV signals are difficult to detect accurately by spectrum sensing alone and this situation could result in harmful interference to users who have deployed TV receiving antennas on the top of their buildings. Therefore, the performance of spectrum sensing in urban areas may be low. However, in rural areas, especially those of countries in the developing world, where white space could be used to provide broadband connectivity, buildings are unlikely to cause considerable fading, shadowing or bring about the *hidden user problem* since rural areas are sparsely populated with only small isolated traditional building structures.

Many regions of Africa and other parts of the developing world have vast tracts of unused spectrum in the TV broadcasting spectrum, especially in sparsely populated areas, as there is not enough return on investment for broadcasters to provide many simultaneous TV channels [26]. One such region is Sub-Saharan Africa, cited by authors in [63]. The

availability of vast tracks of TVWSs in these regions does not require the same stringent restrictions as required in the developed regions, and as enforced by the geo-location database approach.

The measurement campaigns that have been conducted so far, both in the developed and developing regions, that confirm the availability of unused spectrum in the RF band, have largely been based on spectrum sensing. This confirms two important points about spectrum sensing: 1) it is easier to implement than geo-location database and 2) it generates results that are reliable such that major decisions can be based on them. Moreover, the analysis in this section has shown clearly that conditions in the developing world countries do not favour the geo-location database approach as the best approach for detecting TVWSs optimally. Therefore, there is a need to investigate a different approach based on spectrum sensing, which favours existing conditions in the developing world.

1.7   Research problem

At the moment, there are no known propagation models confirmed to predict signal attenuation well in Africa, which are part of the geo-location database components, and which assist in detecting white spaces accurately. Related to this, the behaviour of these models is not very well known in the developing world. Most of the countries in Africa and in other parts of the developing world do not have the required telecommunication infrastructure to support DSA, which is required by the geo-location database approach, for optimal performance. Consequently, in these prevailing conditions, the use of a geo-location database-based approach to detect TV white spaces in most countries of the developing world is unlikely to produce optimal results.

1.8   Research gaps

The literature review [4, 5, 26, 29, 32, 54, 58, 59, 62, 64] has revealed some research gaps and opportunities that have motivated this study. These are summarised as follows:

1. Although a geo-location database-based approach to TVWS access is the one that is preferred in developed world countries, the approach does not favour conditions existing in developing world countries, especially the rural areas. Consequently, there is a need to investigate a framework that is more suitable to these areas.

2. The literature study has also revealed that although cooperative detection has been proposed as the solution to the hidden terminal problem, it does not completely eliminate the problem. Therefore, there is a research gap to finds ways and means of improving the detection.

3. The literature study has also revealed that finding a single detection threshold that simultaneously gives a low false alarm rate and a low mis-detection rate is difficult and almost impossible. Consequently, more research is required to find a way out of this threshold detection decision dilemma in order to be able to achieve optimal results.

4. The literature review on auction mechanisms, meant for secondary spectrum markets, has shown that they are in the early stages of development and there is room for improvement. Therefore, there is a need for more research in this area, in order to develop an auction mechanism eventually, that really reflects the practicality of secondary spectrum markets.

1.9 Research questions

This research work intends to investigate a novel distributed architecture based on real-time spectrum measurement data, which does not use propagation models in detecting TVWSs. To achieve that, the research seeks to answer the following research questions:

1. Is there framework that is well adapted to AFRICA and the developing world, where RF spectrum usage is different from that in developed countries?

2. If such a framework exists,

   (a) How will frequency sensing be implemented?

   (b) How will spectrum be shared among participating entities/players?

1.10 Research aims and objectives

The aims of this research are three-fold: white space spectrum quantification, white space spectrum allocation and white space-aware network design. Firstly, the research aims at investigating a white space network detection architecture based on cooperative spectrum sensing. The research also aims to investigate a suitable spectrum sharing/-trading mechanism for short-time leasing of the primary users' spectrum (white spaces)

to secondary wireless operators and finally, the research also aims to investigate the design of a white space-aware network.

The aims of the research are addressed through the following specific objectives:

1. Design a white space spectrum detection network architecture based on cooperative detection that utilizes new proposed spectrum sensing design principles to further protect primary users, that minimises both mis-detection and false alarms and that addresses the challenge of defining a single detection threshold that produces optimal results.

2. Develop an auction-based mechanism that mimics the process employed in genetic algorithm (GA) to maximise the spectrum allocation for sharing/allocating white space spectrum to secondary wireless operators.

3. Develop a white space-aware mesh network topology reduction algorithm that can be used during the network feasibility study in white space frequencies to guide the network engineer in selecting the most relevant performance metrics during the implementation process. Related to this, develop a white space-aware network utility function for selecting network nodes of a hierarchical backbone mesh network topology.

1.11   Research Methodology

In order to accomplish the objectives stated in Section 1.10, the following research methodologies are applied: literature review, experimental measurements and simulations. An explanation of where each of the research methodologies is used in the research follows:

1. A thorough literature review of the proposed approaches to white space spectrum access, what spectrum regulators of other countries say about the approaches and what the current standards on white space access say about the approaches, is carried out, in order to have a better understanding of these approaches, while laying down the foundation for this proposal. A thorough literature review is also carried out on traditional approaches to sharing/allocating the radio frequency spectrum to wireless operators in order to understand their limitations on being used for sharing white space spectrum to secondary wireless users.

2. Measurement experiments of the RF spectrum in the UHF band of the TV frequency spectrum are carried out with a spectrum analyser in different scenarios (indoor and

outdoor) to compare the performance of the sensing/detection approach with some common propagation models recommended for use in the geo-location approach. The spectral measurements are also used in the evaluation of the proposed white space detection architecture.

3. Simulations are used during the performance comparison of the sensing/detection approach with some of the common propagation models recommended for use in the geo-location approach. These models are also used in the performance evaluation of the proposed auction-based mechanisms for sharing white space spectrum to secondary users, and also in the performance evaluation of the proposed network topology reduction algorithm and the utility function for selecting nodes for inclusion in a hierarchical backbone network topology.

1.12 Research contributions

Clearly, the geo-location database approach will not perform optimally in most developing world countries, especially in the rural areas where white spaces are anticipated to provide broadband access to the Internet, due to lack of infrastructure to provide dynamic spectrum access. The work in this research proposes a cooperative sensing-based framework for TVWS detection that includes a new concept called multi-threshold detection design where more than one detection threshold is used to detect the white spaces. To the best of the author's knowledge, the proposed framework is the first of its kind to include multi-threshold detection design. Existing proposals including the ones reviewed in this research include single-threshold detection design in their frameworks, where only one detection threshold is used to detect the white spaces. In addition to this addition to the existing knowledge, the proposed framework also includes a new concept called virtual pricing design, to rank the detected white spaces in terms of the probability to cause interference to the primary users. As a direct result of ranking the white spaces, the proposed framework includes a sequential allocation design of the white spaces to the secondary users, based on their probability to cause interference to the primary users. As far as the author's knowledge is concerned, these two designs have never been used before in any of the existing frameworks.

Dynamic spectrum markets for future wireless network devices will involve complex spectrum transactions. The nontrivial dynamics in channel quality, spatio-temporal spectrum availability and the existence in the market of many diverse players with different power limit and channel bandwidth requirements, will call for new ways of allocating the spectrum [65]. To attract primary users of the white spaces to participate in secondary

spectrum markets, an auction strategy has been advocated as the best strategy for spectrum trade [65, 66]. As a contribution to the existing knowledge on spectrum auctions, the work in this research proposes a spectrum auction mechanism design, that not only meets the economic properties that are essential for any auction mechanism design for selling merchandise, but also meets the complementary requirements that are specific for the secondary spectrum market auctions. While most of the existing spectrum auction mechanism designs meet the economic properties of any auction mechanism for selling merchandise, to the best of the author's knowledge, none meet all the complementary requirements specific to secondary spectrum market auctions.

In order to utilize the white space spectrum efficiently, white space spectrum users can be divided into groups, so that those whose networks do not interfere on a spectrum segment can share the same spectrum segment for broadcasting. It is reported in [66] that the spectrum buyer grouping problem into non-interference buyer groups is NP-hard hence only heuristics exist. As a contribution to knowledge in this area, a new non-interference buyer-grouping strategy called the Interference Graph-Complement (IG-C) strategy, has been designed, which extracts the non-interference buyer groups from the complement of the interference graph. The strategy produces optimal results, i.e., it produces a minimum number of non-interfering buyer groups leading to improved spectrum reusability.

The multi-hop wireless mesh networks in Wi-Fi frequencies incur prohibitive costs for network carriers to deploy ubiquitous Wi-Fi, because of the node spacing required for Wi-Fi propagation [67]. However, the TVWSs have made available new spectrum opportunities with a far greater transmission range and better penetration properties than Wi-Fi, for the deployment of multi-hop wireless mesh networks, which could cost less. Part of the work in this thesis investigated the deployment of mesh networks in white space frequencies and discovered dense mesh network topologies. Therefore, a network topology reduction algorithm has been developed that could guide network engineers, during network feasibility studies done in white space frequencies, to select the most relevant performance metrics in the actual implementation process. In addition, a network utility function, which takes parameters, specific to white space frequencies, into consideration, has been formulated for selecting mesh network nodes to be part of a hierarchical backbone mesh network topology, which is more scalable than a flat sparse mesh network topology. To the best of the author's knowledge, this work on network engineering in white space frequencies is the first of its kind.

1.13   Declaration of publications

Some ideas and figures in the thesis have appeared in the following recent articles published from the research work.

Journal articles

Mauwa H, Bagula BA, Zennaro M, Pietrosemoli E, Lysko A, and Brown TX. "Systematic Analysis of Geo-Location and Spectrum Sensing as Access Methods to TV White Space". *Journal of ICT Standardization*, Vol. 4, 147-176, 2016.

Mauwa H, Bagula BA, and Zennaro M. "Improving Spectrum Sensing as a Method for White Space Identification Through Design Principles". *Journal of ICT Standardization*, Vol. 3, 177-200, 2016.

Refereed conference publications

Mauwa H, Bagula BA, Zennaro M, Pietrocemoli E, Lysko A, and Brown T. "Systematic Analysis of Geo-location and Spectrum Sensing as Access Methods to TV White Space". *Proceedings of International Telecommunications Union (ITU) Kaleidoscope 2016*, Bangkok, Thailand, November, 14-16, 2016.

Mauwa H, Bagula BA, and Zennaro M. "Exploring TV White Spaces for Use in Campus Network". *Proceedings of 7th EAI International Conference on e-Infrastructure and e-Services for Developing Countries (AFRICOMM 2015)*, Cotonou, Benin, December, 15-16, 2015.

Mauwa H, Bagula BA, and Zennaro M. "WhiteNet: A White Space Network for Campus Connectivity Using Spectrum Sensing Design Principles". *Proceedings of International Telecommunications Union (ITU) Kaleidoscope 2015*, Barcelona, Spain, December, 9-11, 2015.

Mauwa H, Bagula BA, Zennaro M, and Zodi GL. "On the Impact of Propagation Models on TV White Space Measurements in Africa". *Proceedings of 2015 International Conference on Emerging Trends in Networks and Computer Communications 2015 (ET-NCC 2015)*, Windhoek, Namibia, May, 17-20, 2015.

Brown TX, Pietrosemoli E, Zennaro M, Bagula BA, **Mauwa H**, and Nleya SM. "A Survey of TV White Space Measurements". *Proceedings of 6th International Conference on e- Infrastructure and e-Services for Developing Countries (AFRICOMM 2014)*, Kampala, Uganda, November, 24-26, 2014

1.14 Thesis outline

Figure 1.6 depicts the thesis structure in relation to the three main components of the research; spectrum quantification, spectrum allocation and network design. Chapters 2 and 4 contain the groundwork information necessary for answering the research questions. Chapter 2 also answers Research Question 1. Research Question 2a (Spectrum Quantification) is answered in Chapter 3 and Chapter 5 answers Research Question 2b (Spectrum Allocation). Chapter 6 constitutes the network design component and Chapter 7 is the conclusion.

In summary, the contents of the chapters are as follows:

- Chapter 2: Literature Review
  The chapter reviews the literature on the approaches and the developments that have taken place, in terms of TVWS access, since the idea was proposed by the FCC in 2004 [68]. The developments in TVWS that have taken place from national/regional registration to international standards and the recognition of the role that spectrum sensing can play in TVWS detection, highlighted by these national/regional registrations and international standards, are presented in the chapter. Cooperative detection and reviews of some TVWS detection architectures based on cooperative detection are also discussed in the chapter. Finally, the chapter reviews the problem of sharing/distributing TVWS spectrum to secondary users and the auction mechanism, as a promising solution to this problem.

- Chapter 3: White Space Network Management Model Formulation and Experimental Evaluation
  The formalisation of the architecture for the TVWS network management that includes the white space detection component based on cooperative detection is presented. New spectrum sensing design principles incorporated in the white space detection component to minimise the challenges of spectrum sensing as a method for TVWS detection are presented in the chapter. Evaluation of the principles, using real-world outdoor spectral measurements in the TV frequency band, is also presented in the chapter.
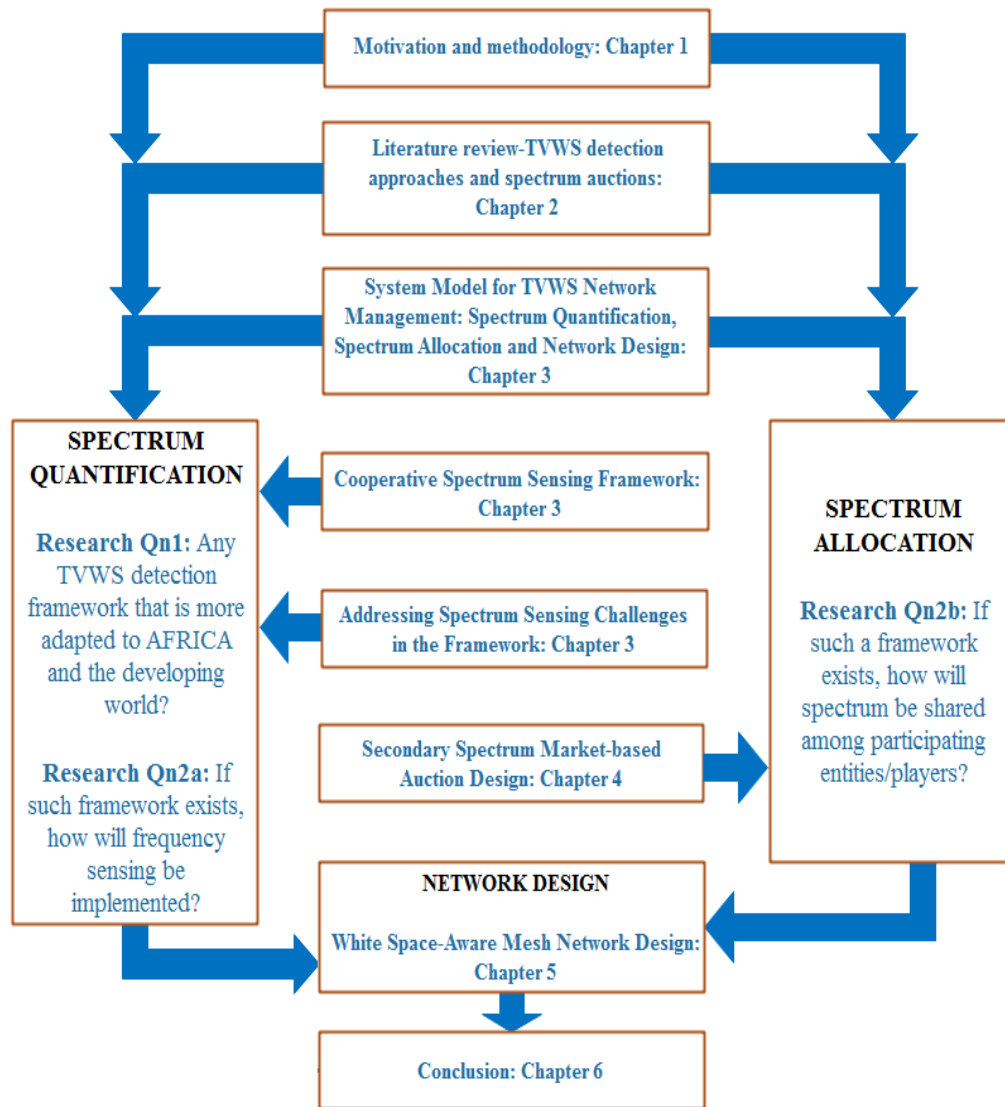
FIGURE 1.6: Overview of the thesis structure

- Chapter 4: Secondary Spectrum Market-Based Auction Design
  In this chapter, an auction mechanism design that meets the specific requirements for a secondary spectrum market, in addition to having the economic properties of an auction mechanism for selling general merchandise, is presented. Specific requirements for a secondary spectrum market auction are analysed first to ensure completeness of the proposal. In order to utilize spectrum efficiently, which is one of the key elements that a secondary spectrum market auction should address, a non-interfering buyer grouping strategy is presented in the chapter. The chapter also includes an evaluation of the proposal on arbitrary heterogeneous buyer networks.

- Chapter 5: White Space-Aware Mesh Network Engineering
  The chapters starts by highlighting the design challenges most likely to be met when

designing mesh networks using TVWS frequencies; identifying relevant TVWS param-
eters and dense network topology are mentioned, and are what the chapter focuses
on to address. A link-based topology reduction algorithm for reducing a dense mesh
network topology to a sparse mesh network topology, is presented. A network op-
timisation function based on three metrics that determine a centrality measure of a
node in a network graph and a network optimisation function based on white space
parameters, are also presented in the chapter, in order to introduce a hierarchical
backbone-based network topology from the sparse network topology. Performance
evaluation on the designs is also presented in chapter.

- Chapter 6: Conclusion and future research
  The chapter commences by restating the research problem and the research questions.
  A synthesis of how the research questions were addressed is presented. The chapter
  concludes by providing suggestions for future potential research in the area of dynamic
  spectrum access.
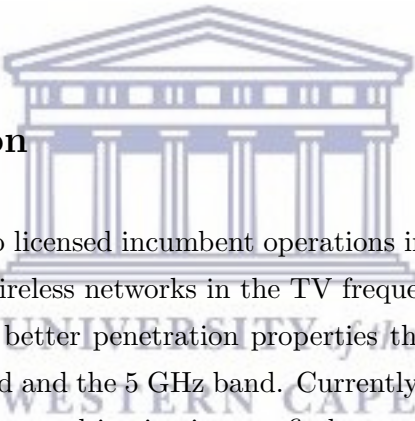
Chapter 2

Literature Review on Approaches to TVWS Access and Spectrum Auction

2.1 Introduction

Interference by WSDs to licensed incumbent operations in the TVWSs could hinder the proliferation of future wireless networks in the TV frequency band, which has a greater transmission range and better penetration properties than higher frequency bands [1] such as the 2.4 GHz band and the 5 GHz band. Currently, extensive research is going on in various research centres and institutions to find ways of avoiding the interference as much as possible [69–72]. WSDs could avoid causing harmful interference by accurately detecting the white spaces and transmitting only at times when the licensed spectrum incumbents are not transmitting. As discussed in Chapter 1, the geo-location database approach and spectrum sensing approach are the acceptable proposals for the TVWS detection so far.

This chapter reviews the literature on the developments that have taken place in relation to the two approaches. The developments in TVWS that have taken place from national and regional registration to international standards and the recognition of the role that spectrum sensing can play in TVWS detection highlighted by these national/regional registrations and international standards, are presented first in this chapter. Factors that affect the performance of each approach and how the availability or absence of these factors in a region will influence the decision as to which approach to use, are discussed next in this chapter. The next section discusses cooperative detection method and reviews some of the TVWS detection architectures based on this method. The

25

final part of this chapter reviews the literature on spectrum auction, which has been proposed as a method for sharing white space spectrum, that could encourage spectrum incumbents to trade their unused spectrum.

2.2 Review of developments in TVWS access

In a move to support opportunistic access to TVWSs, telecommunications regulatory authorities in the US and Europe have developed rules and standards governing the use of WSDs in TVWSs. This section discusses the developments that have taken place in this area, in order to understand the background to the research problem.

2.2.1 Developments undertaken by FCC in the US

FCC's TVWS work efforts date back to 2004 when it first released the Notice of Proposed Rule Making in ET Docket 02-380 [68] that proposed to allow unlicense radio transmitters to operate in the broadcast television spectrum at locations where that spectrum was not being used. Over the years, the FCC has taken steps to allow unlicensed operations in TVWSs. Finally, in November 2008, in its Second Report and Order (R&O) [20], it decided to open the TVWS to unlicensed use. A number of requirements for the unlicensed use of TVWS spectrum were specified. Three types of WSDs (referred to by the FCC as TV band devices) were introduced:

1. Fixed devices, which transmit and/or receive radio communication signals at a specified fixed location and can be used to provide wireless broadband access in urban and rural areas. They employ both geo-location/database access and spectrum sensing capabilities in order to identify unused channels for opportunistic access.

2. Mode II personal/portable devices, which use internal geo-location capability to gain access to a geo-location database, either through a direct connection to the Internet or through an indirect connection to the Internet through fixed TV band devices (TVBDs) or another Mode II TVBD to obtain a list of available channels. Mode II TVBDs are assigned lower power limits than fixed TVBDs.

3. Mode I personal/portables do not access a geo-location database directly as they do not have internal geo-location capability to access a TV band database directly and obtain a list of available channels. Mode I device obtain a list of available channels on which it may operate from either a fixed TVBD or a Mode II personal/portable TVBD. Mode I TVBDs operate at the same power limit as Mode II TVBDs.

In September 2010, the FCC issued a Second Memorandum Opinion and Order (MO&O) [59] determining the final rules to make the unused spectrum in the TV bands available for unlicensed broadband wireless devices. The new rules removed the mandatory requirement that TVBDs that incorporate geo-location and database access must also listen (sense), in order to detect the signals of TV stations and low power auxiliary service stations (wireless microphones). The FCC stated that the geo-location and database access method and other provisions of the rules would provide adequate and reliable protection for incumbent devices, thus making spectrum sensing not necessary.

2.2.2   Developments undertaken by Ofcom in the UK

Ofcom, the UK regulator, in its review, called Digital Dividend Review [73] released in December 2007, made a proposal to allow a license-exempt use of interleaved spectrum for cognitive devices that can detect unused spectrum and transmit without causing harmful interference. In the review, Ofcom guaranteed the need to protect licensed users of the spectrum (digital terrestrial television (DTT) and programme-making and special events (PMSE) systems, against harmful interference that could result from the use of the cognitive devices on the interleaved spectrum. Thus, Ofcom promised not to allow cognitive equipment use on interleaved spectrum until satisfied with the protection of license holders against harmful interference. As a follow-up to the Digital Dividend Review, in February 2009, Ofcom opened a cognitive consultation that proposed a number of technical parameters that would prevent harmful interference while enabling the license-exempt cognitive use of interleaved spectrum [74]. In the cognitive consultation, Ofcom proposed three main approaches to detect unused spectrum; detection, geo-location database and beacon transmission. As a conclusion to the cognitive consultation, Ofcom released a statement called Digital dividend: cognitive access [1], in which some of the issues raised in the consultation were concluded. Some of the major conclusions in the statement were:

- Beacon transmission was discarded as it was considered the least appropriate method.

- The detection approach was proposed to be used alone to detect unused spectrum. However, Ofcom noted in the statement that the implementation of detection-only devices would likely be many years ahead, and hence it would not go ahead making the necessary regulations to license-exempt such devices.

- The geo-location approach was the most important mechanism to detect unused spectrum in the short to medium term. Hence Ofcom would proceed with the definition of the specific technical requirements for its use.

Following the conclusions drawn from the statement, Ofcom released a number of consultations [75–77], statements [60, 78] and technical reports [79, 80] on TVWSs and geo-location until it finally came up with regulations that enabled license exempt use of WSDs in the UHF TV band in December 2015 [64] with geo-location database approach as the approved method.

2.2.3   Developments undertaken by the ECC

In the report called ECC Report 159 [32] released in January 2011 containing recommendations on technical and operational requirements for the possible operation of WSDs in the UHF TV frequency band, the Electronic Communications Committee (ECC), working within the Conference of European Postal and Telecommunications (CEPT), addressed a method for calculating an appropriate sensing threshold method and the corresponding maximum emission limits for WSD under various configurations. In the report, the recommended detection threshold values range from -91 dBm to -155 dBm depending on the DTT planning scenario. The report further says that these values are too low, when compared with other values, and way below a WSD receiver noise floor, which makes the spectrum sensing techniques extremely challenging to implement. The ECC further argues in the report that setting sensing thresholds very low in order to protect spectrum incumbent services would result in an increasing device cost and complexity as well as in a reduced number of available channels. It is also reported in the report that in some scenarios, even these low detection threshold values do not guarantee a reliable detection of the presence/absence of the broadcasting signals at a distance corresponding to the interference potential of a WSD. Based on these shortfalls of the spectrum sensing technique investigated, the report states that the spectrum sensing technique, if employed by a stand-alone WSD (autonomous operation), is not reliable enough to guarantee interference protection of DTT receivers using the same channel. Therefore, the use of a geo-location to avoid possible interference to DTT receivers is recommended in the scenario investigated in the report. In addition, the report concludes that in cases where the use of a geo-location database can provide sufficient protection to the broadcast service, sensing is not required.

2.2.4   IEEE Standards on TVWS

The Institute of Electrical and Electronics Engineers (IEEE), an organization that develops and maintains networking standards internationally, has come in to develop standards that provide a common operating architecture and mechanisms for WSDs that satisfy regulatory domains internationally. IEEE 802.22 [81], is a standard for wireless

regional area network (WRAN) primarily designed for a white space device (WSD) to operate in the TVWSs from 54 MHz to 862 MHz on a non-interfering basis with the primary users. The standard is aimed at providing wireless broadband access to hard-to-reach, low population density areas, typical of rural environments. The 802.22 standard utilises cognitive radio technology principles to meet regulatory requirements for protection of spectrum incumbents as well as to provide for efficient operation of IEEE 802.22 networks [81]. Three cognitive radio capabilities are supported by the Standard: spectrum sensing, geo-location database access and specially designed beacon [82]. One or more cognitive radio capabilities can be adopted based on the regulatory domain requirements. The IEEE 802.22 standard is the first worldwide standard to define a standardized air interface based on cognitive radio techniques for the opportunistic use of TV bands on a non-interfering basis.

IEEE 802.11af standard [58], also referred to as White-Fi and Super Wi-Fi, is a wireless computer networking standard in the 802.11 family that allows wireless local area network (WLAN) operation in the TVWS spectrum in the VHF and UHF bands between 54 MHz and 790 MHz [83]. It defines international specifications for spectrum sharing among unlicensed WSDs and licensed services in the TVWS band. The standard uses CR technology principles to limit interference to primary users, such as analog TV, digital TV, and wireless microphones, from the use of unused TV channels by WSDs. One of the key components of the IEEE 802.11af architecture is the geo-location database as the standard's only cognitive property, which helps the WSDs to find the available spectrum resources. The geo-location database stores, by geographic location, the permissible frequencies and operating parameters for WSDs in order to fulfill the regulatory requirements [84]. The databases are authorized and administrated by regulatory authorities, and as such, their operation depends on the security and time requirements of each particular applied regulatory domain [85].

2.2.5   Protocol to Access White Space (PAWS)

The Internet Engineering Task Force (IETF), an organization that develops and promotes open Internet standards, is defining a standardised protocol to access the spectrum database in the Protocol to Access White Space (PAWS) [29] that allows a secondary user to access white spaces for non-interfering use. According to IETF, a geo-location database can track available spectrum in accordance with the rules of many regulatory domains and make this information available to WSDs [29]. In the protocol, the IETF states that the geo-location database approach shifts the complexity of spectrum-policy conformance out of the WSD and into the database and also simplifies the adoption of policy changes, limiting updates to a handful of databases, rather than numerous devices

[29]. IETF also states that the approach opens the door for innovations in spectrum management that can incorporate a variety of parameters, including user location and time and has the potential to include other parameters such as user priority, signal type and power, spectrum supply and demand, payment or micro-auction bidding, and more, [29] in the future.

2.3 Recognition of spectrum sensing's role in TVWS access

The analysis of the regulations and international standards/protocols developed so far on TVWS access clearly favours the geo-location approach, as a secure method of accessing TVWSs, as compared to the spectrum sensing approach. Although this is the case, the value of sensing for TVWS access is still acknowledged by the spectrum domains and some standards analysed in the previous section. This section highlights those acknowledgments.

The FCC removed spectrum sensing as a mandatory requirement for TVBDs in the Second Memorandum Opinion and Order (MO&O) [59] that determined the final rules to make TVWSs available for unlicensed broadband wireless devices, but made the following statement, which in a way symbolises its recognition of the value of sensing for TVWS access.

> While we are eliminating the sensing requirement for TVBDs, we are en-
> couraging continued development of this capability because we believe it
> holds promise to further improvements in spectrum efficiency in the TV
> spectrum in the future and will be a vital tool for providing opportunistic
> access to other spectrum bands.

The FCC also showed the importance of sensing for TVWS access by going ahead with the definition of the technical rules for its use [59] although spectrum sensing was no longer a mandatory requirement for TVBDs.

Ofcom went ahead to propose the use of the detection approach alone as a method for detecting unused spectrum in the TV frequency band, but with sensing levels and transmit levels lower than it had originally proposed in the cognitive consultation [74], in its statement [1] released following that consultation. The decision to use more conservative sensing and transmit levels followed the argument of license holders and other affected stakeholders that sensing and transmitting parameters should provide greater levels of protection, and Ofcom accepted this argument. Ofcom's proposal to

allow the detection approach to be used alone, was based on its view that the likelihood of interference occurring in such a case depends on the sensing and transmitting parameter values selected. In the statement, Ofcom went on to say that a further possibility of improving the performance of detection currently being considered at a research level was for multiple cognitive devices to share information on signal detection (cooperative detection). In its view, Ofcom thought this would improve the probability of detection, since if one device were in a shadow of the wanted signal, it might be able to receive a signal from another nearby device which was not shadowed, warning that the frequency was in use. All these explanations, made in the statement about detection, show Ofcom's confidence in the approach. As already mentioned in Section 2.2 Subsection 2.2.2, Ofcom did not go ahead with making the necessary regulations to license-exempt WSDs based on detection alone, as it thought that the implementation of such devices would be many years away [1].

As discussed in Section 2.2 Subsection 2.2.4, the IEEE 802.22 Standard [81] utilises cognitive radio technology principles to meet regulatory requirements for protection of spectrum incumbents as well as to provide for efficient operation of IEEE 802.22 networks, in which spectrum sensing is included as one of the three cognitive radio capabilities. The Standard also goes on to say that one or more cognitive radio capability can be adopted, based on the regulatory domain requirements. All this clearly shows the value that spectrum sensing can contribute as an approach to TVWS identification.

2.4 Cooperative detection

Single sensor detection suffers from poor performance due to multipath fading and shadowing, which results in a *hidden user problem* or *hidden terminal problem* [9, 22, 56, 86, 87], as discussed in Section 1.4 subsection 1.4.2. An approach that has been suggested recently to overcome the *hidden user problem* is to use cooperative detection with multiple independent detection sensors.

Cooperative detection occurs when a group of cognitive radios, distributed in different locations, share the sense information they obtain from their respective locations with each other (see Figure 2.1). Cooperative detection relies on the variability of a primary user's signal strength at various locations [50] and is most effective when collaborating cognitive radios observe fading or shadowing independently [44, 88]. In general, cooperative detection consists of the following steps [89]:
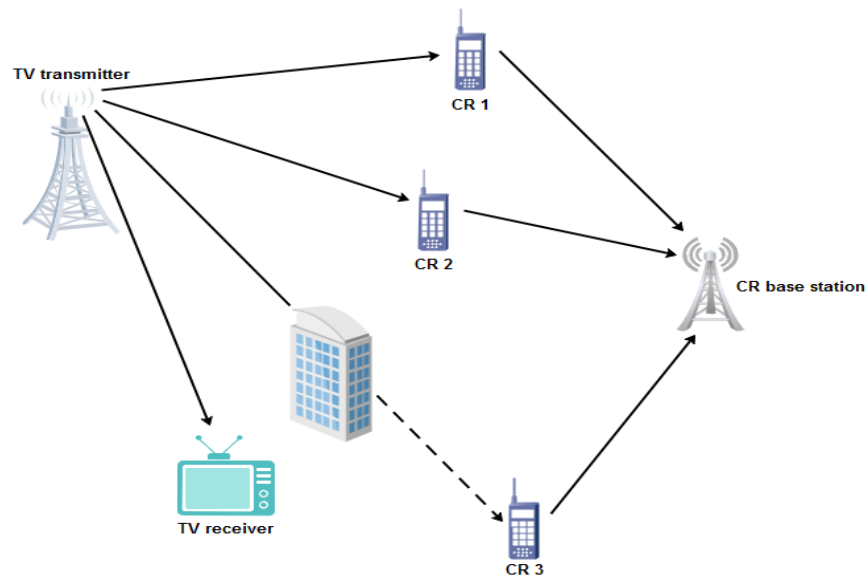
FIGURE 2.1: Cooperative detection [2]

- Every cognitive device performs local spectrum sensing measurements and based on that, makes a binary decision (1or 0) on whether the primary user is present or not.

- All of the cognitive devices forward their binary decisions to a common receiver.

- The common receiver fuses the cognitive radio decisions using some fusion logic (Xoring or ORing) and makes a final decision to infer the absence or presence of the primary user in the observed channel.

A cooperative detection network can be built either among cognitive device (internal sensing) or external sensors. Using cognitive devices, cooperative detection can be implemented in two coordinating techniques: centralized and distributed [23].

In centralized detection, a central unit collects sensing information from cognitive devices, which is tasked to identify the presence or absence of a primary transmitter or receiver. The central unit broadcasts the hard (binary) sensing results it makes to other cognitive devices or directly controls the cognitive radio traffic [11]. By centralizing the final hard binary sensing results, the fading effects of the channel are mitigated and detection performance is increased [11].

In distributed detection, cognitive devices share sensing information with each other, but each cognitive device makes its own decision as to which part of the spectrum it can use [11]. Distributed detection does not require a backbone infrastructure, as centralized detection does, and as such, incurs reduced costs [11].

In external detection, an external agent performs the detection and broadcasts the channel occupancy information to cognitive devices [11]. External detection has some advantages over internal detection, for example, spectrum efficiency is increased if external detection is used as cognitive radios do not spend time sensing [11]. External sensing also addresses the power utilization dilemma of internal sensing because the detection network is not required to be mobile and does not therefore, need to be powered by batteries [11, 90], as is the case with internal detection.

2.5 Review of some TVWS detection models based on cooperation detection

Many of the challenges faced by a single detection model for detecting TVWSs accurately are eliminated by a cooperative detection model. In this section, some of the well-known TVWS detection models that have been proposed, with cooperative detection as their main concept that help to detect the white spaces accurately, are reviewed.

In [3], a cooperation detection model using externally coordinated sensing network is proposed. The sensing network is a separate network fully dedicated to performing spectrum sensing. The model has two types of networks: the detection network and the operational network. The detection network comprises a set of sensors deployed in the desired target area, sensing the spectrum either continuously or periodically and communicating the results to a sink node. The sink node processes the collected data and eventually makes the information about the spectrum occupancy in the sensed target area available to the operational networks. The operational network, thus informed, is the one that opportunistically uses the unused spectrum and accepts information about the spectrum occupancy map in order to determine which channel to use, when to use, and for how long [3]. Their proposal is dependent on changing the hardware architecture of the sensors in the detection network, e.g., spectrum sensors designed specifically for sensing single band can include specific feature detection techniques in their hardware architectures [3]. A possible indoor deployment scenario of this model is depicted in Figure 2.2. [3].

Ying *et. al* in [4] propose an indoor cooperation detection model also having a separate detection network fully dedicated to performing spectrum sensing called WISER. The model consist of three components: a real-time sensing module, a white space database, and an indoor positioning module. The function of the real-time sensing module is to perform real-time outdoor and indoor spectrum sensing and to report the results to the white space database [4]. The white space database receives real-time channel signal
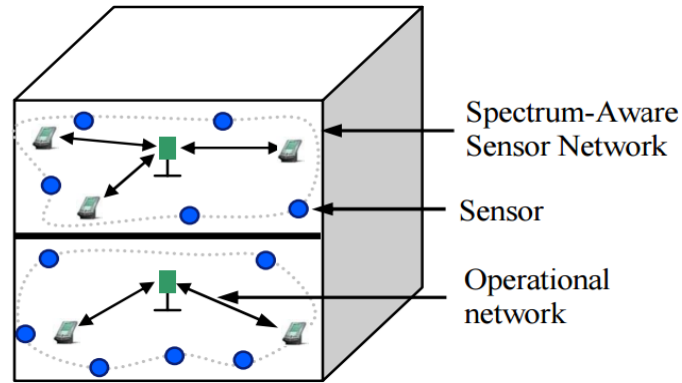
FIGURE 2.2: External-based cooperative detection using sensors [3]

strength data from the spectrum sensors of the real-time sensing module and processes that data to obtain corresponding up-to-date indoor white space availability. The white space database also handles white space availability queries from the white space devices. The indoor positioning module is used by the white space device to determine its indoor location before querying the white space database for a list of vacant channels at its location that it can use for communication in a separate white space networking infrastructure. One of the most important features of this model is that it takes sensor cost into consideration by proposing to strategically place the sensors by utilizing correlations in signal strength across multiple locations, which were observed in experiments. In their experiments, Ying *et al.* [4] observe strong correlations in signal strength across multiple indoor locations from a single channel and also strong correlations in multiple channels in their signal strengths and white space availability patterns across all locations. As a result of this, they suggest clustering of both the channels and the locations and focus on monitoring representative channels at representative indoor locations. To avoid random placement of the sensors in the clusters, which might results in a waste of the sensors, i.e., many unnecessary detectors deployed or insufficient sensors deployed, they devise a greedy algorithm for placing the spectrum sensors in the clusters, which ensures both coverage and performance requirements. The greedy algorithm ensures that every cluster is covered by at least on sensor [4]. Their model is depicted in Figure 2.3.

In [5], indoor white space exploration model with an externally detection network to perform spectrum sensing called FIWEX is proposed. In their model, Liu *et al.* exploit the location dependence and channel dependence of TV channels signal strength, to strategically deploy a limited number of sensors, which are able to reconstruct the white space availability map of an entire floor of a building, with high accuracy. In their experiments, Liu *et al.* also observed that indoor white space signal strength has both location dependence and channel dependence. They use these two key characteristics in their model to propose a novel data reconstruction algorithm based on compressive
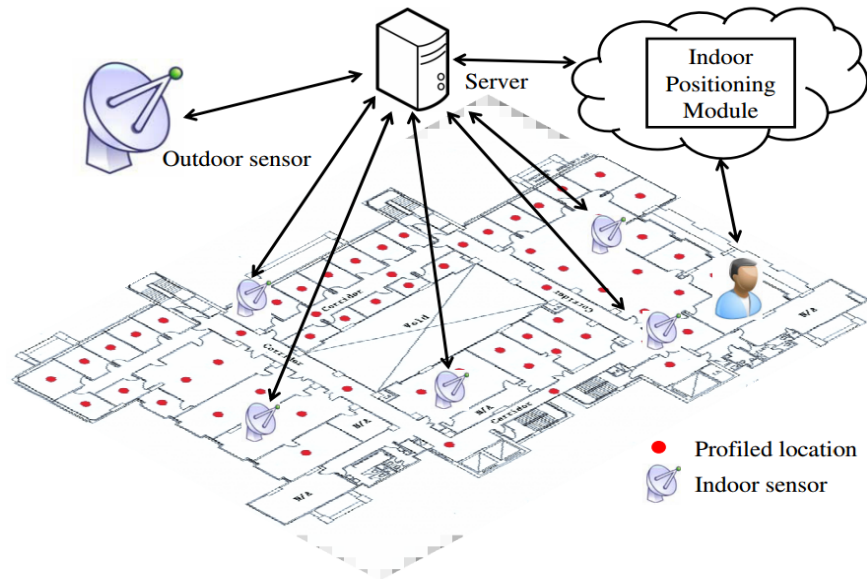
FIGURE 2.3: WISER model architecture [4]

sensing that helps to reduce the number of sensors needed to explore indoor white spaces efficiently. To avoid random placement of the sensors, Liu *et al.* also designed a sensor deployment method that helps to improve the data reconstruction accuracy. The system architecture of their model is shown in Figure 2.4.
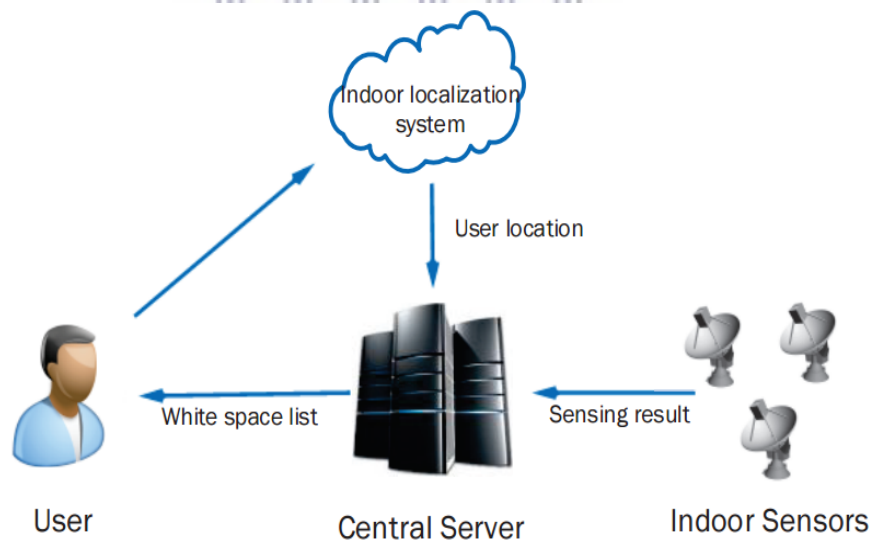
FIGURE 2.4: FIWEX model architecture [5]

Zhang *et al.* in [6], propose an outdoor white space detection model based on an externally sensing network that uses spectrum sensors, mounted on public vehicles, to collect and report measurements from the road, which they called V-Scope. The measurements are used to refine various signal strength models, which can be used by geo-location databases to manage outdoor whites paces efficiently. They note that geo-location databases have inevitable inaccuracy in predicting the signal strength of primary users

because the propagation models used in them are unable to capture the environment-induced variations. As a result, the databases under-utilize some white space channels because of the conservative model configuration used. To improve the accuracy of databases with spectrum measurements, V-Scope uses an enhanced version of feature detection to accurately detect primary signals while measuring their power up to the FCC-mandated sensing threshold of -114 dBm. Using the measured power of primary users, V-Scope refines the parameters of a propagation model used in a geo-location database not only to predict the signal strength of primary users better but also to improve the accuracy of the database. Zhang *et al.* state that V-Scope provides geo-location databases with extra functions, which other databases cannot provide without the V-Scope, e.g., an estimation of the quality of white space channels and localisation of primary and secondary devices [6]. Figure 2.5 shows the system architecture for V-Scope.
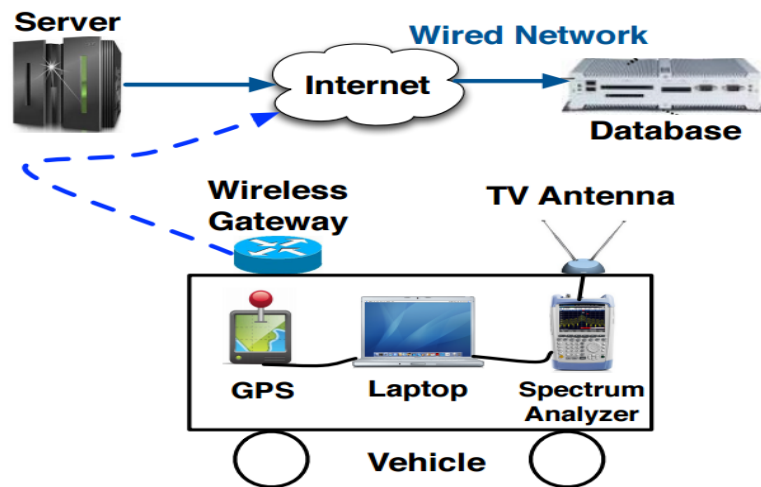
FIGURE 2.5: V-Scope system architecture [6]

2.6 Literature review on spectrum auction

Sharing/distributing the white space spectrum to secondary users is a problem that the research community is trying to solve due to the nature of the white space spectrum and the diversity of the network players involved. Any strategy chosen for assigning white space spectrum to secondary users has to ensure maximisation of spectrum utilisation and also ensure fairness of distribution to each and every secondary user in need of white space use. So far, many dynamic spectrum access technologies have been suggested but one proposal that stands out, and seems to be viable, is the auction strategy. Due to its perceived fairness and allocation efficiency [91], an auction is the best-known market-driven mechanism, so far, that promises to solve the white space spectrum assignment

problem. In a well-designed auction setup, every secondary user has an equal opportunity to win a spectrum segment [92] and primary users are attracted to release their unused spectrum to secondary users because of the income that an auction set-up can generate. Although this is the case, designing an auction mechanism for secondary spectrum markets, like white space spectrum, is not an easy task because of the nature of secondary spectrum market, which has many additional requirements, in addition to the usual economic properties that any auction mechanism for selling general merchandise should meet. The economic properties that are deemed to be essential for any auction mechanism are as follows:

- *Truthfulness.* An auction is considered to be truthful if each bidder bids with his true valuation of the item on auction. It ensures that neither the buyer nor the seller gets a high return by misrepresenting/misreporting their true valuation, thus they have no incentive to be untruthful [93]. A truthful auction simplifies the bidding strategy of each bidder, by encouraging him to bid what he really estimates as his valuation of the item instead of guessing what his competitors would bid [66].

- *Individual Rationality.* An auction mechanism is individually rational if, for each item on auction, its clearing price is not less than the income that the seller expects for it and at the same time not bigger than the payment that the buyer declares [66]. In an individual rational auction, both sellers and buyers achieve non-negative utility.

- *Budget Balance.* An auction mechanism is budget balanced if the auctioneer maintains a non-negative balance at the end of the auction, i.e., charges collected from winning buyers are not less than the payments to winning sellers [66].

Apart from these economic properties, an auction mechanism designed for secondary spectrum markets should also meet the following complementary requirements:

- *Spectrum re-usability.* Spectrum is different from conventional goods in the sense that it can be auctioned to more than one buyer, as long as the networks of those buyers do not interfere with one another. So a spectrum auction mechanism for secondary spectrum markets should include spectrum re-usability.

- *Support of heterogeneous networks.* Secondary spectrum markets are characterised by heterogeneous networks with diverse transmission schemes and channel width requirements. So an auction mechanism for secondary spectrum markets should support auction of spectrum to these heterogeneous networks.

- *Support of multi-unit.* In a secondary spectrum market, both sellers and buyers may want to trade multiple spectrums in order to increase their revenues or alleviate business burdens [66]. Therefore, a spectrum auction mechanism meant for secondary spectrum markets should be flexible and able to support multi-unit trade.

- *Support auction of heterogeneous spectrums.* Segments of a spectrum to be auctioned in a secondary spectrum market may have different central frequencies, which translate to different transmission ranges. So an auction mechanism for secondary spectrum markets should support that.

- *Support of buyer spectrum-specific demands.* Based on the quality of service (QoS) requirements, such as cell size to be covered, bidders may prefer to bid for parts of the spectrum that will enable them to achieve the level of transmission range required to cover the cell size. So an auction mechanism for secondary spectrum markets should be able to support bidders choices for specific parts of the spectrum.

- *Support interference-free transmission.* While it supports spectrum re-usability, an auction mechanism for secondary spectrum markets should also support the interference-free transmission of the spectrum buyers on the leased spectrum by accommodating the different transmission ranges of the buyers.

2.6.1   Review of some spectrum auction proposals

As introduced in this section, a secondary spectrum market auction design has many complementary requirements that it needs to meet in order to reflect the real secondary spectrum market situation. This subsection reviews some of the well-known auction mechanism proposals and also highlights their limitations for use in a secondary spectrum market.

Zhou, *et al.* in [94] propose a truthful dynamic spectrum auction, which is computationally efficient, called VERITAS, to support an eBay-like dynamic spectrum market. To prevent market manipulation by the bidders and to eliminate the expensive overhead of strategising about other bidders, VERITAS is a sealed-bid auction format, i.e., bidders submit their bids privately to the auctioneer. A sealed-bid auction encourages bidders to reveal their true valuation of the spectrum and helps the auctioneer to assign the spectrum to the bidders who value it most. VERITAS supports diverse bidding formats and the auction of multiple units. One limitation of VERITAS, for use in a secondary spectrum market, is that it is a unilateral auction, i.e., single seller and multiple buyers, which is not the case in a secondary spectrum market, where there are multiple sellers and multiple buyers.

Subramanian, *et al.* [95], propose a coordinated dynamic spectrum access (CDSA) model composed of multiple buyers with a heterogeneous channel width and a centralised spectrum broker for the spectrum allocation problem in cellular networks. The broker's responsibility is to collect spectrum supply information from the sellers and spectrum demand information from the buyers, and then execute the auction process with the objective of maximising the overall revenue generated, subject to there being no wireless interference in the buyers' networks. The architecture adopts a physical interference model during spectrum allocation and multiplexes a channel among non-conflicting base stations. However, it is also a unilateral auction, like [94] and does not guarantee the truthfulness of the bidding function [66].

Su, *et al.* in [66] propose a truthful bilateral multi-unit heterogeneous auction scheme called TBMAH for the secondary spectrum market, which supports participation of heterogeneous networks and has polynomial time complexity. To prevent market manipulation by the bidders and to enforce truthfulness among them during the bidding process, TBMAH adopts a bid-independent grouping method. TBMAH also considers spectrum re-usability, i.e., it multiplexes a channel among non-conflicting buyers by implementing a coverage based interference model. The challenge with TBMAH is that it uses a simplistic assumption that demands of buyers are not channel-specific in the performance evaluation, which cannot be the case in the secondary spectrum market, as explained in the introduction to this section on the support and fulfilment of buyer spectrum-specific demands.

Yu, *et al.* in [96], propose a distributed and heuristic spectrum assignment algorithm for multi-radio wireless cognitive networks in a cognitive network environment, called Fairness Bargaining with Maximum Throughput (FBMT) that considers both the fairness and throughput. FBMT models interference among bidders as a graph colouring problem and uses several optimization functions that take into account heterogeneity in both spectrum availability, reward and interference constraint. FBMT's limitation is its assumption that all primary users have the same transmission range and that all secondary users have the same transmission range in the auction process, which is not the case in secondary spectrum markets, as explained in the introduction to this section, on the support of both heterogeneous networks and heterogeneous spectrum auction requirements.

In [97], Chen, *et al.* propose a multi-seller-multi-buyer double auction with a third-party auctioneer for heterogeneous spectrum transactions in secondary spectrum markets, called TAMES. TAMES considers spectrum usability by modelling interference between buyers on a specific spectrum, using a frequency-specific interference graph, and adopts a non-interfering buyer-grouping approach from it. The novel non-interfering

buyer-grouping approach in TAMES ensures truthfulness and individual rationality of the auction. In TAMES, a seller is able to trade multiple spectrum segments and buyers can submit multiple bids for different spectrum segments. A limitation of TAMES is that it only considers buyers with identical spectrum demands, i.e., the same channel width, which is not the case in secondary spectrum markets, as discussed in the introduction to this section on the support of heterogeneous networks.

Parzy and Bogucka [98], propose a non-identical objects spectrum sharing scheme in TVWS that takes bandwidth and power requirements of the secondary users into account. The proposal considers the spectrum sharing and allocation problem in TVWS as a combinational auction, with non-identical objects, due to the diverse power and bandwidth requirements of secondary users. The proposal uses a linear integer programming technique, called a *branch and cut* technique, to reduce the complexity of the optimization algorithm significantly. Like similar auction proposals in secondary spectrum markets for [66, 96, 97], the proposal is also based on a centralized entity, called the spectrum broker, whose target is to maximize the profit and assure the most effective spectrum allocation [98]. One limitation of the proposal is that it does not consider spectrum re-usability. Another limitation is that it only considers the sale of a single spectrum segment, which is not the case in secondary spectrum markets, as discussed in the introduction to this section on the support of both spectrum re-usability and multi-unit requirements. The authors in [98] extended their on-line auction proposal in [99] by adding the time dimension. The second proposal is like their first proposal, in that it does not consider spectrum re-usability.

In their paper [100], Lin, *et al.* propose a spectrum auction mechanism called Flexauc for secondary spectrum markets, which maximises social welfare, enables buyers to reveal their truthful flexible demands and has computational tractability. Flexauc allows flexible bidding strategies from bidders to bid for any amount of spectrum, and with a possibility of winning any amount of spectrum. Unfortunately, Flexauc does not consider spectrum re-usability, ignoring one of the crucial requirements of a secondary spectrum market, as discussed in the introduction to this section.

Zhou and Zheng in [92] propose a general framework for a truthful bilateral spectrum framework, called TRUST, which adopts a bid-independent buyer grouping method. To achieve truthfulness, other economic properties and spectrum utilization, TRUST applies a novel winner determination and pricing mechanism and also considers spectrum re-usability among non-adjacent buyers. TRUST uses spectrum efficiency as a trade off to achieve economic robustness [92]. However, TRUST is a single-unit auction and only supports homogeneous channels [66].

2.7 Reviewed frameworks vs proposed framework

The detailed literature review presented in this chapter reveals the research gaps captured in Chapter 1 and the proposed systems covered in the literature review, are closely or remotely related to the work in this study as follows:

The white space detection frameworks proposed in [3–5] are cooperative detection-based frameworks that use dedicated external sensing networks. While the proposed framework in this research is also cooperative detection-based framework using an external sensing network, it includes a multi-threshold detection design where more than one detection threshold is used to detect the white spaces. To the best of the author's knowledge, the proposed framework is the first of its kind to include multi-threshold detection design. Existing proposals including the ones reviewed in this chapter include single-threshold detection design in their frameworks, where only one detection threshold is used to detect the white spaces.

The proposed framework also includes a virtual pricing design in the framework, to rank the detected white spaces in terms of the probability to cause interference to the primary users, resulting from false negatives. As a direct result of ranking the white spaces, the proposed framework includes a sequential allocation design of the white spaces, based on their probability to cause interference to the primary users. The inclusion of a sequential allocation design in the framework enables to allocate those white spaces, with a low probability of causing interference, first. As far as the author's knowledge is concerned, these two designs have never been used before in any of the existing frameworks. Existing frameworks, including the ones reviewed in this chapter, do not rank the detected white spaces in terms of the probability of causing interference to the primary users. Consequently, these frameworks include a random allocation design, where the detected white spaces are randomly chosen and allocated to WSDs.

The frameworks in [4, 5] also include a clustering design concept of both the channels and the locations to reduce the implementation cost. The frameworks utilize only the signal strength observed in the channels to perform the clustering. In addition to utilizing the signal strength observed in the channels to perform the clustering, like the frameworks in [4, 5], the proposed framework also utilise the Euclidean distances between the measurement locations to perform location-aware clustering. In the clustering design concept included in the proposed framework, a measurement location is added to a cluster if it is close, in terms of Euclidean distance, to the cluster head and its signal strength is similar to the signal strength at the cluster head location.

Section 2.6 has highlighted the economic properties that are deemed to be essential for any auction mechanism design, for selling merchandise, including the complementary

requirements that are specific for the secondary spectrum market auctions. While most of the auction mechanisms, reviewed in Subsection 2.6.1, meet the economic properties of any auction mechanism for selling merchandise, none meet all the complementary requirements specific to secondary spectrum market auctions, and the limitation of each mechanism is highlighted in the same section. In addition to meeting the economic properties of any auction, the auction mechanism design for sharing/trading white spaces, proposed in this research, meets all the complementary requirements listed in Section 2.6.

2.8   Chapter summary

This chapter provided a detailed literature review of geo-location databases and spectrum sensing, as access methods to TVWS. Specifically, the chapter discussed the developments in TVWS access that have taken place from national/regional registration to international standards, in relation to the two approaches, since the idea to use TVWSs was introduced by the FCC. Cooperative detection was also discussed in the chapter as a follow up to the detection approach presented in Chapter 1.
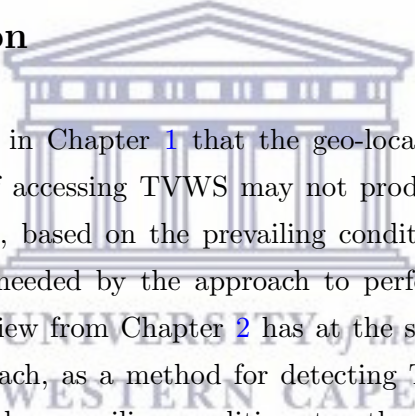
The analysis of the regulations and international standards/protocols developed so far on TVWS access clearly favours the geo-location approach as a secure method of detecting TVWSs over the spectrum sensing approach. However, the review on the performance contributing factors of the approaches when considering the prevailing conditions in the countries of the developing world, has shown that the geo-location database approach may not be the best solution for TVWS detection for countries in the developing world.

In the next chapter, the architecture for white space network management, that includes the white space detection component based on cooperative detection, and its evaluation, is presented.

Chapter 3

Architecture formulation and experimental evaluation

3.1 Introduction

It has been established in Chapter 1 that the geo-location spectrum database-based approach as a means of accessing TVWS may not produce optimal results in regions of the developing world, based on the prevailing conditions of these regions together with the requirements needed by the approach to perform optimally. On the other hand, the literature review from Chapter 2 has at the same time established that the spectrum sensing approach, as a method for detecting TVWS, is more favourable for these regions, based on the prevailing conditions together with the requirements needed by the spectrum sensing approach to perform optimally. Therefore, this chapter presents a spectrum sensing-based architecture for TVWS detection, based on external sensing, suitable for implementation in regions of the developing world. The architecture is suitable for implementation in a region where the demand for TVWS use comes from local network devices. It addresses most of the challenges associated with spectrum sensing as a method for TVWS detection by using both the existing and new proposed design principles. The design principles play a crucial role that help the architecture to identify the TVWSs accurately. In addition, the proposed design principles also help the architecture to detect more white spaces than architectures that use existing principles only. The proposed architecture is also well-suited to the environment in developing nations as it takes cost of implementation into consideration and it is also very easy to implement when compared with any geo-location database-based architecture.

43

3.2 System model for a TVWS network management
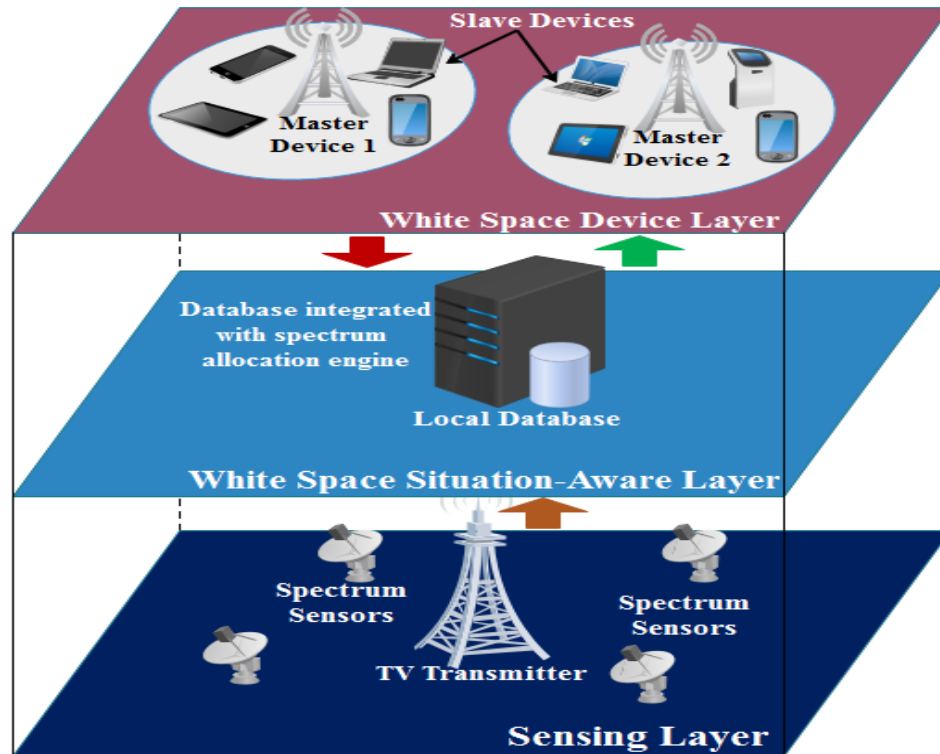
FIGURE 3.1: TV white speace network management model

Figure 3.1 presents an overview of the TVWS network management architecture that consists of three layers; the sensing layer, the white space situation-aware layer and the white space device layer. The sensing layer is comprised of the spectrum sensors and the TV transmitter. The spectrum sensors sense and send real-time sensed information about TV transmission from the TV transmitter to the white space situation-aware later for centralised processing. Using spectrum sensing design principles, the local database processes the sensed data from the different sensors, deployed in the area concerned, in order to identify channels that are not being used for TV broadcasting at the TV transmitter, located in the sensing layer. The spectrum allocation engine, which is integrated with the local database, in fixed-time stamps, periodically advertises the white space channels to the white space devices, located in the white space device layer. The spectrum allocation engine also receives and processes TVWS spectrum requests from the white space devices, and allocates the available TVWSs to them. Communication within a layer, if any, and between the layers does not use the white space spectrum frequencies, but other means such as a wired local area network (LAN) or 2.4 GHz/5 GHz Wi-Fi.

The next section discusses how existing spectrum sensing challenges that are met when spectrum sensing is used as an approach to TVWS detection, are addressed in the

architecture.

3.3 Addressing spectrum sensing challenges in the architecture

Spectrum sensing as a method for identifying TVWSs, has a number of technical challenges, such as the determination of a single detection threshold that is optimal, the *hidden terminal problem* and the implementation costs. The proposed architecture needs to address these challenges, as a measure of its uniqueness and viability, for use in identifying TVWSs. This section discusses how the challenges are addressed in the architecture.

3.3.1 Addressing the single detection threshold

Deciding on a single detection threshold to be used in spectrum sensing is a challenging issue that has been at the heart of debates concerning an absolute value to be used. The architecture incorporates a new principle that addresses the challenge.

3.3.1.1 Multi-threshold detection design

The detection threshold of *-114 dBm* for Advanced Television Systems Committee (ATSC) TV signal detection, as mandated by the FCC, has been shown to be too conservative by several measurement studies [22, 54, 56, 57]. This is because it leads to significant loss of TVWSs [57], and hence too many false positives. For example, [54] found no TVWSs in any of the locations where the studies were done in China when a detection threshold of *-114 dBm* was used. However, when relying on the analog terrestrial television (ATT) database as ground-truth data for the ATT channel occupancy situation in Beijing, changing the detection threshold to *-97 dBm* was enough to find white space ATT channels in indoor scenarios. In other studies, different signal detection thresholds have been used. These studies have claimed that their thresholds led to low false positives and/or low false negatives. Therefore, to make a compromise between the two extremes, *many false negatives or many false positives*, which is the expected result when a single detection threshold is used, the proposed architecture uses more than one detection threshold value to detect the white spaces. The FCC's mandated detection threshold of *-114 dBm* is taken as the start threshold in the architecture because it is conservative and enables the finding of white spaces in some locations. The end detection threshold is based on the TV transmitter allocation scheme on the TV radio frequency bands, for the closest transmission site servicing the area where the

architecture is deployed, because it helps to choose a suitable end detection threshold that excludes channels being used for TV broadcasting at the closest transmission site servicing the area. Since small variations in detection threshold values have a very big impact on the number of white spaces found [101], the difference between one detection threshold to another detection threshold from the start and end detection thresholds is small, and is not fixed. While the multi-threshold detection design solves the problem of the single detection threshold, it also leads to much better performance in the sense that it leads to more TVWSs being detected and also minimises the probability of mis-detection and false alarms.

3.3.2 Addressing the hidden terminal problem

A number of design principles have been incorporated in the architecture that address this problem, some are already existing design principles while others are new proposed design principles.

3.3.2.1 Cooperative spectrum sensing design

The proposed architecture consist of a number of pieces of spectrum sensors, deployed in an area to do cooperative detection. Each piece of the spectrum sensor senses the spectrum at its location and sends the raw sensed data to the database. The final hard binary decision of whether a channel is occupied or not is made by combining detection data from each piece of spectrum sensor.

The cooperative detection design is used firstly in the architecture to minimize the probability of causing interference to primary users, due to false negatives. This is based on the idea that a network of cognitive radios with their sensing information centrally processed, have a better chance of detecting the primary user than an individual spectrum sensor [50]. It is reported in [39] that it is possible to achieve a lower false alarm rate with cooperative detection than with single sensor detection.

Cooperative detection is the only existing principle known to address the *hidden terminal problem*, which the proposed architecture has also utilized. Besides this principle, the proposed architecture also utilizes other principles proposed in this research to address the *hidden terminal problem*. They are discussed next.

3.3.2.2   TVWS grouping and sequential allocation

Originating from the concept of using more than one detection threshold to identify TVWSs, introduced in the last subsection, to address the difficulty of arriving at a single detection threshold that produces optimal results, another design principle incorporated in the architecture is the grouping of the TVWSs, based on the detection thresholds used. Allocation of the TVWSs to secondary users is done sequentially, starting with those TVWSs identified in the group with the lowest detection threshold. Groups of TVWSs identified with lower detection threshold values are safer in terms of causing interference to spectrum incumbents than those TVWSs identified with higher detection threshold values, because lower detection threshold values are more conservative than higher detection threshold values. Since the architecture is applicable in an area where the demand for TVWSs use comes from local network devices, the demand for TVWSs is normally expected to be lower than the available TVWSs in the area. In such a situation, the TVWS demand is met well before all the actual TVWSs in the area have been used. Consequently, the grouping and sequential allocation design provides a greater level of protection to spectrum incumbents from interference due to false negatives than using random or haphazard allocation of TVWSs identified using a single detection threshold.

3.3.2.3   Virtual-price of TVWSs

The virtual-price design of TVWSs originates from the concept of using more than one detection threshold to identify TVWSs and the design of grouping TVWSs based on the detection threshold values used. TVWSs within a TVWS group, i.e., a group of TVWSs that have been identified with one detection threshold, have different probabilities of causing interference to incumbents due to false negative, because of the different energy levels or signal strengths measured in each TVWS channel. Therefore, random allocation of TVWS channels within a TVWS group is not safe, since some TVWS channels may have higher probabilities of causing interference than others. The virtual-price concept helps to rank TVWSs within each TVWS group in terms of each one's probability of causing interference to incumbents due to mis-detection/false negatives. The energy level/signal strength measured in each TVWS channel is used to rank or virtual-price them. Those TVWS channels with higher energy levels/stronger signal strengths within a TVWS group are ranked or virtual-priced higher than those with lower energy levels/weaker signal strengths. Once ranked or virtual-priced, they are now sequentially allocated to WSDs starting with the TVWS channel ranked lowest or virtual-priced lowest, i.e., the one with the lowest probability of causing interference to the incumbents.

It is logical to expect a channel which is in use by a primary user, but has been iden-
tified as free (white space), to have a higher energy level/stronger signal strength than
a channel which is actually free on the ground. The signal measured in a channel
that is not TVWS, but has been detected as such, is a signal resulting from the spec-
trum incumbent's broadcast signal plus some channel interference, while the signal from
a channel that is actually TVWS on the ground, is only from channel interference.
With the virtual-price concept, channels which are not TVWSs on the ground but have
been identified as TVWSs, are expected to have higher rankings or higher virtual-prices
than those that are actually TVWSs on the ground. Therefore, the approach provides
some level of interference protection to spectrum incumbents, due to false negative/mis-
detection, because those channels with missed detection can never be allocated to any
TVWS device, unless all the channels that are actually TVWSs on the ground have
already been allocated.

3.3.3 Addressing implementation cost

Most countries in the developing world are faced with financial challenges. So any
TVWS detection architecture meant for this region that takes the cost of implementa-
tion as a major consideration could be favoured. This subsection explains the design
principles incorporated into the architecture to make its implementation as cost effective
as possible.

3.3.3.1 Location-aware clustering

In their experiments, Ying *et al.* [4] observed that there is a strong correlation between
signal strength from a single channel and multiple indoor locations. This observation
suggests that it is possible to focus on monitoring channels at representative indoor loca-
tions and infer the results of the other representative locations by exploiting the location
correlations [4]. In order to do that, locations need to be clustered. While this was an
indoor observation and also a correlation between signal strength from a single channel
and multiple indoor locations, it is also logical to expect outdoor measurement points
close to each other to receive similar signal strengths across all measured channels. This
is so because their distances from each other are small, which means that they have
almost the same transmissions distances to any TV transmission site. In such cases,
the TVWS availability is expected to be similar across the measurement points. This
suggests that the outdoor measurement points can also be clustered and the focus can
be on conducting the spectral measurement at representative measurement points and
infer the results of the other measurement points from the results of the representative
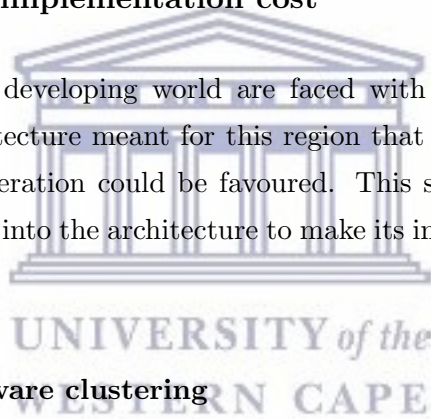
measurement points. The architecture utilizes the clustering concept design to cluster measurements points that are close to each other in both the Euclidean distance, and signal strength. To avoid random placement of the measurement equipment in the clusters, which may results in a waste of energy detectors, i.e., many unnecessary detectors deployed, or coverage not guarantee, i.e., insufficient detectors deployed, the measurement equipment are placed at the cluster-heads, which are strategically located in the clusters. Cluster-heads are chosen based on the optimization function in equation 3.1.

$$O_f(i) = \Pi * sp(i) + \Psi * st_d(i) \tag{3.1}$$

where $O_f(i)$ is the optimization function (cost/penalty to be minimized), $sp(i)$ is the average distance from measurement point i to all other measurement points using the Dijkstras shortest path algorithm, $st_d(i)$ is the average signal strength difference of measurement point i from all other measurement points, Π and Ψ are coefficients of proportionality used to express the preference for a given factor.

The equations for calculationg $sp(i)$ and $st_d(i)$ are give in 3.2 and 3.3 respectivily, where ρ are all measurement points.

$$sp(i) = Avg_{sp}(i, x) \ \forall \ x : (i, x) \in \rho \tag{3.2}$$

$$st_d(i) = Avg_{st}(i, x) \ \forall \ x : (i, x) \in \rho \tag{3.3}$$

Measurement points with smaller costs/penalties, i.e., $O_f(i)$, are more likely to be chosen as cluster-heads than the ones with bigger costs/penalties because they are centrally located in the network in both their Euclidean distances to all other points in the network and their average signal strength differences from all other measurement points.

Clustering of the measurement points is dependent on two factors: the closeness of the measurements points in Euclidean distance and the similarity in received signal strength of measurement points across the measured channels. That is to say, two or more measurement points are clustered together only if they are close to each other in Euclidean distance and their averages in received signal strength across the channels are similar. The similarity in average received signal strengths is included because it is possible to have measurement points that are close to each other but do not receive similar signal strength as a result of having different signal obstructions on their individual paths. The Euclidean distance and the average signal strength difference for the clustering decision can be varied, and depend on the protection that is needed to be achieved for the spectrum incumbents.

Before the measurement points are clustered, there is a need to conduct large-scale signal measurements at all measurements points. Then the data collected from the measurements can then be used to cluster the locations.

3.3.3.2 Using low-cost off-the-shelf spectrum sensing devices

Commercial high-end spectrum analysers are expensive, in the order of many thousands of dollars [102], which may make the adoption of a cooperative sensing-based architecture for TVWS detection prohibitive for the countries in the developing world. But recently, off-the-shelf spectrum sensing devices are emerging on the market at low cost, making them more attractive to the developing world. A Radio Frequency (RF) Explorer is one example of such devices, which is affordable and easy to use. Taking advantage of these low-cost devices, the spectrum sensing component of the architecture uses an RF Explorer as a spectral measuring device. It can be connected to a laptop or to an android phone to make a complete piece of spectrum measuring equipment.

3.4 Algorithm implementation

A number of design principles have been proposed that address challenges of spectrum sensing when used as a method to identify white spaces. This section discusses algorithmic implementation for each of the proposed principles. These algorithms are implemented at the database where the final hard binary decision of whether a channel is occupied or not is made, by combining detection data from each piece of spectrum sensing equipment.

3.4.1 Multi-threshold detection and TVWS grouping

The multi-threshold detection design and the grouping of TVWS design based on the detection thresholds, are presented in Algorithm 1. The algorithm also shows how cooperative spectrum sensing design is implemented alongside the two designs.

The inputs to the algorithm are signal strength values of all the channels from the frequency spectrum sensors deployed and the channels under consideration. The algorithm first checks if a channel under consideration is an already identified white space, using any of the previously used threshold values, if any. This is done in lines *4* to *11*. This helps to make sure that each channel is not identified as white space by more than one detection threshold, as the detection threshold values keep changing. Once the algorithm has found that a channel is not a white space already, it compares the signal strength

---

Algorithm 1: Multi-threshold detection, TVWS grouping and cooperative detection

---

input : Two-dimensional matrix of signal strength values **st** of size **m** by **n** where **m** is the number of channels under consideration and **n** is the number of sensors deployed; channels ch_1, ch_2, ch_3, ..., ch_m.

output: white space channel groups $ws(i)$ each consisting of white space channels identified with a single threshold; signal strengths groups $ss(j)$ each consisting of signal strengths measured in white spaces channels in the corresponding white space channel group $ws(i)$.
$i = j = number of thresholds$

1 *initialize* $t \leftarrow startThreshold, x \leftarrow 1$;
2 **repeat**
3   **for** $i \leftarrow 1$ **to** m **do**
4   **for** $j \leftarrow 1$ **to** x **do**
5   **while** $ws(j)$ *is not empty* **do**
6   ***check*** *if ch_i is in $ws(j)$*;
7   **end**
8   **if** ch_i *is found in $ws(j)$* **then**
9   break;
10   **end**
11   **end**
12   **if** ch_i *is not found in any of $ws(j)$* **then**
13 $strongestSignal \leftarrow 0$;
14   **for** $j \leftarrow 1$ **to** n **do**
15   **if** $st[i][j] > strongestSignal$ **then**
16 $strongestSignal \leftarrow st[i][j]$;
17   **end**
18   **end**
19 $rss_i \leftarrow strongestsignal - t$;   // rss_i is representative relative signal strength for channel ch_i
20   **if** $rss_i <= 0$ **then**
21   ***add*** ch_i *to $ws(x)$*;
22   ***add*** *strongestSignal to $ss(x)$*;
23   **end**
24   **end**
25   **end**
26 $t \leftarrow t + increment$;
27 $x \leftarrow x + 1$;
28 **until** t *is equal to endThreshold*;
29 ***return*** *ws(1), ws(2),...,ws(x), ss(1), ss(2),...,ss(x)*;

---

values for that channel from all the sensors deployed from line *12* to *18* to find the representative signal strength value, which is the strongest signal measured in that channel from all the sensors deployed. The strongest signal is used to calculate the relative signal strength for that channel by subtracting the current threshold from it in line *19*. Then the algorithm decides whether or not the channel is white space in line *20*: it is white space if the relative signal strength is less than or equal to zero. If it is found to be white space, it is added to the set *ws* for that detection threshold in line *21*. The process is repeated for all the channels using the current threshold value (*lines 3 to 20*). Once all the channels are considered using the current threshold value, the next threshold value is considered (*line 24*) and the process is repeated from the beginning (*from line 2*). This process is repeated until all the threshold values have been considered. The output from this algorithm is the white space channel groups $\{ws(i) \mid i \geq 1\}$ identified using different thresholds and their corresponding signal strength groups $\{ss(j) \mid j \geq 1\}$.

3.4.2   Virtual-price of TVWSs

Once TVWS channels have been identified, using the different threshold values, and put into groups, based on the thresholds, Algorithm 2 follows to compute their virtual prices, based on signal strengths recorded in each TVWS channel.

Algorithm 2: Compute virtual prices of white space channels identified

---

input : $SS = \{SS(1), SS(2), SS(3), ..., SS(x)\}$.

output: $VP = \{VP(1), VP(2), VP(3), ..., VP(x)\}$. {**VP** is a corresponding set of sets of virtual prices of white space channels}

1 *initialize* $j \leftarrow 1$;

2 **for** $i \leftarrow 1$ **to** x **do**

3 | $strongestSignal \leftarrow ss(i)(j)$;

4 | **while** *SS(i) has elements* **do**

5 | | **if** $strongestSignal < ss(i)(j)$ **then**

6 | | | $strongestSignal \leftarrow ss(i)(j)$;

7 | | | $j \leftarrow j + 1$;

8 | | **end**

9 | **end**

10 | **for** $a \leftarrow 1$ **to** $(j - 1)$ **do**

11 | | $vp(i)(a) = \{|ss(i)(a)|/|strongestSignal|\}^{-1}$;

12 | | ***add*** $vp(i)(a)$ to $VP(i)$;

13 | **end**

14 | *initialize* $j \leftarrow 1$

15 **end**

16 ***return*** VP;

The input to the algorithm are the groups $\{ss(j) \mid j \geq 1\}$ of signal strength values that correspond to the groups $\{ws(i) \mid i = j, i \geq 1\}$ of TVWSs channels identified in **Algorithm 1**. The algorithm first searches through the first group $ss(1)$ of signal strength values to find the strongest signal in that group from line *3* to *9*. Then the algorithm calculates the virtual price corresponding to each signal strength in that group by taking the inverse function of dividing the absolute signal strength with the absolute strongest signal found earlier, from line *10* to *13*. The process is repeated for each signal strength group $ss(j)$ until all the signal strength groups are considered. The output of the algorithm are the groups $\{vp(k) \mid k = j, k \geq 1\}$ of virtual prices corresponding to the groups $\{ss(j) \mid j = i \geq 1\}$ of signal strength values that correspond to the groups $\{ws(i) \mid i \geq 1\}$ of TVWS channels identified in Algorithm 1.

3.4.3 Location-aware clustering

The goal of clustering is to organize unstructured data/objects into groups (clusters) such that data/objects within a group (cluster) are similar or related to one another and different (or unrelated) to the data/objects in the other groups, using distance measures. As discussed earlier in the previous section, two distance measures are used: the Euclidean distance between the measurement points and the average received signal of the measured channels of the measurement points.

The inputs to the algorithm are the Euclidean distances between the measurement points, the average received signal differences across the measured channels of each measurement point, the clustering distance radius and the clustering signal threshold. At first, each measurement point is put into its own cluster in line 1. Then the algorithm computes the cost of being a cluster-head for each measurement point, in lines 3 to 5. Then the best point to be a cluster-head is selected in line 6. Using the cluster-head selected, the algorithm performs the clustering until none of the non-clustered points lies within the clustering distance radius from the cluster-head, and has its average signal strength difference with the cluster-head less than the clustering signal threshold. This is done from line 9 to 14. The number of points that have not been clustered is calculated in line 16. Then the algorithm re-calculates the cost for each non clustered point from line 17 to 19. Then the best point to be a cluster-head is selected in line 20 and then the algorithm loops back to perform the clustering using that cluster-head chosen. This process is repeated until the number of non clustered points is 0. Then the algorithm returns the clusters.

Algorithm 3: Location-aware clustering algorithm

---

input : A two-dimensional matrix D_{eu} of size NXN of Euclidean distances between the measurement points, a two-dimensional matrix of S_{df} of size NXN of the average received signal differences between the measurement points, clustering distance radius D_{st}, clustering signal threshold S_{st}.

output: C clusters, $C \leq N$.

---

1 let each measurement point be a cluster;
2 let $C \leftarrow 0$; `// counts number of clusters`
3 **for** *each measurement point i* **do**
4 $\quad$ compute its $O_f(i)$;
5 **end**
6 select i with smallest $O_f(i)$;
7 **repeat**
8 $\quad$ let $n \leftarrow 1$; `// counts number of points put in a cluster`
9 $\quad$ **for** $j \neq i \leftarrow 1$ **to** N **do**
10 $\quad\quad$ **if** $D_{eu}[i][j] < D_{st}$ *AND* $S_{df}[i][j] < S_{st}$ **then**
11 $\quad\quad\quad$ cluster j with i;
12 $\quad\quad\quad$ n = n + 1;
13 $\quad\quad$ **end**
14 $\quad$ **end**
15 $\quad$ C = C + 1;
16 $\quad$ N = N - n;
17 $\quad$ **for** *each remaining measurement point i* **do**
18 $\quad\quad$ re-compute its $O_f(i)$;
19 $\quad$ **end**
20 $\quad$ select i with smallest $O_f(i)$;
21 **until** *N=0*;
22 *return* C *clusters*;

3.4.4 Superiority of proposed design

The following section provides an analysis that shows that these proposed designs perform better than existing designs for white space detection, based on the number of white spaces that can be detected and the interference probability on the spectrum incumbents at each point in time during the allocation of the white spaces detected. Table 3.1 provide a summary of the differences between the proposed design and the current design.

TABLE 3.1: Summary of proposed and existing design

Category name	Proposed design	Current design
No of threshold(s)	Many threshold	One threshold
Allocation type	Sequential allocation	Random allocation

Let $\{t_1, t_2, ..., t_n \mid n > 1 \epsilon \mathbb{Z}^*\}$ be the set of thresholds that the proposed mechanism is going to used to identify TVWSs arranged in ascending order. Let $w_i \mid i\epsilon n$ be the

corresponding number of TVWSs that threshold $t_i \mid i\epsilon n$ produces when used alone. Since the thresholds are arranged in ascending order, then $w_1 \leq w_2 \leq ... \leq w_n$ is true. The total number of TVWSs that the thresholds identify when used together, as in this proposed mechanism, is equal to $w_1 + (w_2 - w_1) + (w_3 - w_2) + ... + (w_n - w_{n-1}) \equiv w_n$. Therefore, using any one of the thresholds $t_i \mid i\epsilon n$ alone as in current mechanisms, the following is true about the number TVWSs it produces: $w_i \leq w_1 + (w_2 - w_1) + (w_3 - w_2) + ... + (w_n - w_{n-1})$. This shows that using any single threshold $t_i \mid i\epsilon n$ by the current mechanism, the total number of white spaces identified will always be fewer than or equal to the number of white spaces produced by the set of thresholds $\{t_1, t_2, ..., t_n \mid n > 1\epsilon\mathbb{Z}^*\}$ as proposed in this proposed mechanism.

Considering interference probability, that can be caused by mis-detection, at any point in time during the allocation, the interference probability is greater than one, regardless of whether there are still channels that are indeed white spaces on the ground within the identified white spaces that are not yet allocated or not, using random allocation, as in the current mechanism. However, if sequential allocation is used to allocate the white spaces as in this proposed mechanism, the interference probability is always zero, up until the time when all the channels that are indeed white spaces on the ground, are allocated, because of the ascending order arrangement of the white spaces based on the signal strengths detected in them.

3.5 Experimental evaluation

To establish the reliability and effectiveness of this proposed white space detection design against the existing design, their performances were compared using real spectrum sensing data conducted in a number of police stations in the Western Cape Province of South Africa. The choice to evaluate the designs on a public safety network is based on the need to provide public safety in cities of the developing world. A public safety mesh network connecting police stations allows the police stations to share vital public safety information seamlessly. This study envisages a public safety mesh network connecting police stations, using white spaces, on an opportunistic basis in the future, which have a better penetration and transmission range than the currently used ISM band.

The experiment involved 42 police stations where measurements were taken. The names of the police station are shown in Appendix A. The table also shows the GPS coordinates and height above average terrain (HAAT) of the police stations. The HAAT was calculated using the GLOBE 1 km Base Elevation database [103] with the number of evenly spaced radials equal to 360° in each case. Figure 4.2 shows the Cape Town map derived from google maps and the locations of the police stations.
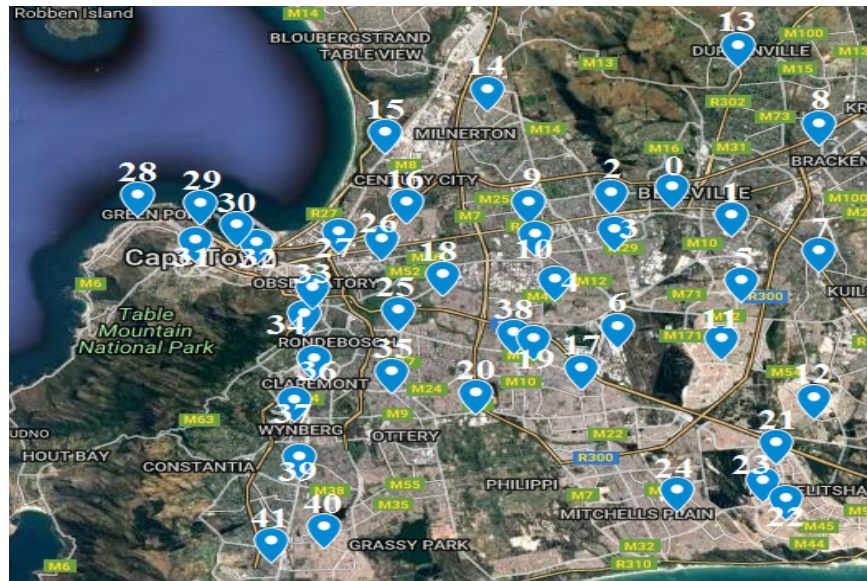
FIGURE 3.2: Police Stations in Cape Town

3.5.1 Spectral measurement setup

Outdoor spectrum measurements in the UHF ATT frequency band (470 MHz to 862 MHz) were done at the police stations using a hand-held RF Explorer model WSUB1G, which has a measurement frequency range of 240 MHz to 960 MHz. The model was fitted with a Nagoya NA-773 wide band telescopic antenna with vertical polarization, which has wide band measurement capability. The RF Explorer was connected to an Android phone, installed with a Python script program, that starts to measure spectrum immediately after the RF Explorer is connected, using an On-The-Go (OTG) cable. The Python script program is also capable of setting the start and stop frequencies and of saving the measurement results in *csv* file format. The Python script program also includes a GPS, which helps to identify the exact locations of the measurements. At each police station, the spectrum monitoring was done for 8 hours from 08:00 in the morning to 16:00 in the afternoon. Figure 3.3 shows a sample screen of an Android phone displaying the spectral measurements.

The ATT frequency band instead of the DTT frequency band (470 MHz to 694 MHz) was considered during the measurement because most of the countries in Africa including South Africa, which is considered as one of the leading nations in terms of development, have not completed the digital switch-over. Due to the technology adoption challenges that most African nations and other parts of the developing world face, it is not wrong to suspect that countries in Africa and other parts of the developing world will take years to complete the analog-to-digital TV switch-over.
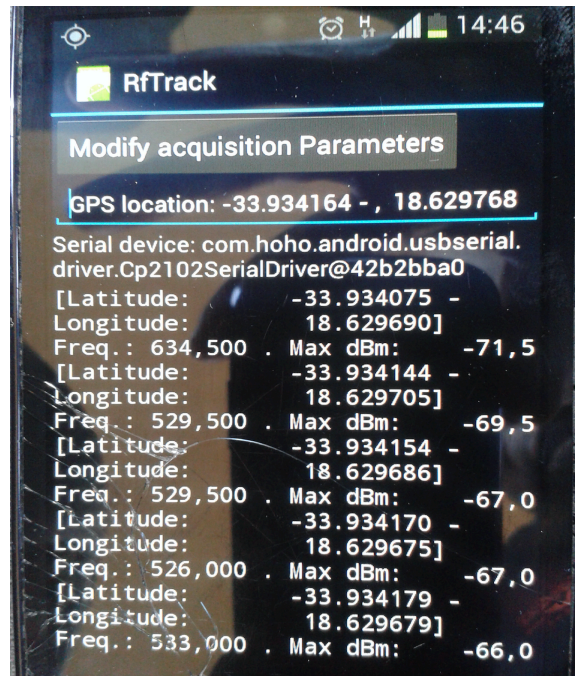
FIGURE 3.3: Sample android phone screen showing the spectral measurements

3.5.2 Measurement results

The 8-hour measurements at each police station were averaged and the mean value obtained in each channel was taken as the received signal power for that channel. To have a clear picture of the pattern of the measurements from all the police stations, the received signal powers were plotted on graphs as shown in Figure 3.4.
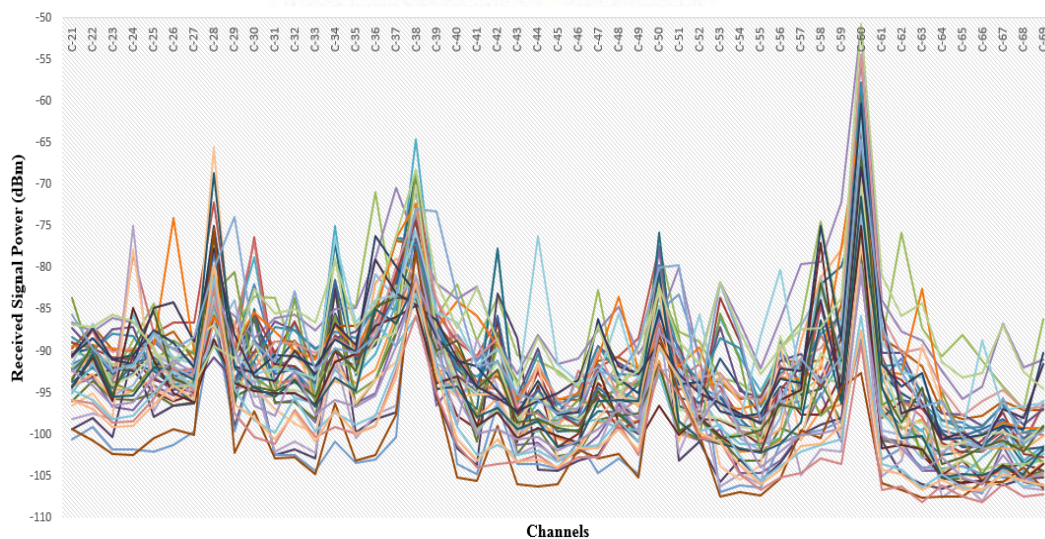
FIGURE 3.4: Received signal power from each police station

The standard deviation of the signal power of each channel from the 42 police stations is shown in Table 3.2. As seen from the table, the standard deviations are small, with

TABLE 3.2: Standard deviation of each channel's signal power (+/- dBm)

Channel	21	22	23	24	25	26	27	28	29	30	31	32
STDEV	3.8	3.5	3.9	5.7	3.9	4.2	2.8	5.3	5.1	5.7	4.9	4.9
Channel	33	34	35	36	37	38	39	40	41	42	43	44
STDEV	4.2	6.0	4.7	6.9	6.5	5.5	4.6	5.3	5.5	5.8	3.5	5.4
Channel	45	46	47	48	49	50	51	52	53	54	55	56
STDEV	3.6	3.2	5.1	4.1	4.1	5.0	5.3	3.8	6.8	5.3	4.3	5.8
Channel	57	58	59	60	61	62	63	64	65	66	67	68
STDEV	5.2	7.8	7.1	**10.3**	6.1	6.2	4.5	4.0	4.5	4.5	3.7	5.0

the largest standard deviation being equal to *10.3 dBm* from channel 60. The small standard deviations signify that, for each channel, the signals collected from the 42 police stations varied very little from each other, which means that the police stations receive similar signal power across all the channels. This observation strongly supports the idea of clustering measurement points.

3.5.2.1   White space detection results

To decide what detection thresholds to use for the detection of the white spaces, a TV transmission site and a police station close to that transmission site were identified to act as a base for the TVWS detection, and the same reasoning was applied to the remaining police stations, in order to identify the white spaces at each location. Tygerberg transmission site, located on latitude -33°52′31″ and longitude 18°35′44″ [16] and Bellville South Police Station were considered. No TVWSs were detected at the station when the detection threshold of 114 dBm was used as recommended by the FCC. Therefore, a range of values were tried by incrementing the 114 dBm sequentially by 0.5 dBm at a time. The first TVWSs were detected with a −101 dBm detection threshold and this figure was taken as the start detection threshold. An adequate criterion had to be used to select the final detection threshold to ensure maximum protection of the primary users. The Terrestrial Broadcasting Plan 2013 document [16] from the Independent Communications Authority of South Africa (ICASA) was examined to see how the UHF TV channels are arranged in the band. According to the document, the UHF ATT frequency band contains 49 channels of 8 MHz bandwidth each. The 49 channels are arranged in 12 groups of 4 channels each, which mean that 4 channels are available for assignments at any transmitting site on a national basis. In areas of great demand, 7 to 11 channels are assigned to a particular area by either combining lattice node points or using both VHF and UHF channels. At Tygerberg transmission site, there are 6 UHF channels being

used by different TV stations with the first TV station broadcasting from channel 22. The TV stations are shown in Table 3.3. Based on this allocation on the transmitting

TABLE 3.3: TV stations broadcasting from Tygerberg Transmitting site [16]

TV name	Broadcasting freq	Channel
SABC2	479.25 MHz	22
SABC1	511.25 MHz	26
MNET	543.25 MHz	30
SABC3	575.25 MHz	34
CSN	639.25 MHz	42
eTV	671.25 MHz	46

site, it was concluded that these channels cannot be detected as TVWSs, i.e., the final detection threshold signal (maximum threshold signal) should be less than the minimum signal power detected from these channels. The minimum signal power detected from these channels was -97.4 dBm from channel 46 used by the eTV broadcasting station. Therefore, it was decided to use -98 dBm as the final detection threshold. Since small variations in threshold values have a very big impact on the number of white spaces found [101], the detection thresholds were separated by an absolute value of 1 dBm difference, resulting in the following detection thresholds; 101 dBm, 100 dBm, 99 dBm and 98 dBm. Based on measures that were used to determine the detection thresholds at Bellville South Police Station, the same thresholds were expected to work for every police station.

The white spaces were detected using Algorithm 1 from the signal power recorded in each channel. Table 3.4 shows the white space channels that were identified at Bellville South Police Station by each of the signal detection thresholds used. A list of the white spaces identified at each station is included in Appendix B. To have a clear picture of the white space channels at Bellville South Police Station, graphs were plotted of the relative spectrum occupancy of all the channels for each of the four signal detection thresholds; these graphs are shown in Figures 3.5 to 3.8. The relative spectrum occupancy of each channel is defined by the following three equations:

$$O_{RS}(i) = 100 * R_{SS}(i, T_j)/M(i, T_j) \tag{3.4}$$

$$R_{SS}(i, T_j) = SS(i) - T_j \tag{3.5}$$

$$M(i, T_j) = max(R_{SS}(i, T_j)) \tag{3.6}$$

where $O_{RS}(i)$ is the relative spectrum occupancy in channel i, R_{SS} is the relative signal power collected in channel i using threshold T_j, $SS(i)$ is the representative signal power in channel i, which is equal to the strongest signal measured in channel i from the 14 locations and $M(i,T_j)$ is the maximum relative signal powr
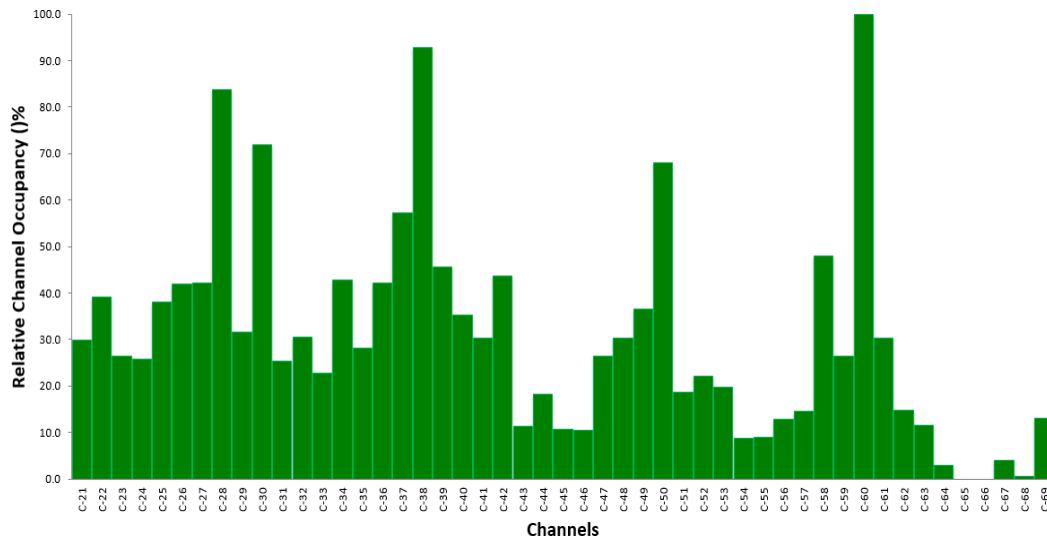
FIGURE 3.5: Spectrum occupancy with -101 dBm threshold
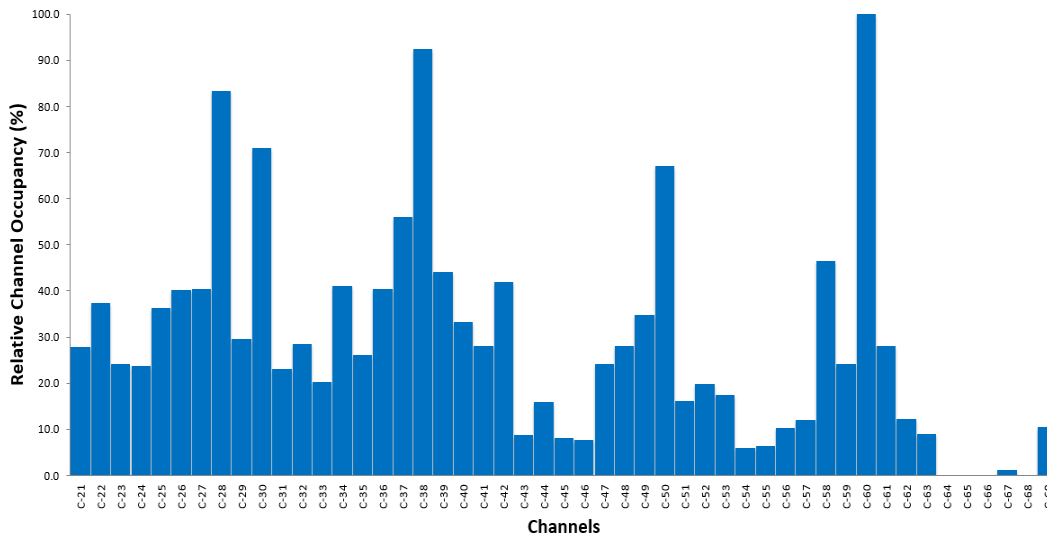
FIGURE 3.6: Spectrum occupancy with -100 dBm threshold

in the band collected in channel i using threshold T_j.

TABLE 3.4: White spapces identified at Bellville Police Station

Police station	Threshold	White spaces identified
Bellville South	-101	65, 66
	-100	64, 68
	-99	67
	-98	54, 55

Using Algorithm 2, the virtual prices for the white space channels detected were calculated using the measured signal powers of the channels. Table 3.5 shows the virtual prices of the white space channels at Bellville South Police Station.
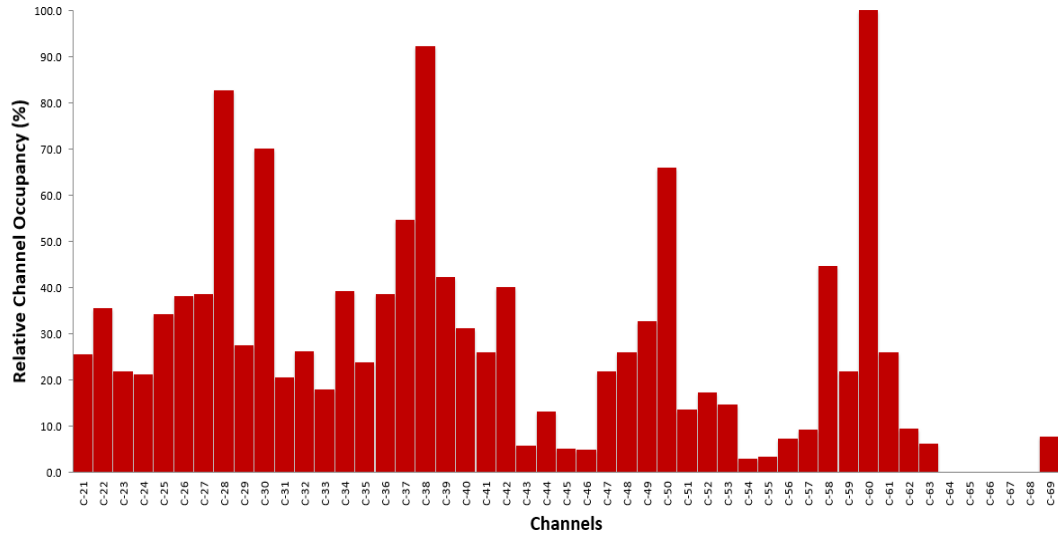
FIGURE 3.7: Spectrum occupancy with -99 dBm threshold
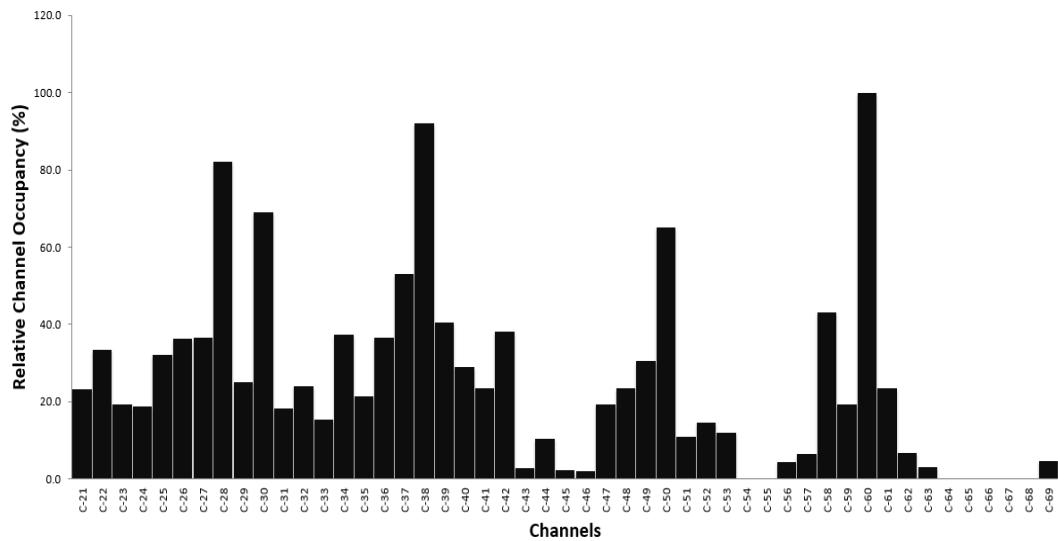
FIGURE 3.8: Spectrum occupancy with -98 dBm threshold

TABLE 3.5: Virtual prices for white space channels at Bellville Police Station

WS channel group	WS channels with prices
-101 dBm	65: 1.000, 66: 0.998
-100 dBm	64: 1.000, 68: 0.992
-99 dBm	67: 1.000
-98 dBm	54: 0.999, 55: 1.000

3.5.2.2 Measurement points clustering results

A Python code implementation of the proposed location-aware clustering algorithm (Algorithm 3) was run to obtain the clustering results. Using the GPS coordinates of the police stations, corresponding Cartesian coordinates were obtained from them, which were used to calculate the Euclidean distances between the police stations. The signal

powers for all the channels measured at each police station were averaged, and these were used to calculate the signal power differences between the police stations. The signal powers are shown in Table A.2 in Appendix A. In order make sure that only measurement points close to each other are clustered, the clustering distance radius was taken as short as 5 km, and to make sure that measurement points receiving similar signal strengths are clustered, the clustering signal threshold was taken as small as 3 dBm. The clustering results are shown in Table 3.6.

TABLE 3.6: Clustering results

Cluster	Cluster-head ID	Cluster members IDs	Cluster	Cluster-head ID	Cluster members IDs
1	0	0, 1	12	17	17, 4, 10, 19, 26
2	2	2	13	20	20
3	3	3, 9	14	21	21, 22, 23
4	5	5, 7	15	24	24
5	6	6, 11, 18	16	25	25, 33, 36
6	8	8	17	30	30, 28
7	12	12	18	31	31, 29
8	13	13	19	34	34, 27, 32
9	14	14	20	35	35, 37
10	15	15	21	38	38
11	16	16	22	39	39, 40, 41

3.5.3 Discussion

The grouping of white space channels, based on the signal detection threshold used, as show in Table 3.4, helps to start allocating these channels to WSDs with the most reliable group in terms of not causing interference to the spectrum incumbents due to mis-detection, which, in this case, is the one detected with *-101 dBm*. The least reliable group of TVWSs, out of the three groups considered, is the one identified with *-98 dBm* detection threshold. White spaces in this group are allocated only if the demand for their use is not met after using the white spaces in the first two groups. The situation is different if the white space channels are identified using only one threshold and if they are also allocated randomly to WSDs.

An additional layer of security is provided within a group of white spaces if the channels are virtual-priced based on their measured signal power. Channels with stronger signals are virtual-priced higher than channels with weaker signals, as shown in Table 3.5, because channels with stronger signals are the ones that are more likely to have primary users than channels with weaker signals. For example, looking at the white space channels in Table 3.5, allocating the least expensive channels, such as 52, 53, 48 first to WSDs, adds some protection to the expensive channels, such as 47, 58 and 64, which are the more likely channels to result in false negatives in that group. In this case, allocating the channels sequentially, based on their virtual prices, starting with channel

52, provides some level of protection to the expensive channels, such as channel 47 or channel 58 if there were any mis-detection.

Using the white spaces identified at Bellville South Police Station, in Table 3.4 and Table 3.5, this proposed method of detection and allocation of white spaces to WSDs is next compared with the current method of detection and allocation of white spaces to WSDs. Comparison is done based on the number of white spaces detected and the probability of causing interference to the spectrum incumbents at any white space allocation point in time. To have a clear understanding of the comparison, an assumption is made that there will be some missed detection during the detection of the white spaces. As seen from Table 3.7, the number of white spaces detected using more than one detection threshold, as in this proposed method, is always greater than or equal to the number of white spaces detected using one threshold, as in the current method. In terms of interference probability, the proposed method (sequential allocation) has a 0 interference probability at any application point in time, until all the channels that are white spaces on the ground and have been identified, have been allocated, while with the current method (random allocation), the interference probability at any allocation point in time is always greater than 0 regardless of whether channels that are white spaces on the ground and have been identified, have been allocated or not. Conclusively, it can be said that the proposed design outperforms the current design in all the aspects considered.

TABLE 3.7: Statistical analysis of current and proposed methods

	Current mechanism	Proposed mechanism
Threshold(s) (dBm)	-101 or -100 or -99 -98	-101, -100, -99, -98
No. of WSs identified	2 wth -101 threshold 4 with -100 threshold 5 with -99 threshold 7 with -98 threshold	7
Allocation type	Random	Sequential
Interference probability	> 0 with -101 threshold > 0 with -100 threshold > 0 with -99 threshold > 0 with -98 threshold	Always 0 until all actual TVWSs on the ground are allocated

For the clustering results, 22 clusters were created with the largest cluster having 6 members (cluster 13) (Table 3.6). This decrease the implementation cost, as the number of sensing equipment required to be deployed is reduced from 42 (number of police stations) to 22 (number of clusters). While many of the police stations were in individual clusters, some were able to be clustered with others, even with the clustering signal

threshold as low as 3 dBm. This confirms that clustering of outdoor measurement points is possible. The location-aware, i.e., using the clustering distance threshold, made sure to cluster only measurement points that were close to each other.

3.6 Chapter summary

This chapter discussed and presented the proposed spectrum sensing-based architecture for TVWS detection based on external sensing, that is well suited to conditions in the developing world. Challenges associated with spectrum sensing as a method for TVWS detection are addressed in the architecture by using both the existing and new proposed spectrum sensing design methods. Experimental evaluation of the spectrum sensing design methods on the proposed architecture has shown they can help the architecture to detect TVWSs with a minimal probability of causing interference to the primary users from false negatives. The methods have also been shown to assist the architecture to detect more TVWSs.

In the next chapter, the challenge of sharing/trading the white spaces to WSDs is tackled and a solution is proposed.

Chapter 4

Secondary spectrum market-based auction design

4.1 Introduction

Apart from the challenge of detecting white spaces accurately, distributing white spaces to secondary users is also another problem that the research community is trying to solve due to the nature of the white space spectrum and the diversity of the network players involved. Any strategy chosen for assigning the white spaces to secondary users has to ensure efficient spectrum utilization and also ensure fairness of distribution to every secondary user in need of the white space use. So far, many spectrum access technologies have been suggested but one proposal that stands out and seems to be viable is the auction strategy. An auction is the best-known market-driven mechanism for selling general merchadise, and due to its perceived fairness and allocation efficiency [91], it promises to provide a solution to the white space spectrum assignment problem. In a well-designed auction setup, every secondary user has an equal opportunity to win a spectrum segment [92]. Although spectrum administrators of some countries have successfully held spectrum auctions in primary spectrum markets [66, 92], the mechanisms used in these markets cannot be applied directly to auctions in secondary spectrum markets because of the nature of secondary spectrum markets that have so many diverse players. Consequently, designing an auction mechanism for secondary spectrum markets, like TVWS spectrum is challenging because the design has to meet many complementary requirements, in addition to the usual economic properties that any auction mechanism designed for selling general merchandise should meet, as discussed in the literature review on spectrum auction in 2. Many auction mechanism design attempts for secondary spectrum markets from researchers result in spectrum auctions that meet

65

only a few of these requirements. Motivated by that, this chapter proposes and designs a spectrum auction mechanism that not only depicts the reality of a secondary spectrum market, but also ensures optimal allocation of the spectrum leading to efficient spectrum utilization.

The Chapter is organized as follows: Section 4.2 describes the problem scenario being addressed and its proposed solution; Section 4.3 describes the problem space formally; Section 4.4 discusses the auction mechanism design proposal for the problem space described in Section 4.3; Section 4.5 discusses an experimental evaluation conducted and the results generated using the proposed auction mechanism; Section 4.6 highlights the distinctive features of the proposed auction mechanism design that make it unique and different from the existing proposals; Section 4.7 concludes the Chapter by highlighting what has been discussed in the Chapter.

4.2 Problem scenario and solution description

The problem scenario consists of multiple TV broadcasting service providers that have low spectrum utilization, and thus have unused spectrum that they are willing to lease temporarily. At the same time, there exist many heterogeneous wireless service providers (WSPs), e.g., telecommunication mobile operators and smaller wireless networks, that require more spectrum resources to improve quality of service (QoS) at times when there is heavy traffic on their networks. There is a centralised entity called the spectrum broker whose responsibilities are as follows: collecting spectrum resources from the sellers; advertising the resources to the buyers; collecting spectrum demands from the buyers; establishing the trading relationships between buyers and sellers; establishing the interference relationships between the buyers; executing the spectrum allocation; charging the winning buyers; and paying the winning sellers their dues. The potential TVWS spectrum buyers have heterogeneous demands based on their network channel bandwidths and transmit powers needed for successful transmission, and the spectrum broker assigns spectrum to the spectrum buyers in segments suited to their transmission channel-bandwidths. Based on the dynamics of spectrum demands from the potential TVWS spectrum buyers, the spectrum broker devises dynamic short-time periodic auctions in order to maximize the TVWS owners' income. The overall goal of the spectrum broker is to ensure efficient spectrum utilization and income maximization.

The spectrum broker controls a small region consisting of one TV transmission site having more than one TV broadcasting service provider, and many heterogeneous wireless service providers (WSPs). An example of such a region is illustrated in Figure 4.1.
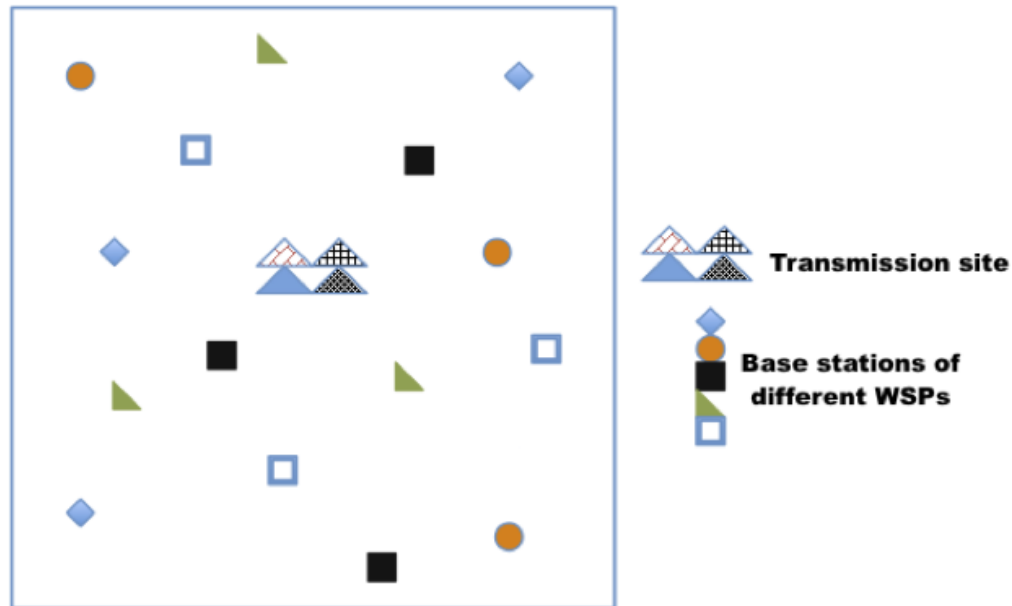
FIGURE 4.1: Region controlled by a spectrum broker

Each TV broadcasting service provider can provide more than one spectrum segment in the auction, in which each spectrum segment is a contiguous multiple of the TV channel bandwidths (8 MHz), and each potential white space spectrum user can bid and win more than one spectrum segment. The potential white space spectrum users/ have heterogeneous demands based on their network channel-bandwidths and the transmit powers needed for successful transmission. The spectrum broker assigns spectrum to the spectrum buyers in segments suited to their transmission channel-bandwidths.

During each auction period, the spectrum broker first announces details of the auction including the lease-time, to the TVWS spectrum owners. In response to the broker's call, the spectrum owners submit their spectrum segments to the broker for the broker's proposed lease period. Then the broker announces the available spectrum segments, including each spectrum's price per unit spectrum and the lease-time, to the potential spectrum buyers, who later submit their spectrum demands to the broker, including how much they are willing to pay for each spectrum segment that they want to buy. Finally, the broker runs the auction and announces the winners. This process is depicted in Figure 4.2. Note that the figure has been divided into two main parts, yellow and blue colour states, to differentiate between the actual spectrum allocation activities from the initial interaction activities between the broker and the spectrum owners and the potential spectrum buyers.

4.3 Proposed auction mechanism design

Learning from the idea and concepts put forward in the literature review, an iterative auction mechanism design is proposed that depicts the dynamics of a real secondary spectrum market. The proposed auction mechanism mimics a similar process employed in the Genetic Algorithm (GA) to shape the groups of eligible non-interfering buyers through the survival of the members that can be served by the remaining spectrum segment at each iteration step. The groups are shaped by deleting members of the groups with channel bandwidth greater/wider than the remaining spectrum segment, during each iteration step. In so doing, the auction mechanism optimizes the spectrum allocation, such that no spectrum segment remains at the end of the auction that it would have been possible to allocate to any surviving non-winning members of eligible buyer groups. To maximize the revenue generated at each iteration step, the proposed auction mechanism considers the allocation problem as a 0-1 Knapsack Problem (KP) where the spectrum segment under consideration is considered as a Knapsack and needs to maximize the benefit (profit) generated by the objects (winning non-interfering buyer
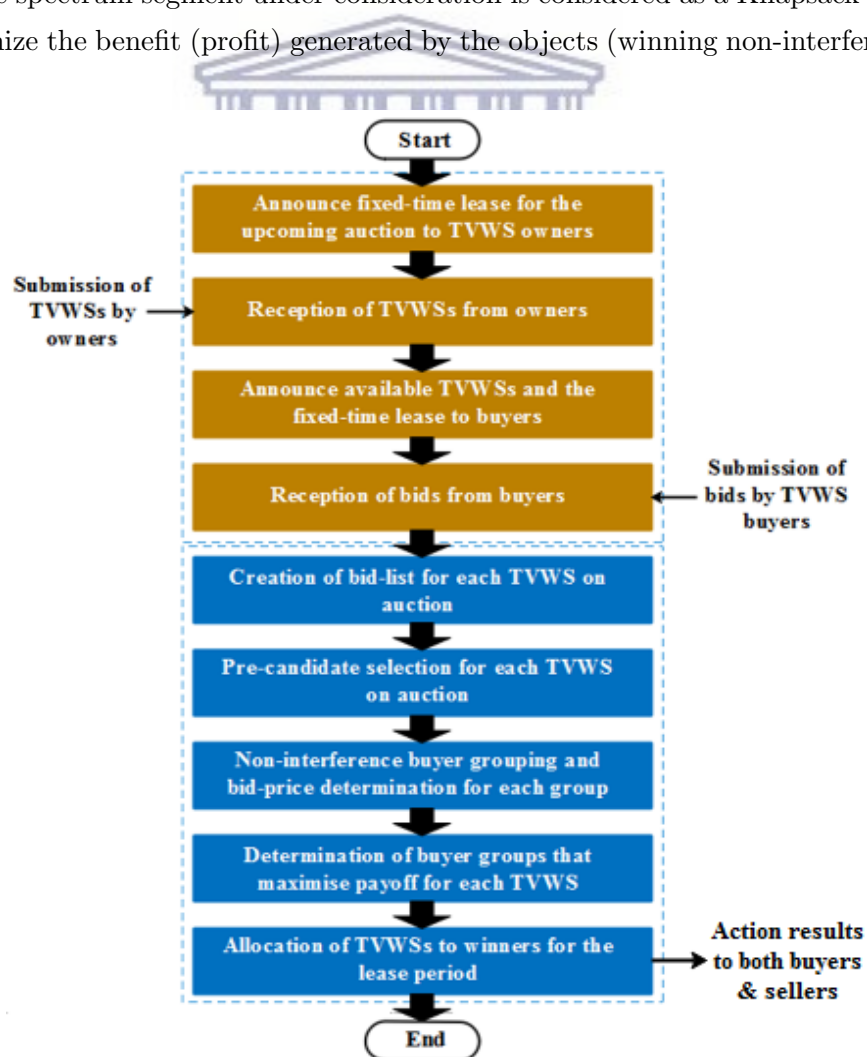
FIGURE 4.2: The auction process

groups) put in the knapsack (the spectrum segment) without exceeding its capacity (size).

4.3.1 Profiles of auction participants

The profiles of the auction participants, i.e., the white space spectrum providers or owners, and the potential white space spectrum users are described formally. Following the terminology in auction theory, the white space spectrum providers or primary users are called *sellers*, and the potential white space spectrum users or secondary users are called *buyers*. The terms white space spectrum providers/primary users and sellers, and potential white space spectrum users/secondary users and buyers are used interchangeably throughout the chapter. Each seller submits to the broker a price per unit spectrum of each spectrum segment that it is selling, i.e., the lowest price at which the seller is willing to sell the spectrum. Like the sellers, each buyer submits a price for each spectrum segment it intends to buy, i.e., the highest price at which the buyer is willing to pay. Using auction theory terminology, the price submitted by the seller and the buyer are called *ask* and *bid* respectively. Each seller can submit more than one ask profile to the spectrum broker depending on the number of spectrum segments that it is selling. Similarly, potential buyers can submit more than one bid profile, depending on the number and type of networks whose QoS they want to improve.

Let M denote the number of white space spectrum owners and let $P = \{P_i \mid 1 \leq i \leq m, m \geq M\}$, denote a list of all ask profiles from the sellers. Let N denote the number of bidders and let $B = \{B_j \mid 1 \leq j \leq n, n \geq N\}$, denote a list of all bid profiles from the potential buyers responding to the ask profiles of the spectrum sellers. Let $B^{P_i} = \{B_y \mid 1 \leq y \leq n\}^{P_i}$, $i = 1, 2, ..., m$, denote a list of bid profiles bidding for each ask profile P_i.

The ask profile of the seller is described formally as follows:

$(g_{s_a}, s_a, f_{s_a}, p_{s_a}, r_{s_a})$, $a \geq 1$, represents the white space spectrum owner's ask profile where g_{s_a} is the GPS location of the white space spectrum owner's TV transmitter for the white space spectrum s_a, f_{s_a} is the start frequency in MHz on TV RF spectrum band of the spectrum, p_{s_a} is the white space spectrum owner's ask price per unit spectrum, which is an indication of the owner's willingness to lease the spectrum and r_{s_a} is the white space spectrum owner's allowed transmission range (TR) on the spectrum.

The bid profile of the potential buyer is described formally as follows:

$(g, w, f_{s_a}, g_{s_a}, x_{s_a}, t_{s_a})$, $a \geq 1$, represents the potential white space spectrum user's bid profile where g is the GPS location of its base station, w is the channel-bandwidth of the buyer's network, $f_{b(s_a)}$ is the start frequency in MHz on TV RF spectrum band of the spectrum s_a that the buyer is bidding for, g_{s_a} is the GPS location of the white space spectrum owner's base station, x_{s_a} is the buyer's bid price per unit spectrum, which expresses the bidder's willingness to pay for the spectrum and t_{s_a} is the TR of the buyer's network that it can achieve on the spectrum.

The auction participants, i.e., the sellers and the buyers, define their asks and bids respectively using their own optimization functions and prediction tools, which are beyond the scope of this thesis as they also require additional comprehensive research.

4.3.2 Pre-candidate selection

This step is meant to disqualify all potential buyers from the auction with bids less than the sellers' asks, and also those whose coverage areas are not entirely within the coverage areas of the spectrum sellers. This condition is shown in Figure 4.3 where the coverage areas of potential buyers 2, 3, and 6 are not entirely within the coverage area of the spectrum seller. These buyers could cause interference to the neighbours of the spectrum seller's network if they were to win a spectrum segment. Pre-candidate selection is performed by Algorithm 4.

For each ask profile, the algorithm compares its start frequency and ask with the start frequency and bid respectively of each bid profile. If the start frequencies match and the
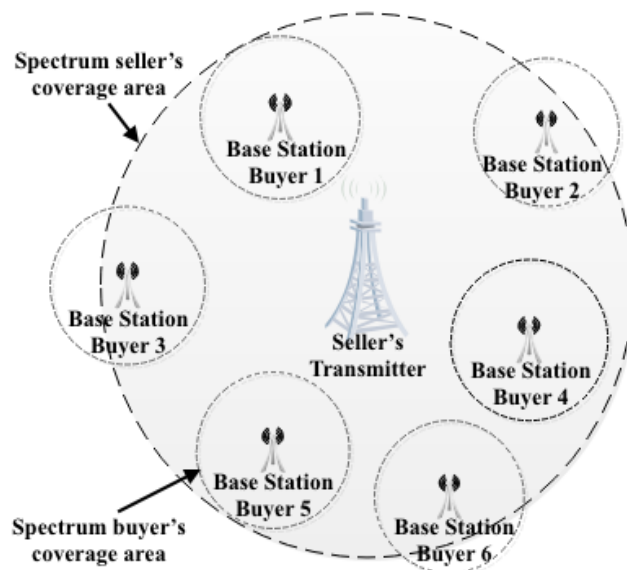
FIGURE 4.3: Spectrum seller's coverage area vs spectrm buyers' coverage areas

---

Algorithm 4: Pre-candidate selection

input : $P = \{P_1, P_2, ..., P_m\}$, $B = \{B_1, B_2, ..., B_n\}$

output: List of eligible bidders B^{P_i} for each ask profile P_i, $i = 1, 2, ..., m$.

1 **for** $i \leftarrow 1$ **to** m **do**

2   **for** $j \leftarrow 1$ **to** n **do**

3   **if** $P_i[f_{s_a}] = B_j[f_{b(s_a)}]$ *and* $P_i[p_{s_a}] \leq B_j[x_{s_a}]$ **then**

4   calculate distance between P_i and B_j; `// Euclidean distance calculated using their GPS positions`

5   subtract distance between P_i and B_j from $P_i[r_{s_a}]$ and assign it to $D_{P_i B_j}$;

6   **if** $D_{P_i B_j} \geq B_j[t_{s_a}]$ **then**

               `// if condition is TRUE, then coverage area of` B_j `is within the coverage area of` P_i

7   add B_j to B^{P_i};

8   **end**

9   delete B_j from B;

10 $n \leftarrow n - 1$;

11   **end**

12   **end**

13   ***return*** B^{P_i};

14 **end**

---

seller's ask is less than or equal to the buyer's bid, then algorithm checks if the coverage area of the potential white space buyer is entirely within the transmission coverage of the white space spectrum owner. If that is the case, the potential buyer's bid profile is added to the list of bid profiles for the ask profile and the bid profile is deleted from the list of all bid profiles. If not, the bid profile is also deleted from the list of all bid profiles. This process is performed from line 3 to 9. The process is repeated for each bid profile. Finally, the algorithm returns a list of bid profiles bidding for the ask profile in line 13.

4.3.3 Non-interference buyer-grouping

In [66],[104] and [105], it is stated that the spectrum buyer-grouping problem is computationally hard (NP-Hard). There are many approximate algorithms for solving it in the literature and some of them are provided here.

1. Greedy-U algorithm [104]: The algorithm works by recursively choosing a node with a minimum degree in the current conflict graph and eliminating the chosen node and its neighbours. The algorithm then updates the degree values of the remaining nodes from the current conflict graph in order to form a non-interfering group.

2. Greedy algorithm [104]: The algorithm works in the same way as Greedy-U algorithm except that at each recursive step, it chooses the nodes based on the degree values of the original conflict graph.

3. Max-IS algorithm [106]: The algorithm works by recursively picking a node which has the minimal size of a maximum independent set and pushes it into the current independent set. This procedure is repeated until all the nodes are processed.

4. Stripe algorithm [107]: The algorithm works by first partitioning the interested area into stripes with each stripe's width equal to $\sqrt{3}d/2$, where d is the radius of the unit disk graph, i.e., intersection graphs of equal-sized disks in the plane [107]. Then the algorithm finds an optimal colouring scheme for each stripe with maximal flow or maximal bipartite matching algorithm. Then the algorithm combines colours of adjacent stripes from left to right to obtain the final colouring scheme of the graph.

5. Rand algorithm: The algorithm works by randomly choosing a node and tries to allocate one channel while satisfying non-conflict constraints [66].

6. Lexicographic algorithm [105]: This algorithm works by ordering vertices first by their X-coordinates and then by their Y-coordinates, then colours each unit disk one by one according to their coverage area. Two disks with identical colours are in the same interfering group.

As in the other auction mechanism designs, in order to utilize the white space spectrum efficiently in the proposed auction mechanism, the spectrum broker divides the potential buyers for each ask profile into non-interfering buyer groups after the pre-candidate selection step, so that those who do not interfere on a spectrum segment can share the same spectrum segment if they win. A coverage based interference model is adopted in this auction mechanism. In a coverage-based interference model, whether or no two networks interfere with each other depends solely on whether their coverage overlaps or not, and the interference relationship is symmetrical.

Since only approximate algorithms for solving the spectrum buyer-grouping problem exist, it was decided to design a new non-interference buyer grouping strategy. This new strategy derives the non-interference buyer groups from the complement of the interference graph of the buyers created, using the GPS coordinates of the potential buyers and their TR on the spectrum included in their bid profiles. This new strategy is called the Interference Graph-Complement (IG-C) strategy. It always derives the minimum number of non-interference buyer groups.

An interference graph of potential buyers on a white space spectrum under ask profile P_i is denoted as $G_i = (V, E)_i$ where V is the set of all potential buyers on the spectrum and E is the set of edges. There is an edge between two potential buyers who interfere on the spectrum otherwise there is no edge between them. Algorithm 5 shows the implementation of the IG-C strategy for creating the non-interference buyer groups.

Algorithm 5: Non-interfering buyer-grouping

input : Seller's ask profile P_i; its list of bidders $B^{P_i} = \{B_y \mid 1 \leq y \leq n\}^{P_i}$

output: Groups of non-interfering nodes $\{\o_{z,i} \mid 1 \leq z \leq y\}$ and their equivalent groups of non-interfering buyers $\{\O_{z,i} \mid 1 \leq z \leq y\}$.

1 create an interference graph G_i from B^{P_i};
2 create G'_i from G_i;
    // G'_i is the complement of the interference graph G_i
3 initialize $z \leftarrow 1$;
4 **repeat**
5   choose any node in G'_i with lowest-degree;
6   add lowest-degree node to group $\o_{z,i}$;
7   add node's equivalent bid from B^{P_i} to group $\O_{z,i}$;
8   **repeat**
9   find common-neighbour nodes in G'_i of all nodes in $\o_{z,i}$;
10   choose any common-neighbour node with lowest-degree;
11   add lowest-degree node to group $\o_{z,i}$;
12   add node's equivalent bid from B^{P_i} to group $\O_{z,i}$;
13   **until** *no common-neighbour nodes exist for all nodes in $\o_{j,i}$*;
14   delete all nodes and their edges in $\o_{z,i}$ from G'_i;
15     $z \leftarrow z + 1$;
16 **until** *G'_i is empty*;
17 **return** $\o_{1,i}, \o_{2,i}, ..., \o_{z,i}, \O_{1,i}, \O_{2,i}, ..., \O_{z,i}$;

An interference graph of potential buyers for each spectrum segment on sale is created in line 1 and from the interference graph, its complement graph is created in line 2. From the complement graph, a node with lowest number of edges is selected and put in its own group from lines 5 to 7. After that, the algorithm searches for all common neighbour nodes of the node with the lowest number of edges selected in the previous step from the complement graph. From the common neighbour nodes, the algorithm selects any node with the lowest number of edges and put it in the same group as the first node with the lowest number of edges selected from lines 5 to 7. This process is done from line 9 to 12, and is repeated until no common neighbour nodes exist in the complement graph for all the nodes that are put in the group of nodes with the lowest number of edges. Then the algorithm deletes all the nodes that are put in group of nodes with the lowest number of edges from the complement graph in line 14. The process repeats from line 4 to line 14 by using a new node with the lowest number of edges selected from the

remaining complement graph. This is done until the complement graph is empty, i.e., has no nodes.

4.3.3.1 Pictorial example

A pictorial example of how the algorithm works in creating non-interfering buyer groups is provided in Figures 4.4 and 4.5. Figure 4.4 shows the interference graph of 6 potential buyers' networks on the spectrum on sale and the interference graph's complement. Figure 4.5 shows the remaining interference graph's complement and the non-interference group/s created after each iteration. Note that two results of non-interference groups are possible; $\left\{\{3\}, \{5, 2, 1\}, \{6, 4\}\right\}$ or $\left\{\{3\}, \{6, 4, 1\}, \{2, 5\}\right\}$.
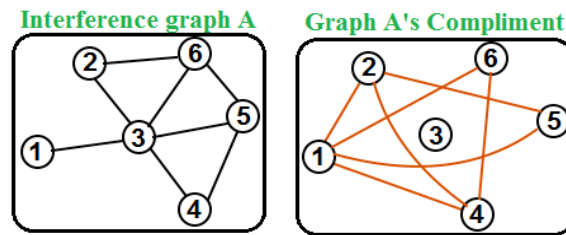
FIGURE 4.4: Interference graph and its complement of potential buyers
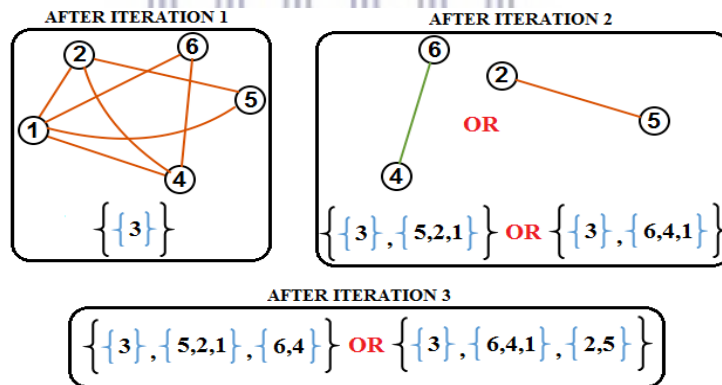
FIGURE 4.5: Results after each iterations

4.3.4 Group bid and total price determination

The group bid per unit spectrum for each non-interfering buyer group is set to the bid of the bid profile of the potential buyer with the lowest bid in the group. Using that bid and each buyer's network channel bandwidth, the total price that each non-interference buyer group is going to pay if it wins is calculated by summing up the products of network channel bandwidth of the buyers and the lowest bid in the group. Note that each potential buyer contribute a price to the group's total price that is proportional to

its network channel bandwidth and is determined by the lowest bid per unit spectrum in its non-interference buyer group.

4.3.5 Spectrum allocation

Each non-interference buyer group's spectrum demand is represented by the largest channel bandwidth in the group and the group's bid is represented by the total price. The spectrum broker uses these two when performing the spectrum allocation to the groups. Now, the spectrum allocation problem has been reduced to a 0-1 KP in which each spectrum on sale is to be allocated to its non-interference buyer groups so that the total spectrum segments allocated (equivalent to the total of the largest channel bandwidths) to the winning groups is less than or equal to the spectrum and the revenue generated by auctioning the spectrum (sum of the winning groups' bids) is maximized. The spectrum is allocated to the groups recursively by mimicking a similar process employed in the GA at each recursive step, to shape the non-winning buyer groups through the survival of their members that can be served by the remaining spectrum segment. At the beginning of each recursive step, potential buyers in the non-interference buyer groups with channel bandwidths larger than the remaining spectrum segment are removed from the groups. The allocation is done until either the spectrum is exhausted or the spectrum segment that remains can no longer serve any surviving members of the remaining non-winning buyer groups. After the spectrum allocation of each ask profile is complete, the bid profiles of all members in the winning buyer groups are removed from the bid profiles of the remaining ask profiles because they have won a spectrum segment and do not need to participate any more in the auctioning of the remaining spectra. The allocation process is shown in Algorithm 6.

At the end of the auction, the broker pays each spectrum seller the total earnings collected from all the winning buyer groups of the seller's ask profiles.

4.4 Maintenance of economic properties in the auction

A number of strategies have been implemented in the auction to make sure that the three economic properties of any action mechanism design are maintained. These strategies are highlighted in this section.

Individual rationality: To make sure that the winning buyers are not charged more than their bids, i.e., winning buyers do not achieve non-negative utility, the group bid per unit spectrum is set to the bid of the bid profile of the potential buyer with the lowest

---

Algorithm 6: Spectrum allocation

---

input : Groups of non-interfering buyers $\{\emptyset_{z,i} \mid 1 <= z <= y\}$, total prices $\{p_{z,i} \mid 1 <= z <= y\}$ to be paid by the groups and their corresponding largest channel widths $\{w_{z,i} \mid 1 <= z <= y\}$ for the ask profile P_i.

output: Winning non-interfering buyer groups $\{\emptyset_{b,i} \mid 1 <= b <= z\}$ for the ask profile P_i.

---

1 allocate spectrum segment $s_{a,i}$ to its buyers groups as a 0-1 Knapsack Problem;

2 assign $s_{a,i}$ minus *allocated-spectrum* to *spectrum-left*;

3 check if there exists any non-winning buyer-group;

4 **while** *spectrum-left* > 0 **and** *any non-winning buyer-group exists* **do**

5   **for** *each non-winning buyer-group of $s_{a,i}$* **do**

6   remove all candidates with channel width larger than ***spectrum-left***;

7   **end**

8   **if** *some non-winning buyer-groups have members* **then**

9   call group bid-price and total-price determination algorithm; `// to recalculate each group's total-price and largest network channel-bandwidth.`

10   allocate *spectrum-left* to non-winning buyer groups as a 0-1 Knapsack Problem;

11   assign *spectrum-left* minus *allocated-spectrum* to *spectrum-left*;

12   **end**

13   check if there exists any non-winning buyer group;

14 **end**

---

bid in each group. In order to make sure that revenues of all winning sellers are not less than their asks, potential buyers with bids less than the sellers' asks are disqualified from the auction participation during the pre-candidate selection step.

Truthfulness: To enforce truthfulness among potential buyers, potential buyers submit their bids to the broker privately, i.e., the auction is a sealed-bid auction format. A bid-independent grouping method for creating non-interfering buyer groups is adopted in the auction to also enforce truthfulness among the buyers. These methods have been used in other well-known spectrum auction formats such as in [94], [66], [97], [92] to enforce truthfulness and prevent market manipulation.

Budget Balance: The broker pays each spectrum seller the total earnings collected from all the winning buyer groups of the seller's ask profiles at the end of the auction. To make sure that the broker does not achieve a negative balance, the broker disqualifies all potential buyers with bids less than the sellers' asks before the auction.

4.5   Uniqueness of auction mechanism

The proposal set out in this study is unique in many ways, and different from any of the existing proposals. It contains features that many of the existing mechanisms do not contain, and it also includes as many details as possible in the ask profile of the spectrum seller and the bid profile of the spectrum buyer.

To the best of the authors' knowledge, the proposed auction mechanism is the first of its kind to propose that the transmission range that a potential buyer can achieve on a spectrum that it is bidding for should be calculated by the potential buyer itself and not the spectrum broker. All the algorithms surveyed leave the responsibility of calculating the transmission range of a potential buyer on a spectrum in the hands of the spectrum broker. The algorithms include maximum power limit as part of the potential buyers bid profile, which the spectrum broker uses to calculate the transmission range that the buyer can achieve on the spectrum. The potential buyer's transmission range and its GPS location determine the interference relationship with other potential buyers, which is important for determining the spectrum reusability. Many parameters are involved in the estimation of transmission range apart from the power limit. The formula for estimating the maximum transmission range on a spectrum is as follows [93]

$$R_m = \exp\left\{\frac{P_t - P_r + 28 - P_f(n) - 10\log f^2}{\gamma}\right\} \tag{4.1}$$

where R_m is the maximum transmission range, P_t is the transmission power, P_r is the targeted receiving power, $P_f(n)$ is the floor loss penetration factor, f is the central frequency of the spectrum in megahertz (MHz) and γ is the distance power loss coefficient.

Leaving the task of estimating the transmission range that a potential buyer can achieve on a spectrum to the spectrum broker would require these other parameters to be included in the buyers bid profile, which would require extra storage space on the part of the spectrum broker and increase the complexity of the already complicated task of spectrum allocation for the spectrum broker.

The ask profile of a spectrum seller and the bid profile of a spectrum buyer for this proposed auction mechanism are much more detailed than any of the existing auction mechanisms. To the best of the authors' knowledge, the proposal is the first to include the RF spectrum location where the spectrum exists and the GPS location of the spectrum seller's transmitter as part of the seller's ask profile. The proposal is also the first of its kind to include the GPS location of the spectrum buyer's transmitter as part of its bid profile. Including location on the RF spectrum of the spectrum segment on

sale in the ask profile helps the spectrum broker to calculate the central frequencies of the spectrum winners. Using the GPS location of the spectrum seller's transmitter and its transmission range on the spectrum, and the GPS location of the spectrum buyer's transmitter and its corresponding transmission range on the spectrum, the spectrum broker is able to calculate and determine if the spectrum buyer will be broadcasting within the acceptable broadcasting area of the spectrum seller, if the buyer wins part of the spectrum. Including the GPS location of the spectrum buyers' transmitters and their corresponding transmission range on the spectrum, helps the spectrum broker to calculate and determine their interference relationships on the spectrum. Existing proposals do not explain clearly how the interference relationships between buyers is calculated.

In addition to including as many details as possible in the ask profile of the spectrum seller and the bid profile of the spectrum buyer, this proposal also includes as many details as possible in the auction winners' results. For instance, the auction results for the spectrum winner include the central frequency that it should use for broadcasting. Letting the spectrum winner know of the central frequency it has to use for broadcasting is important to avoid the spectrum winner broadcasting on an unacceptable central frequency, which could result in interference with other wireless networks. None of the existing proposals include the central frequency as part of the spectrum winner's results.

This auction mechanism achieves efficient spectrum allocation, high spectrum re-usability, both leading to efficient spectrum utilisation, and profit maximization. Efficient spectrum allocation is achieved through the use of a process similar to that employed in GA, in shaping the non-winning groups through the survival of their members that can be served by the remaining spectrum segment until either the spectrum is exhausted or the spectrum segment that remains can no longer serve any surviving members of the remaining buyer groups. High spectrum re-usability is achieved through the use of a new non-interfering buyer-grouping algorithm, which finds a minimum number of maximal independent sets from an interference graph of the potential buyers. Profit maximization is achieved through the way the auction is conducted.This methods regards the spectrum allocation of each spectrum segment on auction as an 0-1 KP: each spectrum segment on auction is considered as a Knapsack and the method maximizes the benefit (profit) generated by objects (winning non-interference buyer-groups) put in the knapsack (the spectrum). To the best of the authors' knowledge, none of the existing proposals can achieve efficient spectrum utilization as well as this proposal. There are few auction mechanism designs, if any, that maximise the profit for the spectrum seller and also achieve efficient spectrum utilization as well as this proposal.

4.6 Experimental evaluation

A Python-code of this auction mechanism proposal was implemented in order to evaluate its performance. In the implementation, the Python library called *networks* was used to successfully implement the non-interference buyer grouping algorithm and the Python library called *pyeasyga* to solve the 0-1 KP using the GA. Other approaches to solving the 0-1 KP exist but the GA approach performs much better than the other approaches, and currently it is the most efficient approach for finding an approximately optimal solution for optimization problems, such as the KP [108].

In the simulation, the area under considered has one TV transmission site where 4 TV broadcasting service providers have unused spectra that they want to lease out temporarily and 30 WSPs that require extra spectra to improve their QoS. The location of the TV transmission site and the position of the base stations of the WSPs, shown in Figure 4.6, are generated using Radio Mobile network planning tool [109]. The TV transmission site exists in reality.
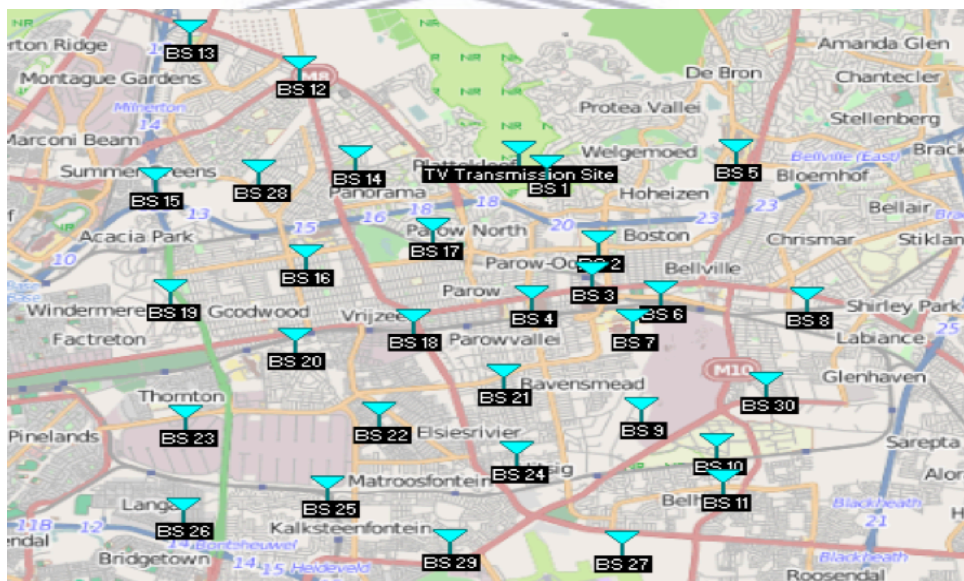
FIGURE 4.6: Base stations positions relative to TV transmission site

The parameters used for the white space spectrum owners are shown in Table 4.1. The unused spectra are denoted as follows: 24 MHz-S1, 16 MHz-S2, 24 MHz-S3, 32 MHz-S4. These spectrum resources are assumed to have the same transmit power constraints but slightly different transmission ranges due to their positions on the RF spectrum.

The WSPs' networks are heterogeneous with different channel bandwidth requirements. The network channel bandwidths considered are 22 MHz for a Wi-Fi network system, 1.4 MHz, 3 MHz, 5 MHz, 10 MHz, 15 MHz and 20 MHz for Long-Term Evolution (LTE)

TABLE 4.1: White space spectrum owners' parameters

Attribute	Value
GPS of transmission site	33°52′31″S 18°35′44″E
Unused spectrum sizes	24 MHz, 16 MHz, 24 MHz, 32 MHz
Starting frequencies of unused spectra	494 MHz, 518 MHz, 534 MHz, 566 MHz
Allowed TR on unused spectra	10.50 Km, 10.47 Km, 10.44 Km, 10 Kms

network systems, 5 MHz for a Universal Mobile Telecommunications System (UMTS) network system. The 30 WSPs competing for the available spectra are distributed as follows: 6 Wi-Fi network providers each demanding 22 MHz, 3 LTE network providers each demanding 20 MHz, 2 LTE network providers each demanding 15 MHz, 4 LTE network providers each demanding 10 MHz, 3 LTE network providers each demanding 5 MHz, 5 LTE network providers each demanding 3 MHz, 4 LTE network providers each demanding 1.4 MHz and 3 UMTS network providers each demanding 5 MHz. Table 4.2 shows the GPS location of the WSPs' base stations and their relative distances away from the TV transmission site. It is assumed that the networks of WSPs require contiguous spectrum, which has the following implications:

- The 22 MHz Wi-Fi network providers and 20 MHz LTE network providers bid for spectrum $S1, S3, S4$, i.e., the spectrum is big enough to accommodate their channel-bandwidths.

- The remaining network providers bid for all the spectra since their channel bandwidths can be accommodated on any of the spectra.

The assumed TRs of the heterogeneous networks on the four spectra are shown in Table 4.3. It is also assumed that the valuation of one unit of spectrum , i.e., 1 MHz, for each of the 4 available spectra is different for all the network providers.

4.6.1 Experimental results

The spectrum broker in the allocation mechanism first ranks the white space spectra using their qualities and frequency distribution on the TV RF band, in order to decide the order of allocating them to the potential white space spectrum users, before the allocation takes place. After computing the ranking of the four spectra, the broker makes the following allocation order: $S4, S1, S3, S2$.

This new strategy derives the non-interference buyer groups from the complement of the interference graph of the buyers created, using the GPS coordinates of the potential

TABLE 4.2: GPS coordinates of measurement sites and their distances away from BS transmitter

BS name	System	Latitude Longitude	Distance (Km)	BS name	System	Latitude Longitude	Distance (Km)
BS 1	UMTS	-33°52′41″ 18°36′1″	0.53	BS 16	3 MHz LTE	-33°53′46″ 18°33′28″	4.19
BS 2	1.4 MHz LTE	-33°53′36″ 18°36′34″	2.38	BS 17	UMTS	-33°53′27″ 18°34′49″	2.23
BS 3	1.4 MHz LTE	-33°53′59″ 18°36′30″	2.96	BS 18	3 MHz LTE	-33°54′32″ 18°34′36″	4.12
BS 4	UMTS	-33°54′15″ 18°35′52″	3.22	BS 19	Wi-Fi	-33°54′11″ 18°32′2″	6.48
BS 5	1.4 MHz LTE	-33°52′30″ 18°38′1″	3.51	BS 20	5 MHz LTE	-33°54′46″ 18°33′21″	5.55
BS 6	3 MHz LTE	-33°54′12″ 18°37′14″	3.88	BS 21	3 MHz LTE	-33°55′12″ 18°35′34″	4.98
BS 7	Wi-Fi	-33°54′32″ 18°36′56″	4.17	BS 22	5 MHz LTE	-33°55′39″ 18°34′14″	6.25
BS 8	15 MHz LTE	-33°54′17″ 18°38′47″	5.72	BS 23	10 MHz LTE	-33°55′42″ 18°32′12″	8.02
BS 9	10 MHz LTE	-33°55′36″ 18°37′1″	6.05	BS 24	10 MHz LTE	-33°56′8″ 18°35′42″	6.70
BS 10	Wi-Fi	-33°56′2″ 18°37′49″	7.26	BS 25	15 MHz LTE	-33°56′33″ 18°33′41″	8.11
BS 11	20 MHz LTE	-33°56′28″ 18°37′54″	8.04	BS 26	Wi-Fi	-33°56′49″ 18°32′10″	9.68
BS 12	3 MHz LTE	-33°51′30″ 18°33′24″	4.06	BS 27	Wi-Fi	-33°57′12″ 18°36′49″	8.84
BS 13	20 MHz LTE	-33°51′4″ 18°32′14″	6.02	BS 28	5 MHz LTE	-33°52′45″ 18°32′58″	4.28
BS 14	1.4 MHz LTE	-33°52′34″ 18°34′0″	2.67	BS 29	Wi-Fi	-33°57′11″ 18°34′59″	8.73
BS 15	20 MHz LTE	-33°52′50″ 18°31′52″	5.98	BS 30	10 MHz LTE	-33°55′18″ 18°38′21″	6.54

TABLE 4.3: Transmission ranges of the networks on spectrums

Network system	Transmission radius (Km)			
	S1	S2	S3	S4
Wi-Fi	1.08	-	1.07	1.06
20 MHz LTE	1.38	-	1.36	1.35
15 MHz LTE	1.44	1.43	1.42	1.41
10 MHz LTE	1.82	1.81	1.80	1.78
5 MHz LTE	2.68	2.67	2.65	2.63
3 MHz LTE	3.15	3.13	3.11	3.08
1.4 MHz LTE	3.71	3.69	3.67	3.65
UMTS	2.88	2.86	2.85	2.82

buyers and their TR on the spectrum included in their bid profiles. This new strategy is called the Interference Graph-Complement (IG-C) strategy. It always derives the minimum number of non-interference buyer groups.

Since the non-interference buyer grouping strategy can generates more than one solution of non-interference buyer groups, and in addition, GAs do not always give the optimal solution but a solution that is close enough to the optimal one [108], the best way to get results of highest quality is to run the allocation algorithm a number of times and

average the results. Therefore, the spectrum allocation simulation was run 1000 times. Figures 4.7 to 4.10 show graphs of the number of assigned users, spectrum allocation efficiency, spectrum re-usability and assignment cost of each spectrum auctioned in the 1000 runs. The corresponding graphs of averages are shown from Figure 4.11 to Figure 4.14. The spectrum efficiency is defined as the percentage of the leased white space spectrum segment with respect to the initial available white space spectrum block, and the spectrum re-usability is defined as the ratio of winning profiles to the number of sold spectrum segments for each white space spectrum block auctioned. As can be seen from Figures 4.7 to 4.10, the results repeat themselves after a few runs and that trend is consistent throughout the 1000 runs. This shows that with only a few runs, the allocation algorithm can generate optimal average results.
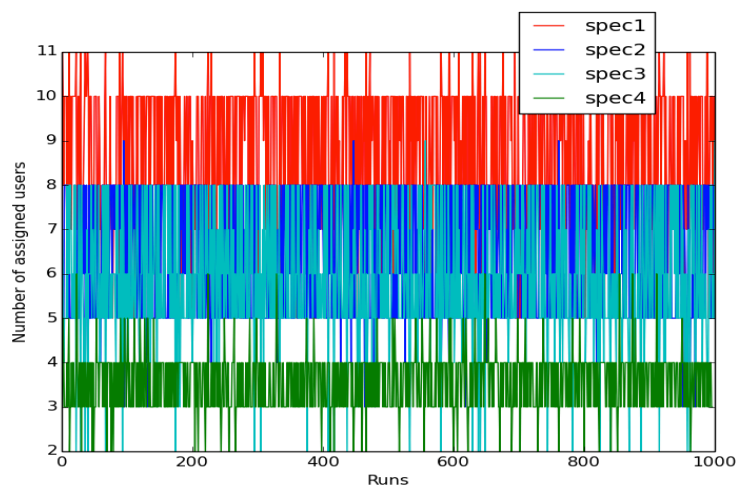
FIGURE 4.7: Number of assigned users' trend in 1000 runs
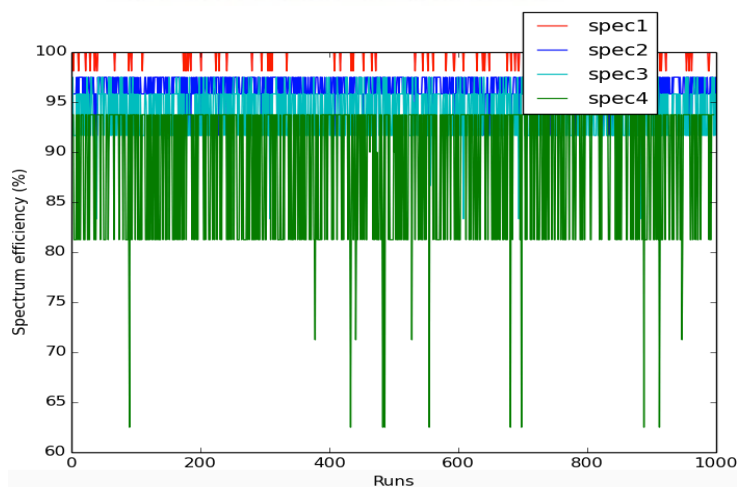
FIGURE 4.8: Spectrum allocation efficiency trend in 1000 runs

Table 4.4 shows the first non-interference bidder groups created on each spectrum by the IG-C algorithm. Note that bidder $BS26$ is not included in any of the non-interference
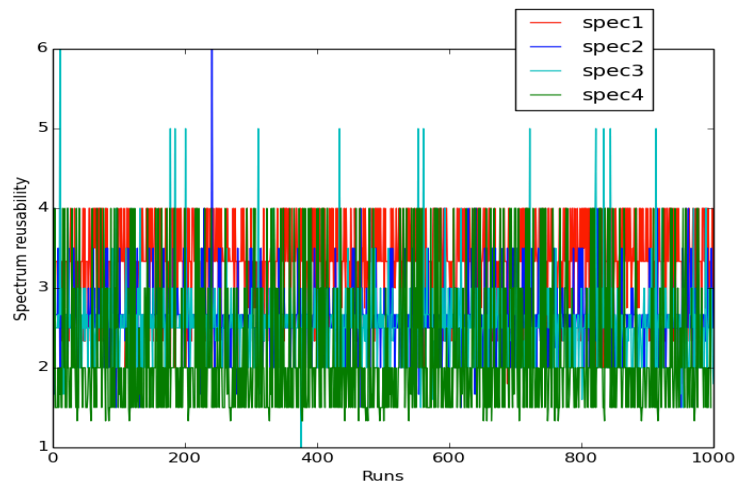
FIGURE 4.9: Spectrum reusability trend in 1000 runs
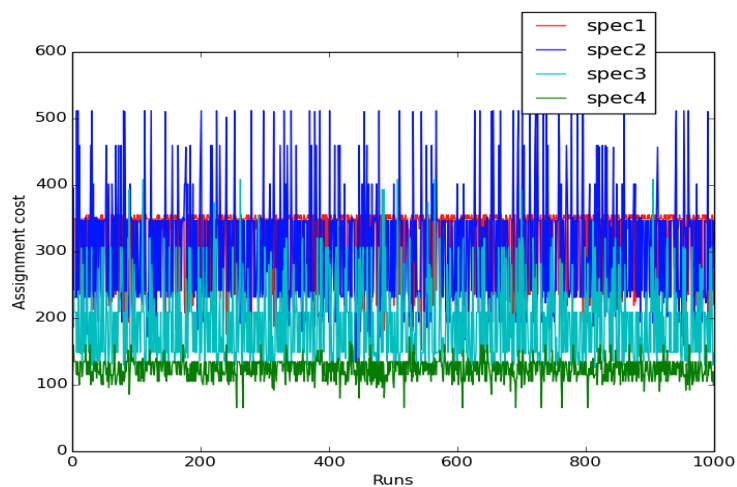
FIGURE 4.10: Assignment cost trend in 1000 runs
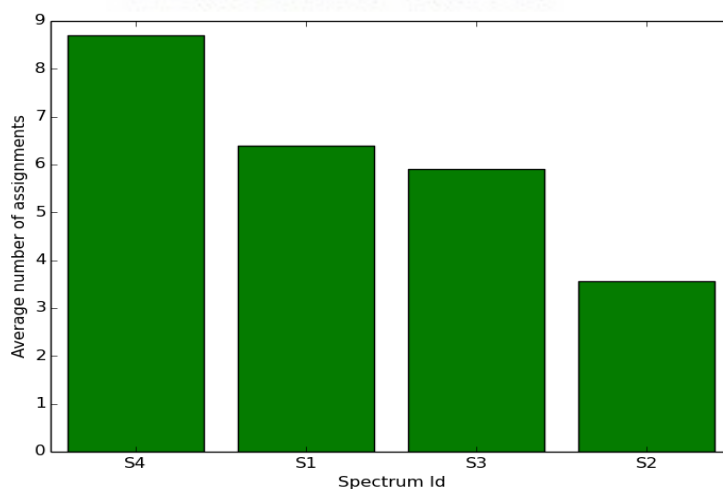
FIGURE 4.11: Average number of assigned users

buyer groups for any of the spectra because this buyer was deleted during the pre-candidate selection stage, as its coverage area is not entirely within the allowed transmission coverage of each white space spectrum. Table 4.5 shows the winning non-interfering
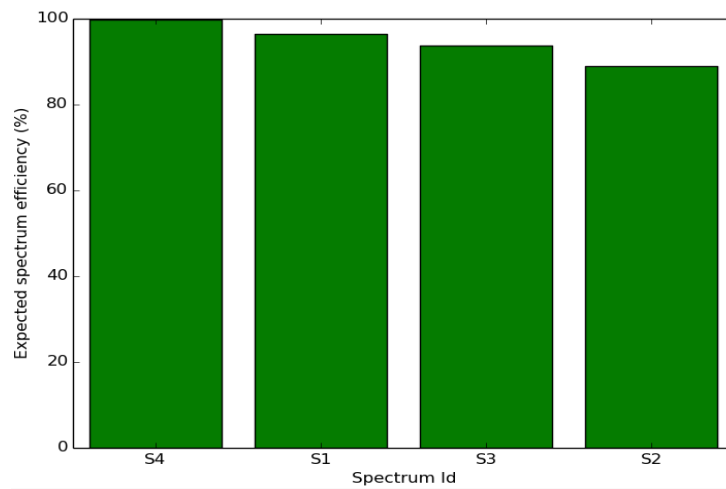
FIGURE 4.12: Expected spectrum allocation efficiency
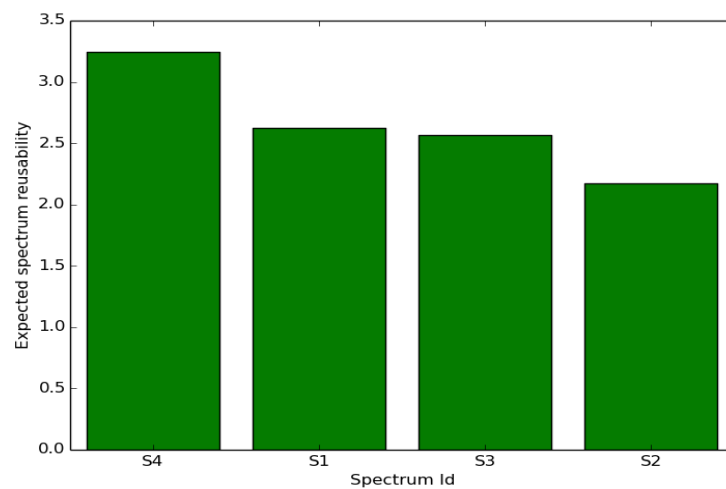
FIGURE 4.13: Expected spectrum reusability
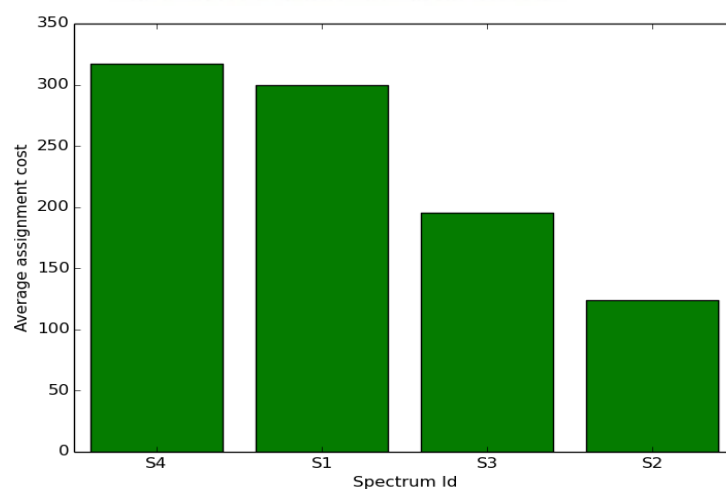
FIGURE 4.14: Average assignment cost

group members on each spectrum. Results from both Table 4.4 and Table 4.5 are taken from the same single run extracted from the 1000 runs. The allocation output reports

TABLE 4.4: First non-interference bidder groups created on each spectrum

Spectrum	Non-interference bidder groups
S4	[BS 21, BS 28, BS 23, BS 8, BS 27], [BS 3, BS 11, BS 19, BS 25, BS 15, BS 13], [BS 2, BS 10, BS 29], [BS 18, BS 30], [BS 4, BS 12], [BS 6, BS 20], [BS 17, BS 9], [BS 14, BS 7, BS 24], [BS 1, BS 22], [BS 5, BS 16]
S1	[BS 3, BS 25, BS 19, BS 15, BS 13, BS 27], [BS 6, BS 20, BS 12], [BS 4, BS 11, BS 23, BS 8], [BS 21, BS 28], [BS 17, BS 9], [BS 14, BS 7, BS 24], [BS 1, BS 22], [BS 5, BS 16]
S3	[BS 14, BS 24, BS 7], [BS 3, BS 25, BS 19, BS 13, BS 15, BS 27], [BS 17, BS 9], [BS 21, BS 28], [BS 1, BS 22], [BS 12, BS 20, BS 6]
S2	[BS 24, BS 1], [BS 25], [BS 22]

TABLE 4.5: Winning non-interference group members

Spectrum	Winning non-interference group members
S4	[BS 2, BS 10, BS 29], [BS 18, BS 30]
S1	[BS 4, BS 11, BS 23, BS 8], [BS 5, BS 16]
S3	[BS 14], [BS 3], [BS 17, BS 9], [BS 21, BS 28], [BS 12, BS 20, BS 6]
S2	[BS 24, BS 1], [BS 22]

on each of the 4 spectra collected from the same single run, use the results of Table 4.4 and Table 4.5 and are shown in Figures 4.6 to 4.9.

TABLE 4.6: Assignment results on spectrum segment S4

Assignment report on spectrum 4				
Assigned_Node	Segment_Assigned (MHz)	Start_Freq (MHz)	Centre_Freq (MHz)	Assignment_Price (willingness to pay)
BS 10	22.0	566.0	577.0	88.0
BS 30	10.0	588.0	593.0	30.0
BS 2	1.4	566.0	566.7	5.6
BS 29	22.0	566.0	577.0	88.0
BS 18	3.0	588.0	589.5	9.0

TABLE 4.7: Assignment results on spectrum segment S1

Assignment report on spectrum 1				
Assigned_Node	Segment_Assigned (MHz)	Start_Freq (MHz)	Centre_Freq (MHz)	Assignment_Price (willingness to pay)
BS 11	20.0	494.0	504.0	100.0
BS 16	3.0	514.0	515.5	18.0
BS 23	10.0	494.0	499.0	50.0
BS 5	1.4	514.0	514.7	8.4
BS 4	5.0	494.0	496.5	25.0
BS 8	15.0	494.0	501.5	75.0

Table 4.10 and 4.11 show the averages of the auction results for the 1000 runs. Table 4.11 shows the average number of sold spectrum segments, the average number of winning buyers, the broker's payoff, which expresses the total willingness of the buyers to pay for each spectrum, and the remaining unallocated spectrum segments. Table 4.11 is derived from Table 4.10, which shows the expected spectrum allocation efficiency and the expected spectrum re-usability.

TABLE 4.8: Assignment results on spectrum segment S3

Assignment report on spectrum 3				
Assigned_Node	Segment_Assigned (MHz)	Start_Freq (MHz)	Centre_Freq (MHz)	Assignment_Price (willingness to pay)
BS 12	3.0	549.0	550.5	12.0
BS 20	5.0	549.0	551.5	20.0
BS 21	3.0	544.0	545.5	12.0
BS 17	5.0	534.0	536.5	20.0
BS 28	5.0	544.0	546.5	20.0
BS 3	1.4	555.4	556.1	5.6
BS 6	3.0	549.0	550.5	12.0
BS 9	10.0	534.0	539.0	40.0
BS 14	1.4	554.0	554.7	7.0

TABLE 4.9: Assignment results on spectrum segment S2

Assignment report on spectrum 2				
Assigned_Node	Segment_Assigned (MHz)	Start_Freq (MHz)	Centre_Freq (MHz)	Assignment_Price (willingness to pay)
BS 24	10.0	518.0	523.0	50.0
BS 1	5.0	518.0	520.5	25.0
BS 22	5.0	528.0	530.5	25.0

4.6.2 Discussion of results

As can be seen from Figure 4.12 and Table 4.11, this new auction mechanism design achieves very high spectrum allocation efficiency, which is one of the most important elements that needs to be achieved in any secondary spectrum market mechanism, as has already been discussed in the previous sections. From the table, the lowest achieved spectrum efficiency is 89.0%, on spectrum $S2$. Its remaining unsold spectrum segment (1.8 MHz from Table 4.10) shows that it could not be allocated to any of the non-winning buyers. The simulation results show that 6 buyers did not win, and they are in the following categories: 3 Wi-Fi network nodes (BS 7, BS 19, BS 27), 2 LTE network nodes with 20 MHz channel bandwidth (BS 13, BS 15), and 1 LTE network node with 15 MHz channel bandwidth (BS 25). Note that none of the other remaining unsold spectrum segments on Table 4.10 from the other spectra could be allocated to any of the non-winning buyers. In other ways, each spectrum auctioned achieved its maximum allocation limit, which is a unique feature for this proposal, i.e., this auction mechanism proposal achieves maximum spectrum allocation efficiency as a result of mimicking the process employed in GA at each recursive step, to shape the non-winning non-interfering

TABLE 4.10: Average auction results for 1000 runs

Spectrum	No. of segments sold	Average no. of assignments	Broker's payoff	Unused spectrum (MHz)
S4	2.7	8.7	317.23	0.1
S1	2.5	6.4	300.03	0.9
S3	2.3	5.9	195.47	1.5
S2	1.6	3.6	123.64	1.8

TABLE 4.11: Expected spectrum efficiency and expected spectrum reusability

Spectrum	Expected spectrum efficiency (%)	Expected spectrum reusability
S4	99.9	3.2
S1	96.4	2.6
S3	93.8	2.6
S2	89.0	2.2

bidder groups through the survival of their members that can be served by the remaining white space spectrum segment.

From Figure 4.13 and Table 4.11, the spectrum re-usability on every spectrum auctioned is more than 2, which means that, on average, every spectrum segment sold, it was won by a winning non-interfering buyer group with more than 2 members who will consequently share the spectrum segment for broadcasting. It is important to mention that the spectrum re-usability depends on the group sizes of winning non-interfering buyer groups. If winning non-interfering buyer groups of a spectrum contain many members, the spectrum's re-usability is expected to be high, and the converse is true when winning non-interfering bidder groups contains few members. For example, on Table 4.11, the spectrum with the least spectrum re-usability is $S4$ with a spectrum re-usability of 2.2, which means that some of its winning non-interfering buyer groups contained few members, resulting in the smallest ratio of its winning profiles to the number of its sold spectrum segments (both values from Table 4.10).

Another key feature achieved by this new auction mechanism is that it maximises the payoff generated by the broker on each spectrum auctioned. Discussion on spectrum allocation efficiency in the first paragraph shows that the remaining unused spectrum segments on all the spectra could not be allocated to any of the non-winning nodes. This shows that the broker could not generate any more payoff on each spectrum, i.e., the payoff generated on each spectrum was maximised. Figure 4.14 and Table 4.10 show the broker's payoff generated on each spectrum.

4.7 Chapter summary

In this chapter, an auction mechanism design was designed that meets specific requirements for a secondary spectrum market auction in addition to meeting the economic properties of a general auction mechanism for selling merchandise. Specific requirements for a secondary spectrum market auction were analysed first to ensure completeness of the proposal. In order to allocate spectrum efficiently, the auction mechanism proposal first reduces the spectrum allocation problem to a 0-1 KP and then mimics the process employed in the GA at each recursive step to shape the non-winning non-interfering

buyer groups through the survival of their members that can be served by the remaining spectrum segment. In order to utilize spectrum efficiently, which is one of the key elements that a secondary spectrum market auction should address, a non-interfering buyer grouping strategy called Interference Graph-Complement was designed, which derives the non-interfering buyer groups from the complement of the interference graph and helps to achieve maximum spectrum utilization. This proposal was simulated and evaluated on arbitrary heterogeneous buyer networks and the results show that it achieves high spectrum utilization, high spectrum efficiency and generates high returns to the spectrum sellers.

The next chapter discusses network design in the white space spectrum.

Chapter 5

White space-aware network design

5.1 Introduction

The multi-hop wireless mesh networks in Wi-Fi frequencies induce prohibitive costs for network carriers to deploy ubiquitous Wi-Fi, as revealed by many in-field trials [67]. White space frequencies provide a better option for deployment of multi-hop wireless mesh networks, since white space frequencies have far greater transmission range and penetration properties than Wi-Fi frequencies. However, if deployed in an uncontrolled manner, white space allocation can suffer the same competition for frequency usage as the ISM band, where Wi-Fi users are competing in a crowded spectrum with other Wi-Fi users and with other devices emerging from the Internet-of-Things (IoT) and other new niche areas. While cognitive radio technology has been proposed as the technology to enable efficient white space spectrum sharing and thus mitigate the scarcity of radio frequency spectra, accurate identification of potential white space links and efficient network design are two important parameters upon which efficient white space network engineering needs to rely in order to deliver relevant services. Without doubt, network design in white space frequencies will require network topology control because of better signal propagation and penetration properties of white space frequencies. Generally, there are three main network topology control mechanisms; power control, power mode control, and hierarchical. However, an alternative approach has emerged based on centrality measure borrowed from social network analysis [110]. Centrality measure is used to identify the most important actors/vertices in a network [111]. With this in mind, the work in this chapter uses centrality measure to identify the most important mesh network nodes that can be included in both reduced network topology and hierarchical

89

backbone network topology, based on three centrality measure metrics during the network design phase. The relevance of this work is to guide the network engineer during a network feasibility study done in white space frequencies in order to select the most relevant performance metrics to choose for the actual implementation process.

The rest of the chapter is structured as follows: Section 5.2 discusses the design challenges most likely to be met when designing mesh networks in white space frequencies; Section 5.3 introduces relevant white space parameters as they need to be taken into consideration when designing communication networks in white space frequencies; Section 5.4 introduces topology reduction and discusses the approaches used to achieve it; Section 5.5 provides a background to the concept of centrality measure, which is borrowed from social network analysis and is currently being used in the topology reduction process; Section 5.6 reviews come current works that have used the concept of centrality measure in topology reduction; Section 5.7 discusses the network optimization function that has been formulated and used to create a hierarchical backbone network topology from the sparse network topology; Section 5.8 discusses the sparse network topology design and the link-based topology reduction algorithm developed for reducing a dense mesh network topology into a sparse mesh network topology; Section 5.9 discusses the hierarchical backbone network topology design and the backbone network topology algorithm used to introduce hierarchical backbone network topology in the sparse network topology, Section 5.10 is a performance evaluation section of the designs formulated in this chapter and Section 5.11 summarises the chapter.

5.2   White space mesh network design challenges

Designing communication networks such as mesh networks using opportunistic access to the white space spectrum comes with particular challenges that have never been met before by network planners and designers. The temporal and spatial variations of the white space spectrum is one of the challenges that makes the planning and designing of communication networks in white space frequencies a difficult task. Due to the temporal and spatial variations of the white space spectrum, it is difficult to find a common control channel that nodes can use to exchange necessary control information. Zhao *et al.*, in [112] found that it is easier to find a common control channel for neighbouring nodes than to find the network-wide availability of a common vacant channel. Cognitive radio technology is expected to eliminate this challenge as it has the ability to sense the spectrum widely and re-configure itself to transmit in targeted parts of the spectrum [113].

Another challenge that makes the planning and designing of communication networks in white space frequencies difficult is the dense network topology revealed by design simulations of wireless communication networks in white space frequencies. This is shown in Figure 5.1 and Figure 5.2. Figure 5.1 shows a public safety mesh network design connecting police stations in Cape Town, South Africa and Figure 5.2 is a public safety mesh network design in Lubumbashi, Democratic Republic of Congo (DRC), connecting most popular locations of the city, which are considered to have a high potential of becoming hot spots for public safety data collection. Both networks have been simulated in white space frequencies using the Radio Mobile network planning tool [109]. The dense network topology entails many nodes being in communication range of each other, which may result in too many network packet collisions in the network. This is a complex operation for the MAC protocol and presents too many paths to choose from for a routing protocol [114, 115]. Therefore, the network topology design problem consists of making the network topology less complex or sparse.

Designing communication networks using opportunistic access is also affected by white space parameters existing at a location, such as quantity, quality, usefulness when compared with the unlicensed 2.4 GHz and 5 GHz frequencies, and diversity. These parameters vary at each white space location, based on the white spaces available. Consequently, identifying these parameters at each white space location is important when designing communication networks in white space frequencies, as they affect the overall communication network performance. The next section discusses these relevant parameters broadly.
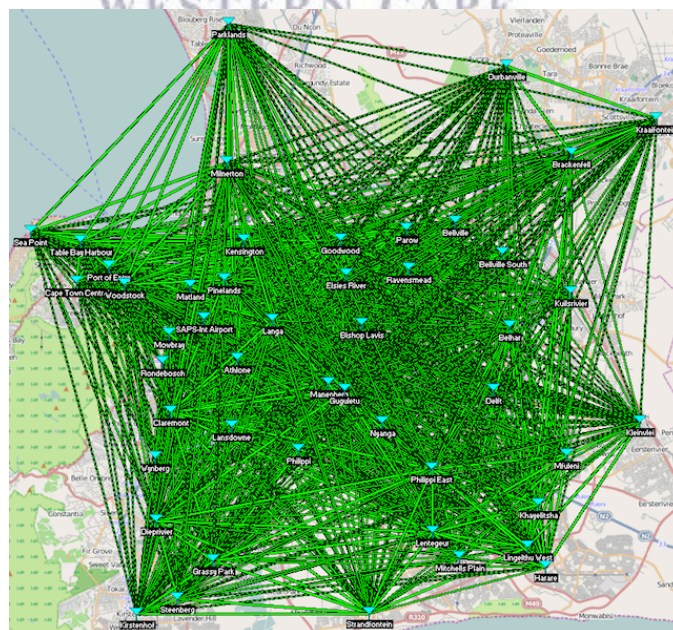
FIGURE 5.1: Cape Town public safety mesh network design in white spaces
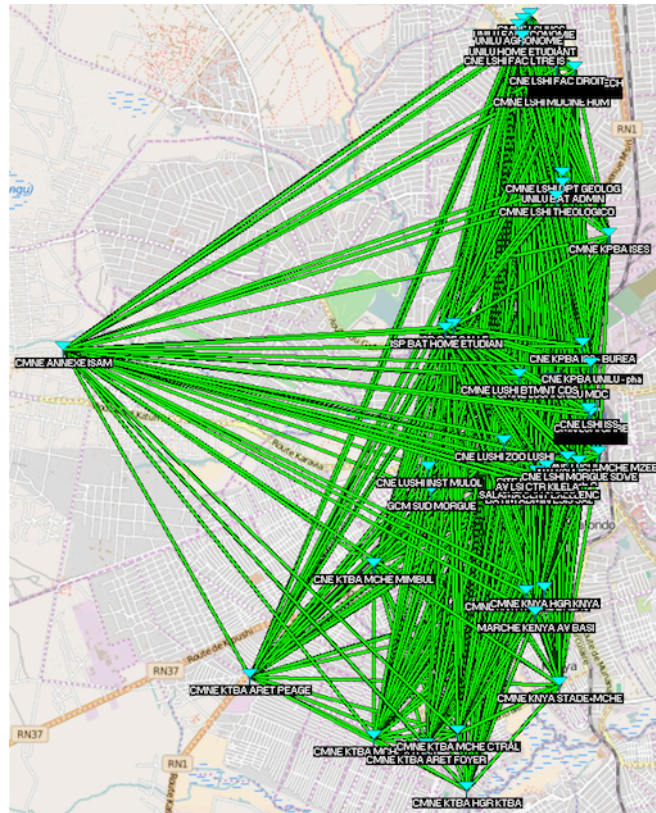
FIGURE 5.2: Lubumbashi public safety mesh network design in white spaces

5.3 Relevant white space parameters

This section discusses the relevant white space parameters mentioned in the last paragraph of the previous section.

5.3.1 Quantity

The amount of white space available at a particular location will determine its relevance. It is expected that the more white spaces there are available at a particular location, the more relevant they are going to be to a WSD and the converse will be true if the available white spaces are limited.

The quantity of white space spectrum available is directly related to the signal detection threshold. The measured or calculated signal value (in the case of the geo-location database approach) of the primary transmitter signal strength must be below the chosen signal detection threshold value to declare a white space. Higher or relaxed signal detection threshold values yield more white spaces while lower or conservative signal detection threshold values yield fewer. From the studies that have been done so far in different parts of the world, when the signal detection threshold requirements, as

mandated by the FCC, are used, the number of TVWSs found is low. Other studies have even found no TVWSs when a sensing sensitivity threshold of -114 dBm is used[54, 57].

Lopez-Benitez *et al.* [101] reports that a small change in threshold value, as little as 5 dBm or less, can change the spectrum occupancy observed from 100% to 0%. Through careful measurements, McHenry *et al.* in [116] were able to determine detection thresholds that provided few missed detections with false alarm rates in the 20% to 60% range. These observations show how critical the value chosen as a signal detection threshold is, in determining how much white space is detectable.

5.3.2 Quality

The value and relevance of TVWSs will also be affected by their quality, defined here as how contiguous or sparse they are. Measurements at either channel or band level result in white spaces of successive variable size blocks alternating between white space and primary user spectrum [26]. Contiguous white space spectrum is expected to be much more relevant to WSDs than white space spectrum that is fragmented. This is so because the use of a particular frequency spectrum by wireless devices is affected by how contiguous or fragmented it is [26] and also currently widespread technologies, such as Wi-Fi and WiMAX, which could theoretically be directly applicable for white space networking, through adjustment in their radio frequency front-end, in order to work in the TV RF frequency bands, require a considerable amount of contiguous spectrum [117]. For example, an IEEE 802.11g network, which utilises a channel bandwidth of 20 MHz, will require three consecutive 8 MHz white space channels to operate. Consequently, it can only utilise consecutive white space channels from 64 to 66, and not white space channel 68, for secondary usage in Figure 5.3. It is important to mention that there are emerging technologies capable of exploiting fragmented spectrum as a whole using carrier aggregation technology [118–120].

5.3.3 Usefulness

Another relevant white space parameter is its usefulness at a particular location. Wi-Fi devices operate in the ISM band where other devices, such as Bluetooth devices, Zigbee, microwave ovens, cordless phones, wireless cameras, and many more also operate. As a result, the band is congested in most locations [26, 117] making it more and more unsuitable for Wi-Fi connection due to interference from these other devices. It is expected that places where the 2.4 GHz and 5 GHz frequencies are congested, TVWSs will be more relevant than at places where the ISM bands are lightly used. There is no question that Wi-Fi solutions work, and without a doubt, the 2.4 GHz band
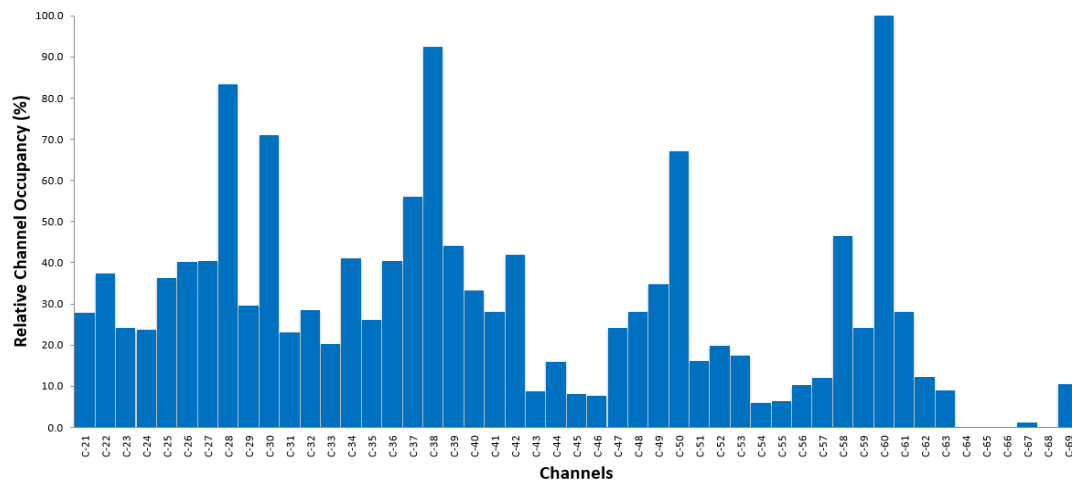
FIGURE 5.3: Useful channels for the 802.11g network

has contributed to their success [121]. Therefore, places where the 2.4 GHz and/or 5GHz frequencies are lightly used, there will be less competition for the white spaces because Wi-Fi and other wireless devises will still find it convenient to use the 2.4 GHz frequencies, as they are unlicensed and free.

5.3.4   Diversity of TVWS

The availability of TVWSs with these relevant characteristics of quantity, quality, contiguousness will correspondingly attract TVWS demands from diverse players with different power requirements and network channel-bandwidths. Consequently, diverse TVWS spectrum will be more valuable than white space spectrum that is homogeneous as it will serve diverse white space spectrum users. Availability of many white space providers at a particular white space location is expected to result in diverse white space spectrum availability with varying degrees of quantity and quality at that location. This variety would serve white spectrum users with different power and network channel-bandwidths requirements.

The next section provides a background to topology reduction and discusses the approaches used to achieve it.

5.4   Topology reduction and approaches

The objectives of topology control techniques are two-fold: to improve the energy efficiency and battery lifetime of networks and to reduce packet collisions, protocol overhead, and interference, by means of a better control over the network connections and

redundancy, without affecting important network performance, such as connectivity and throughput. In general, these objectives can be achieved through three main mechanisms: power control technique, power mode mechanism and hierarchical formation technique.

In the power control technique, the communication range of wireless nodes is controlled by modifying the transmission power parameter of the nodes in the network. This method enables the network nodes to improve the management of their neighbourhood size, interference level, power consumption and connectivity [122]. In power mode mechanism, the node activity is controlled by switching between active and sleep operation modes to dispense with redundant nodes and still achieve the desired connectivity [110]. The main idea of the algorithms using these first two mechanisms is to produce a connected topology by connecting each node with the smallest necessary set of neighbours, and with the minimum transmission power possible [123]. These first two techniques are the main options for flat networks where all nodes have essentially the same role [114, 124], i.e., a homogeneous infrastructure.

Controlling the transmission power of the nodes or their activities, only reduces the network topology to help save energy but the approach does not prevent the transmission of redundant information when several nodes are close to each other, and may not simplify the network topology enough for scalability [123]. The hierarchical formation technique addresses the scalability problem. In the hierarchical formation technique, a reduced subset of the nodes in a network is selected and given more responsibilities on behalf of a simplified and reduced functionality for the majority of the nodes [123]. This approach greatly simplifies the network topology and saves additional energy by assigning useful functions, such as information aggregation and filtering, and routing and message forwarding, to the reduced subset of the nodes [123]. A hierarchical topology can be constructed by using either a backbone network or a cluster-based network. The main goal of the backbone-based techniques is to find a connected subset of nodes in a network that guarantees connectivity by allowing every other node in the network to reach at least one node on the backbone in a direct way [123]. A communication backbone can be created by selecting nodes that form a connected dominating set (CDS). From graph theory, a CDS of a graph is a connected subset in which all other nodes that do not belong to that subset have at least one adjacent neighbour inside the subset. Advantages of this CDS-based topology control are collisions control, protocol overhead control and energy consumption reduction, efficient network organization and scalability improvement [110].

The synergy that exists between social network analysis and ad-hoc networking has been

utilised by researches to design more efficient network routing protocols [125] by borrowing some concepts used there and applying them in computer networks. Specifically, they have used the concept of centrality measure from social network analysis to identify the most important nodes in a network during the topology process control. In the same way, this work uses the concept of centrality measure to identify the most important mesh network nodes that can be included in both sparse network topology and hierarchical backbone network topology, based on the three centrality measure metrics during the network design phase.

5.5   Background on the centrality measure

Social network analysts have developed centrality as one of the most useful mathematical measures to capture the structural properties of social relationships [110]. A centrality measure helps to identify the most important actors within a graph that represents any physical network [111]. The measure is based mainly on the degrees of the vertices or on the geodesic distances between them [125]. By definition, the geodesic path between any two nodes is the path with the shortest distance. A discussion of the three important centrality measure metrics; degree centrality, closeness centrality and betweenness centrality, follows.

Degree centrality is defined as the number of edges (links) attached to a vertex (node) [126]. In a wireless mesh network (WMN) the degree centrality of a mesh station is viewed as the number of one-hop neighbours with which it has a communication link. The magnitude of degree centrality is partly a function of the size of the network on which it is calculated [126] and in order to be a measure independent of the network size, the degree centrality is scaled by the number of nodes in the network [110]. Therefore, the degree centrality Dc_i of a node i in a network graph with N number of nodes is computed as follows [126]:

$$Dc_i = \frac{\sum\limits_{j=1}^{N} x_{ij}}{N-1} \tag{5.1}$$

where $x_{ij} = 1$ if there is a link between node i and node j and $x_{ij} = 0$ otherwise.

Dc_i is large if node i has many one-hop neighbours with which it has communication links and small if node i has few one-hop neighbours with which it has communication links. $Dc_i = 0$ for a node that has no one-hop neighbour with which it has a communication link.

Closeness centrality identifies nodes that spread messages in a shorter time than others do [126]. Actors with high closeness centrality can communicate their ideas faster than

actors with lower closeness centrality in social network analysis [111]. The geodesic path is used to obtain the closeness centrality measure and the distance can be measured in terms of the number of hops and delays [125]. Therefore, for a connected graph, the closeness centrality Cc_i of a node i in a network graph with N number of nodes is computed as [127, 128]:

$$Cc_i = \frac{N-1}{\sum\limits_{j-1}^{N} d_{ij}} \tag{5.2}$$

where N is the number of nodes in the network, $i \neq j$ and d_{ij} is the geodesic distance between nodes i and j.

The equation is valid only for a connected graph. In an unconnected graph, every point is at an infinite distance from at least one other point [126] in terms of closeness centrality, i.e., $Cc_i = \infty$ for all j.

Betweenness centrality measures the frequency with which a node falls between pairs of other nodes on the geodesic paths connecting them [126]. It is a measure of the extent to which a node has control over communications, connections and information flows between other nodes. Consequently, nodes with high betweenness centrality dominate this control [110]. The betweenness centrality Bc_i of a node i in a network graph with N number of nodes is computed as [110, 126]:

$$Bc_i = \sum_{j=1}^{N} \sum_{k=1}^{j-1} \frac{g_{jk(i)}}{g_{jk}} \tag{5.3}$$

where $i \neq j \neq k$, g_{jk} is the total number of geodesic paths between node j and k, and $g_{jk}(i)$ is the number of geodesic paths between node j and k that pass through node i.

5.6   Some related work

Discussion of some recent work done on improving the performance of wireless ad-hoc networks using social network analysis concepts follows.

Cuzzocrea, *et al.* in [129] propose a topology control algorithm for WSNs based on edge betweenness centrality. The edge betweenness metric is used to identify the most relevant links between nodes with regard to energy consumption. The proposal aims at selecting a set of logical neighbours for each node that minimizes energy consumption and fulfills QoS requirements [110].

Stai, *et al.* in [130] and Verma, *et al.* in [131] apply the small world property to reduce the average path length of a network. The basic idea of their proposals is to modify the physical topology of the network based on the social features of the underlying graph [110]. The small world property is achieved either by aggregation of long-ranged links [131] or by a combination of rewiring, deletion and/or addition of links [130].

Kas, *et al.* [132], apply social network analysis metrics to detect critical nodes in a WMN. The authors show the importance of network nodes with the highest centrality measure by simulating how network reliability substantially degrades when the network nodes are attacked. The simulations show that nodes with high betweenness centrality exhibit a greater impact on a network than nodes with a high degree of closeness centrality.

SimBet [133], a routing protocol designed for delay-tolerant Mobile Ad-Hoc Networks (MANETs), uses two social network analysis metrics; centrality measure and similarity measure for message forwarding decisions. The betweenness metric that determines the centrality measure is used to identify more suitable bridge nodes, and the similarity measure is used to find nodes that are closest to the destination neighbourhood [110]. The authors use a utility function that not only combines the centrality and similarity utilities but also allows to adjust the relative importance of each in relation to the other.

While algorithms based on power control, power mode mechanism control, hierarchical formation mechanism and those based on centrality metrics are designed for application in physical networks, the designs proposed in this study are for pre-designing a topology off-line before it is replicated in reality. These designs have been developed to guide network engineers, during network feasibility studies performed in white space frequencies, in selecting the most relevant performance metrics to adopt in the actual implementation process. Characteristics of the terrain, the radio spectrum, and other variables, that may affect the actual communication between nodes, once the network is deployed, have been taken into account in the designs. A topology reduction algorithm has been developed for use in the design of flat networks where all nodes have essentially the same role, and a utility function has also been developed that can be applied to the reduced network design to generate a hierarchical backbone topology design using the combination of the three metrics that determine the centrality measure. The next section discusses these designs.

5.7 Network optimization function

The network design consists of finding a network configuration expressed by the graph $\mathcal{G} = (\mathcal{N}, \mathcal{L})$ where $\mathcal{N}$ is the set of nodes while $\mathcal{L}$ is the set of links connecting the nodes

with the objective of optimizing an objective function representing a penalty to be minimized or a profit/reward to be gained. In this work, two profit/reward functions are considered and their combination, as a third metric, is also considered, to guide the design process. These include i) a traditional network engineering profit function $P_t(\mathcal{G})$ combining reliability and QoS features, which are based on three centrality metric measures; node degree, link margin that determines the connectedness centrality and the Euclidean distance determining the closeness centrality ii) a white space-aware network engineering function $P_w(\mathcal{G})$ that combines the quality, quantity, diversity and usefulness of white spaces found on node locations, to form a reward metric and iii) a combination of both $P_t(\mathcal{G})$ and $P_w(\mathcal{G})$ as a mixed metric that caters for both the network engineering efficiency and the white space awareness.

5.7.1 Traditional network engineering design

This model uses a profit function $P_t(\mathcal{G})$ expressed as follows:

$$P_t(\mathcal{G}) = \sum_{i \in \mathcal{N}} P_t(i) \tag{5.4}$$

$$P_t(i) = \alpha * Dc_i + \beta * Ccn_i + \gamma * Cc_i \tag{5.5}$$

where, α, β and γ are coefficients of proportionality used to express the preference for a given centrality metric measure. A high value of one of the coefficients reveals a preference for the corresponding centrality metric measure, e.g., assigning a high value to α expresses a preference for the node degree centrality measure in the design process. The profit $P(i)$ expresses the resultant centrality measure of node $i \epsilon \mathcal{N}$ to be part of a backbone. The profit function depends on a weighted combination of different routing metrics. These may include traditionally used network engineering metrics and white space-aware metrics. Three of the traditional network engineering metrics are explained below.

1. **Node degree:** The node i of degree centrality Dc_i is considered as a metric that determines the centrality measure of a node to be part of a backbone or not, and preference is given to nodes with higher node degree centrality over nodes with lower node degree centrality. Nodes with higher node degree centrality lead to reduced network topology for the backbone network, which is preferred. The equation for computing the degree centrality is given in Section 5.5.

2. **Link margin:** Links with high link margins are better for communication than links with low link margins. Furthermore, nodes whose corresponding links have small differences in link margins are better for communication than nodes whose

corresponding links have big differences in link margins. Therefore, to know which nodes are well connected, the link margin of each node is considered as the coefficient of variation corresponding to the link margins of all the links connected to the node. For a node i, the coefficient $lm(i)$ of variation is calculated as follows;

$$lm(i) = \frac{Avg_{lm}(i,x)}{Std_{lm}(i,x)} \ \forall \ x : (x) \subset \mathcal{L} \tag{5.6}$$

where, $Avg_{lm}(i,x)$ and $Std_{lm}(i,x)$ are the mean and the standard deviation of the link margins of the links connected to the underlying node, respectively. A high numerator makes a node better, and the denominator supports the idea that large differences in link margins of the links connected to node i make the node less efficient in communication. Using the coefficient of variation $lm(i)$ of a node i, a connectedness centrality Ccn_i of a node is defined as;

$$Ccn_i = \frac{lm(i)}{N-1} \tag{5.7}$$

where N is the number of nodes in the network graph.

Note that the connectedness centrality equation is directly related to the node degree centrality equation in Section 5.5. Nodes with a higher connectedness centrality measure are more likely to be part of the backbone than nodes with a lower connectedness centrality measure.

3. **Average shortest path:** This is the average distance from a node i to all other nodes using the Dijkstra's shortest path algorithm given by Equation 5.8 and denoted by $sp(i)$.

$$sp(i) = Avg_{sp}(i,x) \ \forall \ x : (i,x) \in \mathcal{L} \tag{5.8}$$

The link lengths are considered to be Euclidean distances separating the connected nodes. Nodes with lower average shortest paths are more likely to be part of a backbone than nodes with higher average shortest paths. Using the concept of geodesic path to obtain the closeness centrality measure as discussed in Section 5.5, the closeness centrality Cc_i for node i is computed as;

$$Cc_i = \frac{N-1}{sp(i)} \tag{5.9}$$

where N is the number of nodes in the network graph.

Note that this equation is an adaptation of Equation 5.2. Nodes with a higher closeness centrality measure are more likely to be included as part of the backbone network topology than nodes with a lower closeness centrality measure.

5.7.2   White space-aware network engineering design

The white space-aware design is based on the reward function $P_w(\mathcal{G})$ described by:

$$P_w(\mathcal{G}) = \sum_{i \in \mathcal{N}} P_w(i) \tag{5.10}$$

$$P_w(i) = \alpha_w * QTY_i + \beta_w * QLY_i + \gamma_w * DVY_i \tag{5.11}$$

where, α_w, β_w and γ_w are coefficients of proportionality used to express the preference for a given white space parameter.

White space engineering metrics are network engineering metrics that build on the availability of white spaces on nodes that form a link. They include the white space quantity, quality, diversity and usefulness metrics as explained below.

1. **White space quantity:** The white space quantity on node i, expressed by QTY_i is considered as a metric that determines the number of white space channels found at node i. Nodes with a higher white space quantity will lead to higher throughput during traffic engineering, than nodes with a lower white space quantity, which is preferred. The white space quantity is given by:

$$QTY_i = \sum_{k \in \mathcal{C}} Ch(k) \tag{5.12}$$

   where $\mathcal{C}$ is the set of white space channels in the UHF frequency band.

2. **White space quality:** The quality of the available white spaces on a location/node i depends on the contiguity of the white space channels at that location. A white space quality evaluation, where a score of 1 is assigned to each two consecutive white space channels, was considered. The white space quality is expressed as:

$$QLY_i = \sum_{k \in \mathcal{C}} B_{nd}(k) \tag{5.13}$$

   where $B_{nd}(k) \in \{1, 0\}$ is a boolean function set to 1 when channel k is contiguous with another channel and 0 otherwise. Note that the white space quality is related to the potential of channel bonding provided by a network design.

3. **White space diversity:** This is a measure of the diversity of providers that can be found at a location i. It is expressed by:

$$DVY_i = \sum_{k \in P_u} k \tag{5.14}$$

where P_u is the set of service providers (primary users) and $k \in \{1, 0\}$.

5.8 Sparse network topology design

The sparse network topology design consists of finding a network configuration that maximizes/minimizes a network optimization function (a reward to be maximized or a penalty to be minimized) subject to QoS constraints, expressed in terms of expected throughput by setting a link margin threshold, and reliability by setting a minimum requirement on the path multiplicity, to enable alternative path routing when an active path has failed. Mathematically formulated, this consists of finding a network configuration $\mathcal{C}_{opt}$ derived from the graph $\mathcal{G} = (\mathcal{N}, \mathcal{L})$ such that

$$\hat{\tau}_{opt}(\mathcal{C}_{opt}) = \max_{\mathcal{C}_n \in \mathcal{G}} \sum_{k \in \mathbb{N}[\mathcal{C}_n]} P(k) \tag{5.15}$$

Subject to

(5.15.1) $\tau_{lm}(x, y) > \tau_{lm} \quad \forall \quad x, y \in \mathcal{C}_{opt}$

(5.15.2) $k_{sp}(x, y) > \tau_{sp} \quad \forall \quad x, y \in \mathcal{C}_{opt}$

where $\mathbb{N}(X)$ is the set of nodes in the configuration X. Note that constraints 5.15.1 and 5.15.2 express the QoS in terms of link margin and reliability respectively.

5.8.1 Sparse network topology design algorithm

A Link-Based Topology Reduction (LTR) algorithm (Algorithm 7) is designed to reduce a dense mesh network topology into a sparse mesh network topology. The objectives of the algorithm are i) to improve the quality of the links by retaining the links of high margin and pruning those of low margin and ii) to maintain the reliability of a network at a predefined level. In order to design fault-tolerant networks, the algorithm uses the K-Shortest Path (K-SP) algorithm in [134] to compute k-shortest paths between source-destination pairs where $k > 1$. Links that provide k-disjoint shortest paths from each node to the network sinks are considered and included in a sparse network. The algorithm first marks all the links in a network as non-visited and loops over each one of them. During each iteration, the link with the lowest link margin is artificially deleted. After the link is artificially deleted, then the K-SP algorithm is run to check if the network is still k-connected. If the network is still k-connected, the link is removed permanently, i.e., the link will not be included in the sparse network topology. If the

---

Algorithm 7: LTR algorithm

---

1   mark all links in dense mesh network as non-visited;
2   **for** *each non-visited link of the network* **do**
3   select worst non-visited link of the network; `// i.e.  link with lowest link`
         `margin.`
4   artificially delete the link;
5   run the K-shortest path to detect if the network is still k-connected; `// it is`
         `k-connected if you can find k-disjoint shortest paths for each source-`
         `destination pair of the reduced network.`
6   **if** *it is k-connected* **then**
7   remove the link permanently;
8   **else**
9   leave the link and mark it as visited;
10 **end**

---

network is not k-connected after artificially removing the link, the link is left, and marked as visited.

5.9   Hierarchical backbone network topology design

The backbone design consists of finding a network configuration that maximizes the reward function subject to similar QoS constraints as those in the sparse network design, but with the objective of partitioning the network into two sets: a dominating set, which forms the backbone, and a dominated set, which forms the edge of the network. Mathematically formulated, the design process consists of finding a network configuration $\mathcal{C}_{opt}$ derived from the graph $\mathcal{G} = (\mathcal{N}, \mathcal{L})$ such that $\mathcal{N}$ is divided into a dominating set $\hat{\mathcal{N}}$ and a dominated set $\check{\mathcal{N}}$, and the design objective is achieved and its constraints are met.

$$\hat{\tau}_{opt}(\mathcal{C}_{opt}) = \max_{\mathcal{C}_n \in \mathcal{G}} \sum_{k \in \mathbb{N}[\mathcal{C}_n]} P(k) \tag{5.16}$$

Subject to

(5.16.1) $l_{mg}(x,y) > \tau_{lm} \ \forall \ x,y \in \mathcal{C}_{opt}$

(5.16.2) $k_{sp}(x,y) > \tau_{sp} \ \forall \ x,y \in \mathcal{C}_{opt}$

(5.16.3) $\forall n \in \mathcal{C}_{opt} : n \in \hat{\mathcal{N}} \lor \exists m \in \hat{\mathcal{N}} : (n,m) \in \mathcal{L}$

(5.16.4) $\mathcal{N} = \emptyset \land \hat{\mathcal{N}} \cap \check{\mathcal{N}} = \hat{\mathcal{N}} \cup \check{\mathcal{N}}$

where $\mathbb{N}(X)$ is the set of nodes in the configuration X. Note that constraints 5.16.1 and 5.16.2 express the QoS in terms of link margin and reliability respectively while constraints 5.16.3 and 5.16.4 represent the topology control model in terms of backbone connectivity based on the k-dominated set model [135–137].

5.9.1 Backbone network design algorithm

The algorithm for creating a hierarchical backbone network topology is provided by Algorithm 8. It uses a graph colouring approach, where the nodes of the network are initially assigned a white colour and thereafter changed to black or gray depending on whether they have qualified for backbone or edge status.

Algorithm 8: Backbone formation

---

1. Initialisation.
   Assign a white colour to all nodes of the network,
   Select a node n from $White$ whose profit/reward is highest,
   $Backbone \leftarrow \{n\}$,
   $Grey \leftarrow$ all neighbours of n,
   $White \leftarrow N \setminus (\{n\} \cup Grey)$.

2. Select a node k from $Grey$ whose profit/reward is highest,
   Include k into the $Backbone$,
   Assign a black color to k,
   Remove k and its neighbours from $White$,
   Include the neighbours of k in $Grey$.

3. Repeat Step 2 whenever $White \neq \emptyset$.

The algorithm returns a network configuration where the backbone nodes are coloured black and the edge nodes are coloured gray.
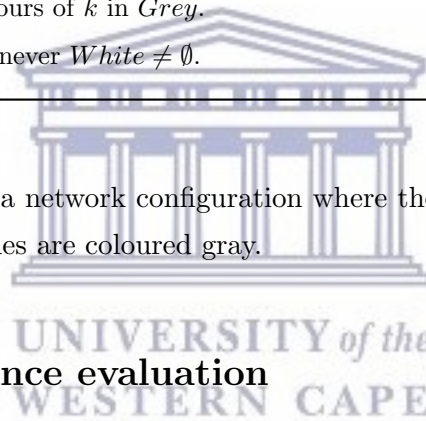
5.10 Performance evaluation

A range of experiments were conducted to evaluate the performance of these designs. The network engineering process in Figure 5.4 was followed to evaluate these designs, where the mesh network design process was initiated by the collection of the GPS coordinates of the node positions of the network. Building upon the elevation map of an area, the Radio Mobile network planning tool [109] was used to produce the feasible links of the targeted mesh network. Then Algorithm 7 for generating a sparse network topology design, was run on the network report produced by Radio Mobile network planning tool, to map the targeted dense mesh network into a sparse network. The final step of the network engineering process consisted of deriving a hierarchical backbone-based topology from the sparse network topology using Algorithm 8 for generating the backbone network.

The experiments for this study focused on using the discovered sparse network topology to evaluate the engineering efficiency achieved by considering three different routing metrics on the network topology 1) the link length in kilometres; 2) the hop count by setting the same weight on all links of the network and; 3) the link margin found on
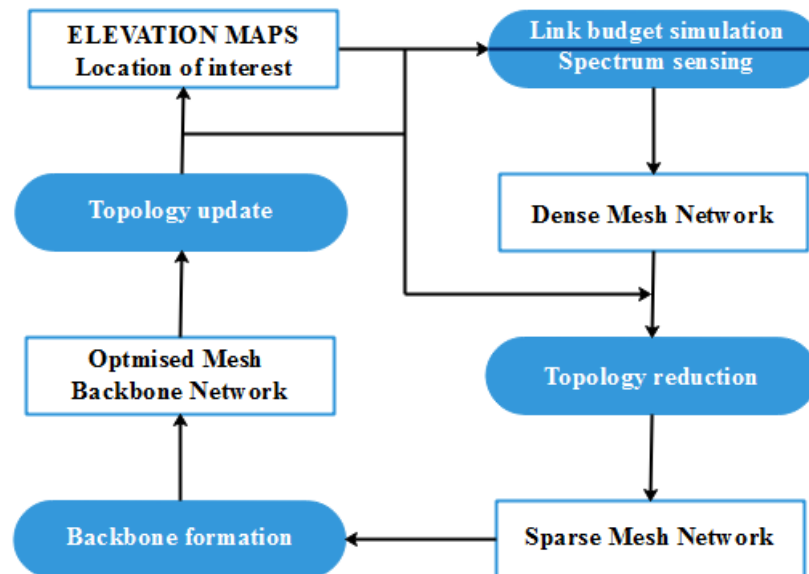
FIGURE 5.4: Network engineering process

each link. These experiments focused on evaluating 1) the impact of the hierarchical backbone-based topology compared to flat mesh network topology; 2) the impact of the centrality metrics on the backbone size; 3) the impact of white space parameters on the backbone size.

5.10.1 Flat network topology reduction

The public safety mesh network design connecting police stations in Cape Town, South Africa, depicted in Figure 5.1, was used in the performance evaluation. 42 police stations, shown in Table 5.1 were considered. Their GPS positions were provided in Chapter 3. A Python code implementation of the LTR Algorithm 7 was run on the network report produced by the Radio Mobile network planning tool, to map the dense mesh network in Figure 5.1, onto a sparse network topology. First, the GPS coordinates of each node in Table 5.1 were transformed into 2-dimensional Cartesian coordinates. These coordinates were used to compute the Euclidean distances separating the nodes, before running the LTR algorithm. During the reduction process, links which provided two disjoint shortest paths from each node to the network sink were considered and included in the sparse network topology. Node 0 (Bellville) was considered as the sink. The reduced network topology is shown in Figure 5.5 and Table 5.2 shows the links in the reduced network topology.

TABLE 5.1: Backbone network topology nodes and links

Node	Name	Node	Name	Node	Name	Node	Name
0	Bellville	1	Nyanga	2	SAPS-Int Airport	3	Bellville South
4	Philippi	5	Matland	6	Parow	7	Lansdowne
8	Rondebosch	9	Kuilsrivier	10	Wynberg	11	Sea Point
12	Bishop Lavis	13	Cape Town Central	14	Table Bay Harbour	15	Delft
16	Mowbray	17	Ravensmead	18	Goodwood	19	Elsiesrivier
20	Port of Entry	21	Kensington	22	Athlone	23	Woodstock
24	Pinelands	25	Belhar	26	Manenberg	27	Claremont
28	Guguletu	29	Durbanville	30	Brackenfell	31	Langa
32	Mitchells Plain	33	Khayelitsha	34	Mfuleni	35	Lingelthu West
36	Dieprivier	37	Kleinvlei	38	Harare	39	Grassy Park
40	Steenberg	41	Kirstenhof				
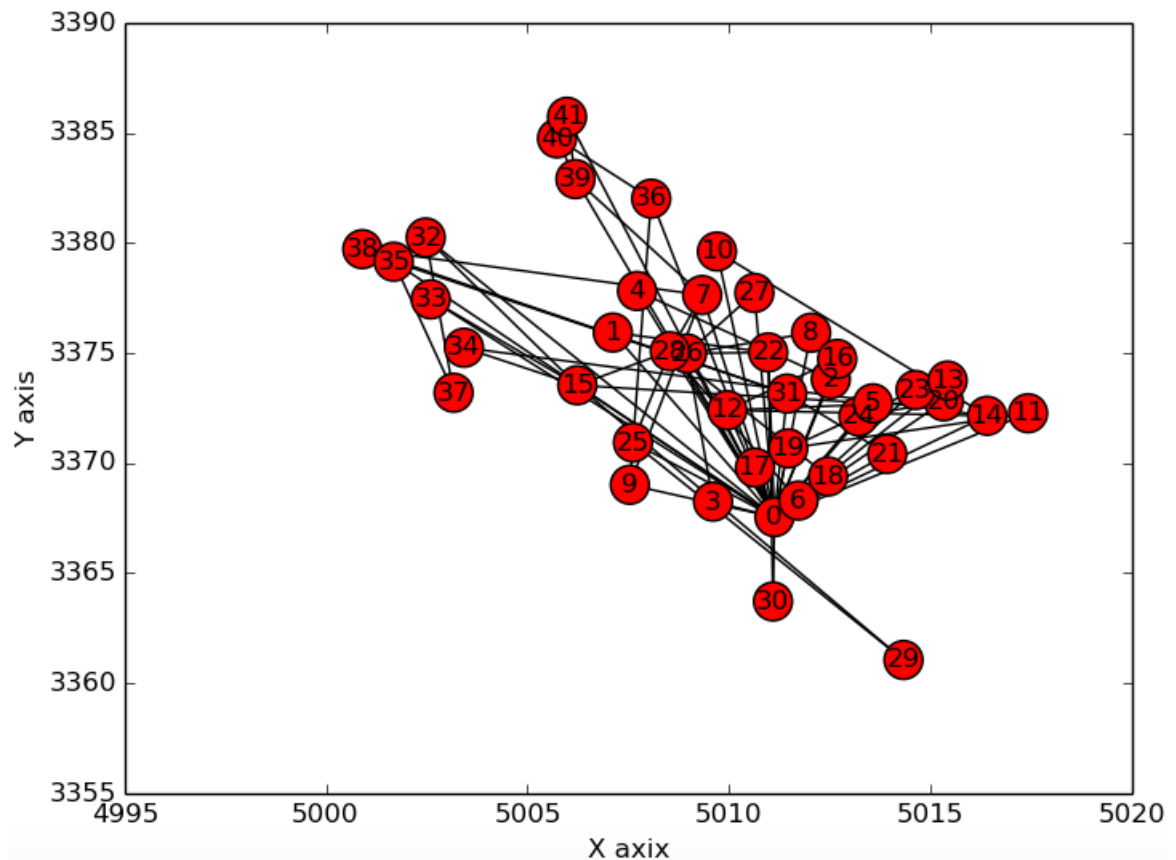
FIGURE 5.5: Reduced sparse network topology

TABLE 5.2: Non-symmetric links in the sparse network topology

Sparse network topology links
(1,0), (0,2), (0,3), (0,4), (0,5), (0,6), (0,7), (0,8), (0,9), (0,10), (11,0), (0,12), (0,13), (0,14), (0,15), (0,16), (0, 17), (0,18), (19,0), (0,20), (0,21), (0,22), (0,23), (24,0), (0,25), (0,26), (0,27), (0,30), (0,35), (2,4), (3,26), (15,5), (9,7), (38,7), (39,7), (8,26), (10,14), (12,16), (12,20), (13,20), (12,14), (15,29), (32,15), (33,15), (15,34), (19,17), (19,11), (19,23), (1,22), (26,22) , (30,22), (24,20), (25,29), (26,27), (0, 28), (28,6), (28,7), (15,28), (18,28), (25,28), (0,31), (31,21), (32,0), (32,37), (33,0), (14,34), (31,35), (37,35), (0,36), (9,36), (36,40), (31,38), (0,39), (39,40), (0,41), (39,41)

5.10.1.1 Sparse network topology reliability using the link length

The reliability of the computation was evaluated by looking at the number of disjoint shortest paths computed by considering the sparse network topology with the link length as a routing metric. The algorithm described in Section 5.8 Subsection 5.8.1 was used to compute the disjoint paths for each node of the sparse topology. The number of disjoint paths from a node to all the other nodes of the sparse network is referred to as the disjoint path multiplicity (DPM) for that node. The following performance metrics were considered.

1. **The Average number of disjoint shortest paths per source-destination pair.** Each node was set as the sink and the number of disjoint shortest paths from any node to the sink was calculated. These values were averaged for each sink, and were evaluated.

2. **The variation of the number of shortest paths per source-destination pair.** Each node was allowed to be a sink and the standard deviation of the number of shortest paths to the sink from each node of the network was evaluated.

3. **The maximum number of shortest paths per source-destination pair.** To determine the likelihood of a node being a sink, the metric that shows the node which most nodes can reach using the most alternatives, was evaluated.

Figure 5.6 shows that node 1 (Nyanga) is the node most likely to be a sink since it has the highest average number of disjoint shortest paths, while node 29 (Durbanville) is the least likely. Figure 5.7 shows that when node 30 (Brackenfell) is chosen to be the sink, the number of shortest paths from each node to it is least variable. However, choosing node 0 (Bellville), the number of shortest paths from each node is the most variable. Figure 5.8 confirms that node 1 (Nyanga) is most likely to be a sink but reveals that when node 30 (Brackenfell) is the sink, the number of shortest paths from each node is the shortest.

5.10.2 Hierarchical backbone formation

A Python code implementation of Algorithm 8 was run on the network report for the sparse network topology depicted in Figure 5.5, to introduce a hierarchical backbone network topology. Using the coefficient parameters in Equation 5.5 set as $\alpha = \beta = \gamma = 10$, the hierarchical backbone network topology produced is shown in Figure 5.9, and Table 5.3 shows the nodes making up the backbone network topology.
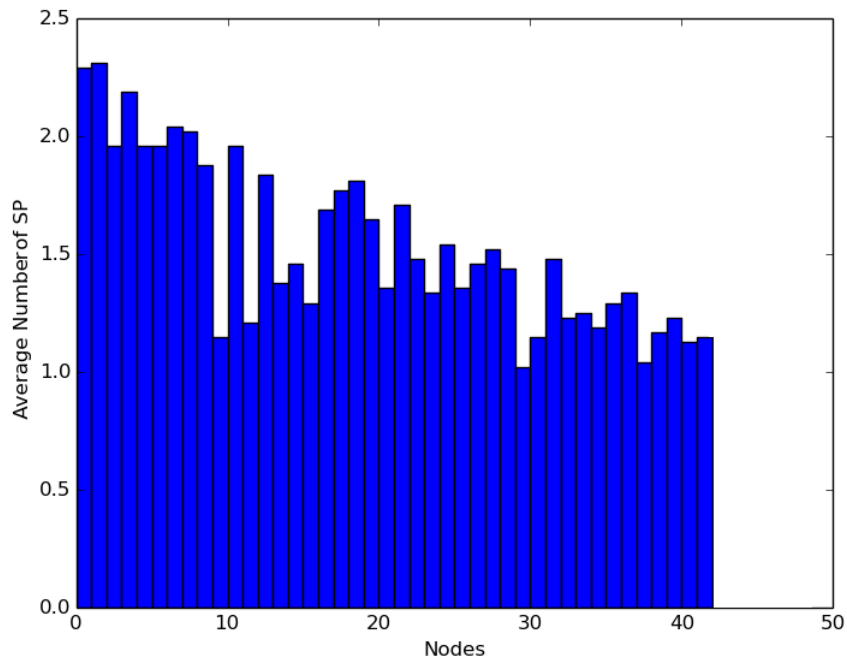
FIGURE 5.6: Average DPM
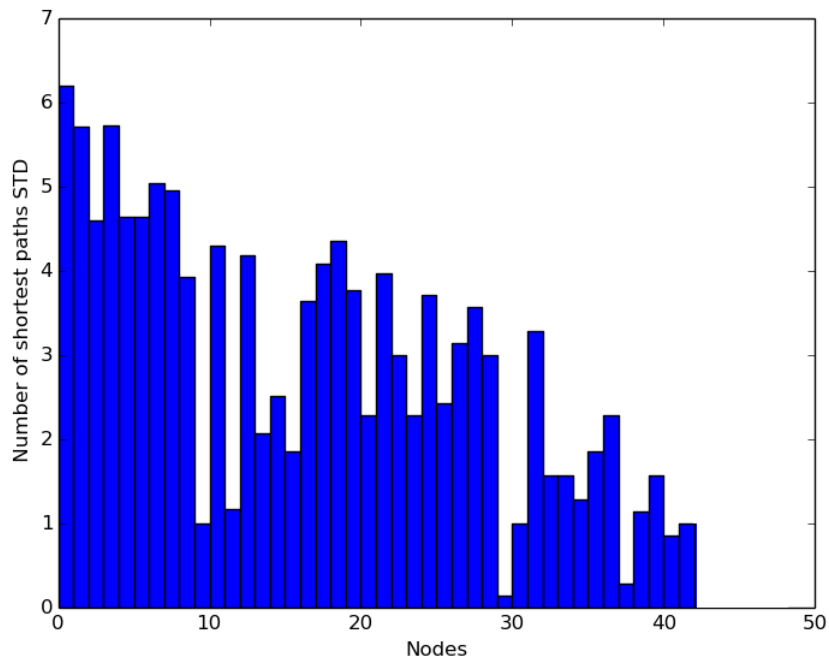
FIGURE 5.7: DPM Variance
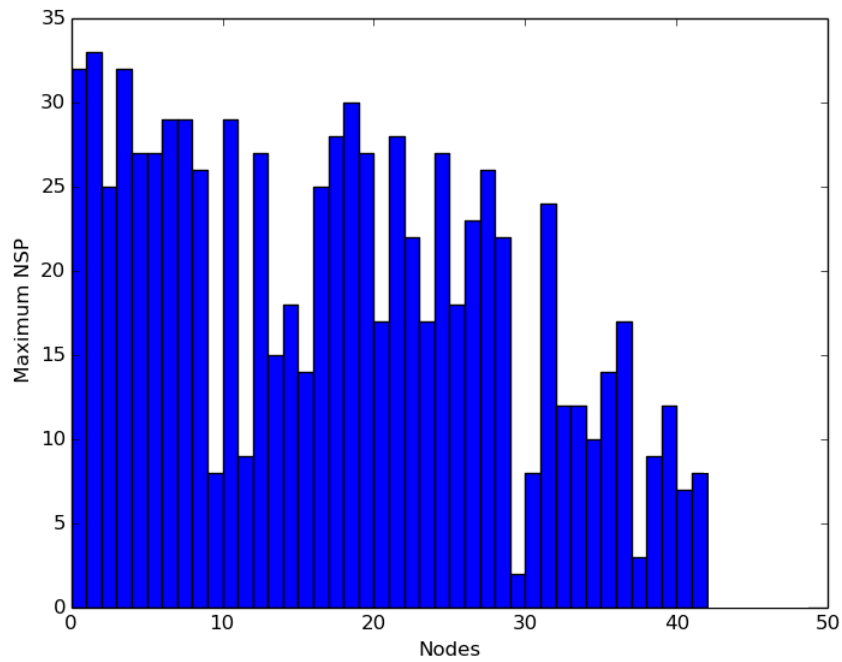
FIGURE 5.8: Maximum DPM
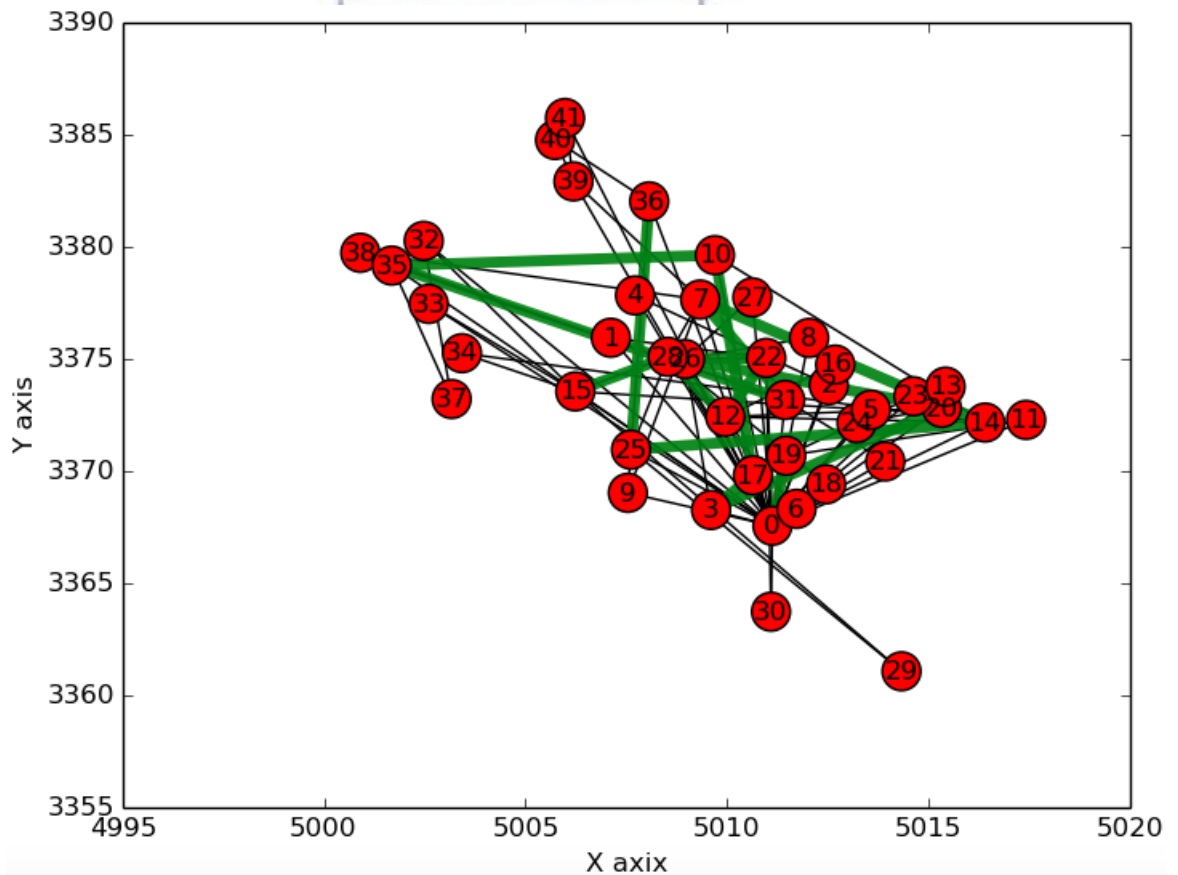
FIGURE 5.9: Hierarchical backbone network topology

TABLE 5.3: Backbone network topology nodes and links using traditional pramaters

Backbone nodes	Backbone links
0, 19, 15, 28, 12, 22, 26, 20, 3, 17, 10, 35, 31, 7, 14, 25, 36	(0,19), (15,28), (28,12), (12,22), (22,26), (26,20), (20,3), (3,17), (17,10), (10,35), (35,31), (31,7), (7,14), (14,25), (25,36)

5.10.2.1   Impact of backbone design on network performance

Table 5.4 shows the main properties of the backbone network that was formed and the associated sparse network. The average node degree and the coefficient of the link margin variation for the backbone are greater than those of the sparse network. This is because a node with the highest degree or coefficient of variation is most likely to be chosen as a backbone node, according to the Algorithm 8. However, the table shows that the average shortest path for the backbone network is smaller than the sparse network. This is because the nodes closest to many of the nodes in the network are also likely to be chosen as backbone nodes, according to the Algorithm 8. The table

TABLE 5.4: Backbone network topology vs sparse network topology

Network performance	Reduced network	Backbone
Node degree	3.81	4.03
Degree centrality	0.09	0.10
Coefficient of variation	2.83	3.86
Connectedness centrality	0.07	0.09
Shortest distance (km)	12.88	12.31
Closeness centrality (km)	3.18	3.33
Path multiplicity	2	1

reveals the advantage of using a backbone model, by showing links with better quality, in terms of link margin and a higher node degree, representing the potential for finding alternative paths for the traffic when a link/node fails. However, this is balanced by the path multiplicity which is 1 because all the edge nodes are directly connected to the cluster heads, thus offering a single path for the edge nodes while a flat network has the potential for building 2 paths for the edge network.

5.10.2.2   Impact of the design parameters on the backbone size

Here, the effect of parameters on the size of the backbone is studied. In each case, two parameter were fixed as the third parameter was changing from 0 to 100. Figure 5.10 shows how the size of the backbone network changed by varying the node degree. The figure shows that the size of the backbone varied but generally approached the convergent point (10 nodes) as the node degree increased.
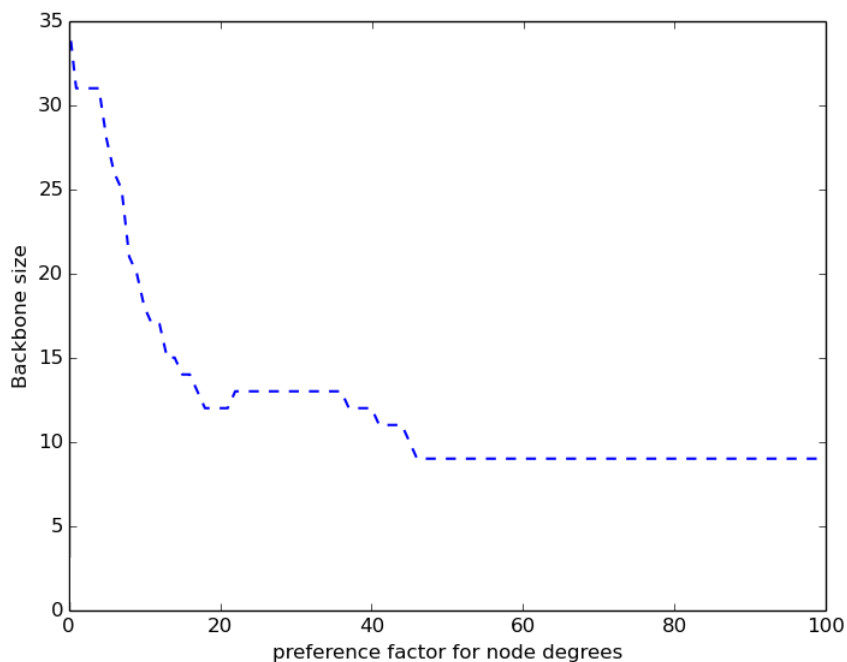
FIGURE 5.10: Impact of α on backbone size
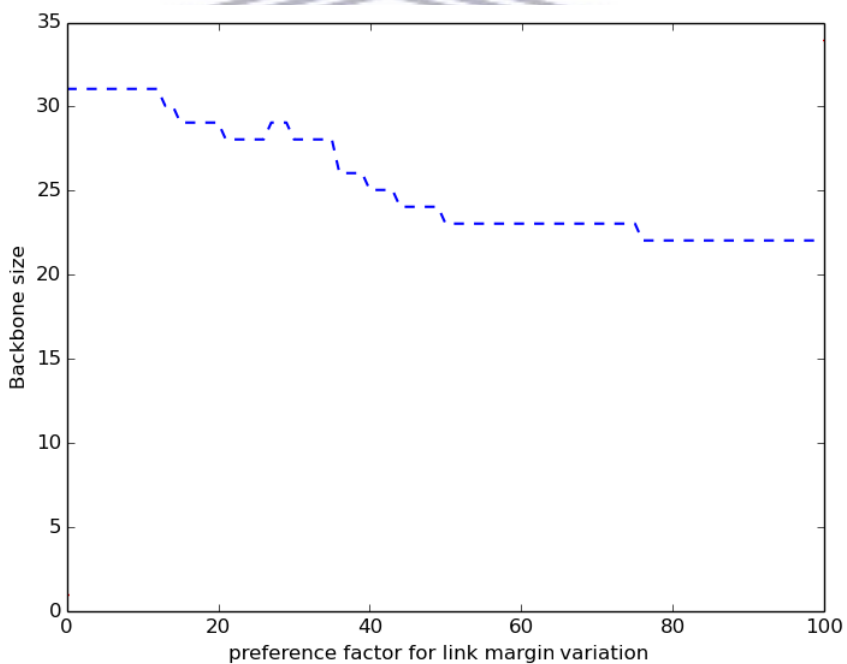
FIGURE 5.11: Impact of β on backbone size

Figure 5.11 shows how the link margin parameter affected the size of the backbone. In a similar way to the trend shown by Figure 5.10, the network backbone size also decreased and converged to a point. However, for link margin parameters, the decrease is slower than for node degree, and hence the size of the backbone converged to a higher number of nodes.
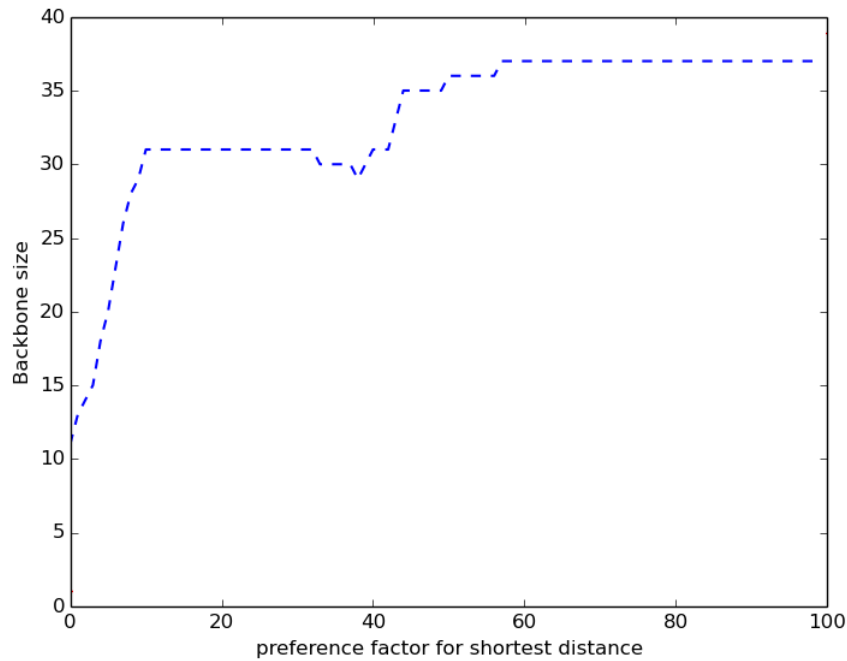
FIGURE 5.12: Impact of λ on backbone size

Considering the effect of the shortest distance between nodes, Figure 5.12 shows a different trend. The size of backbone increased in general until it reached a maximum.

The conclusions drawn from the three graphs depicting the impact of the design parameters on the backbone size are as follows: the backbone size is affected by a change in each of the three parameters; the node degree has the greatest positive influence on the backbone size: the higher the node degree the smaller the backbone size. This situation allows the network to scale while keeping the size of the backbone constant and small.

5.10.3 Effect of white space based parameters

In this section, the effect of white space related observables are discussed. The values were set as shown in the Table 5.5. As the table shows, some coefficients were fixed to particular values and one of them was assumed to take different values which were normally distributed with a mean of 5 and a standard deviation of 10 (denoted as $\mathcal{N} \rightsquigarrow (5, 10)$).

Figures 5.13 to 5.15 show the variation of the backbone size as the white space related parameters had their coefficients increased. Figure 5.13 shows the effect of the white space quantity weighting. It reveals that when the weight was negative, i.e., negative β_w, the backbone size decreased stochastically up to 6 nodes. After the value zero, the backbone size increased quickly and converged to a stable figure when the coefficient

Parameter	Values					
	Case 1	Case 2	Case 3	Case 4	Case 5	Case 6
α	10	10	10	0	0	0
β	10	10	10	0	0	0
λ	10	10	10	0	0	0
α_w	$\mathcal{N} \rightsquigarrow (5, 10)$	1	1	1	1	$\mathcal{N} \rightsquigarrow (5, 10)$
β_w	1	$\mathcal{N} \rightsquigarrow (5, 10)$	1	1	$\mathcal{N} \rightsquigarrow (5, 10)$	1
λ_w	1	1	$\mathcal{N} \rightsquigarrow (5, 10)$	$\mathcal{N} \rightsquigarrow (5, 10)$	1	1

TABLE 5.5: Table of values
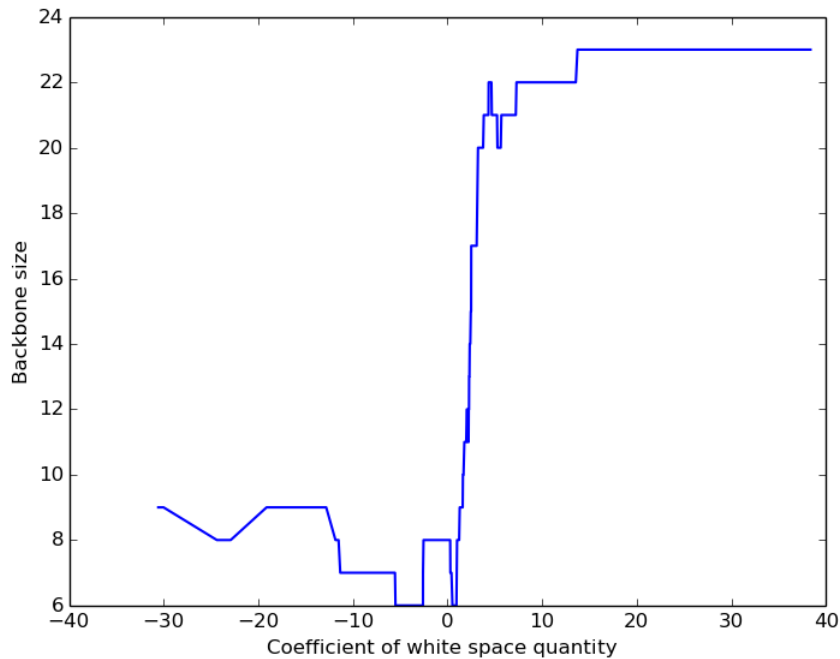
FIGURE 5.13: Impact of α_w on backbone size

takes the value 15. Smallest backbone size, which is preferred as discussed before, was achieved when β_w was around 0. This means that preference for the coefficient of white space quantity does not produce a small backbone size. Figure 5.14 shows the effect of weighting the quality of the white spaces. It shows almost the same trends as shown in Figure 5.13 for the white space quantity weighting. The smallest backbone size is achieved when the coefficient of white space quality is around 0. Similar to the effect of preference for the coefficient of white space quantity, preference for the coefficient of white space quality does not produce a small backbone size, which is desirable. Figure 5.15 shows the effect of changing the coefficient on the white space diversity. Unlike the other coefficients, preference for the coefficient of white space diversity produces a small backbone, and the suitable value of the coefficient is 3. When the coefficient value is 3, the backbone size is 6 and does not change with increasing values of the coefficient.

Figures 5.16 to 5.18 show the case where only the white space parameters were considered to create a backbone network. The trends are similar to the ones when both the
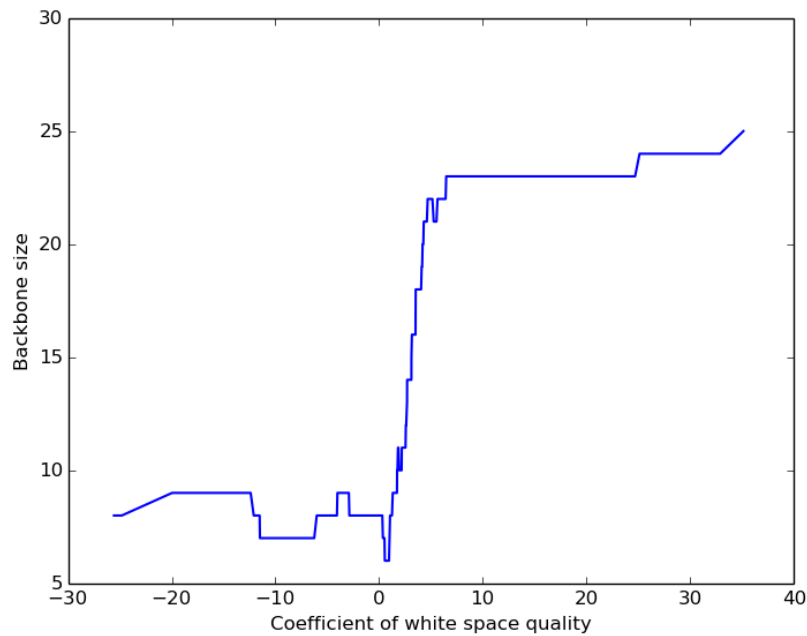
FIGURE 5.14: Impact of β_w on backbone size
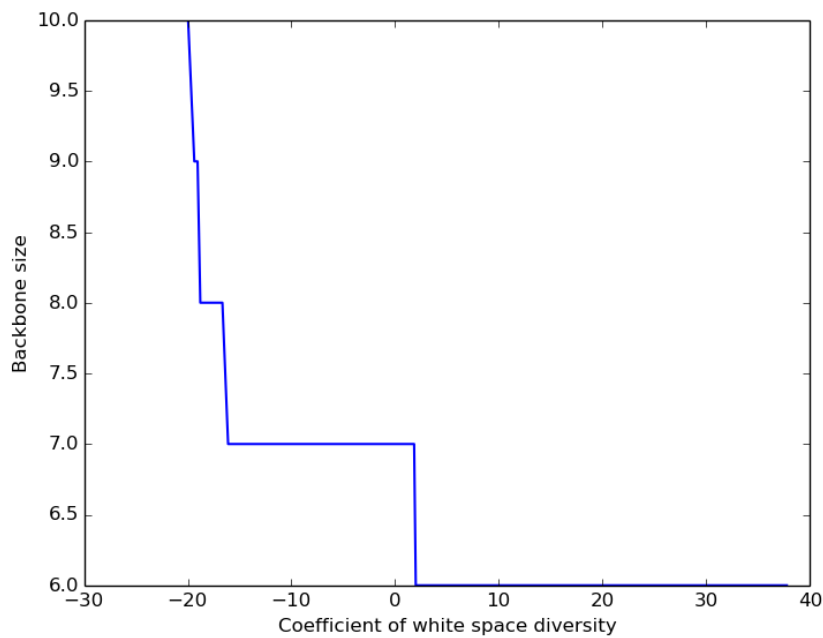
FIGURE 5.15: Impact of λ_w on backbone size

coefficients of traditional network parameters and white space parameters were considered. Figures 5.16 and 5.17 show almost the same trend. In both cases, the backbone size was smallest when the coefficient were close to 0, and preference for both coefficients increased the backbone size, which is not desirable. Figure 5.18 shows the same
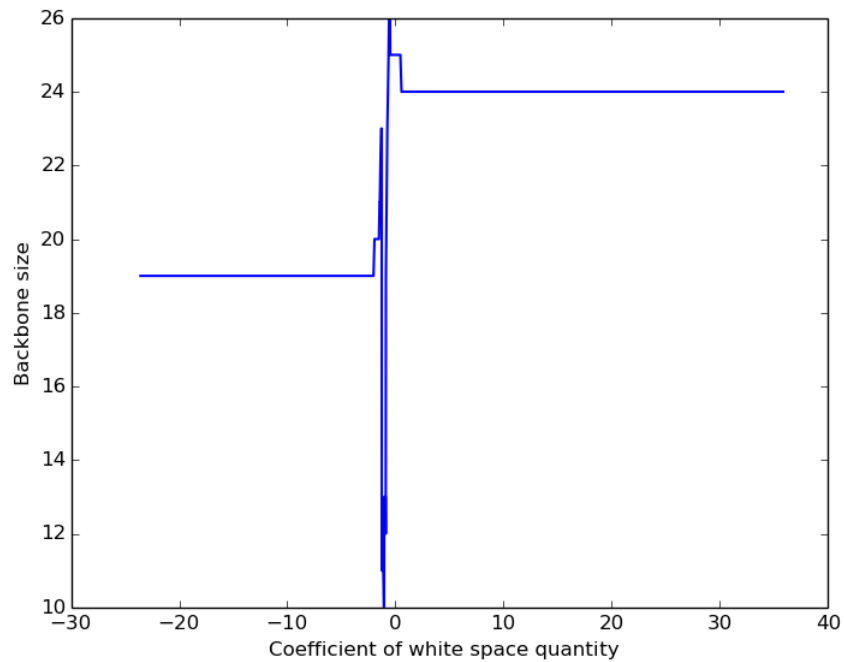
FIGURE 5.16: Impact of α_w on backbone size
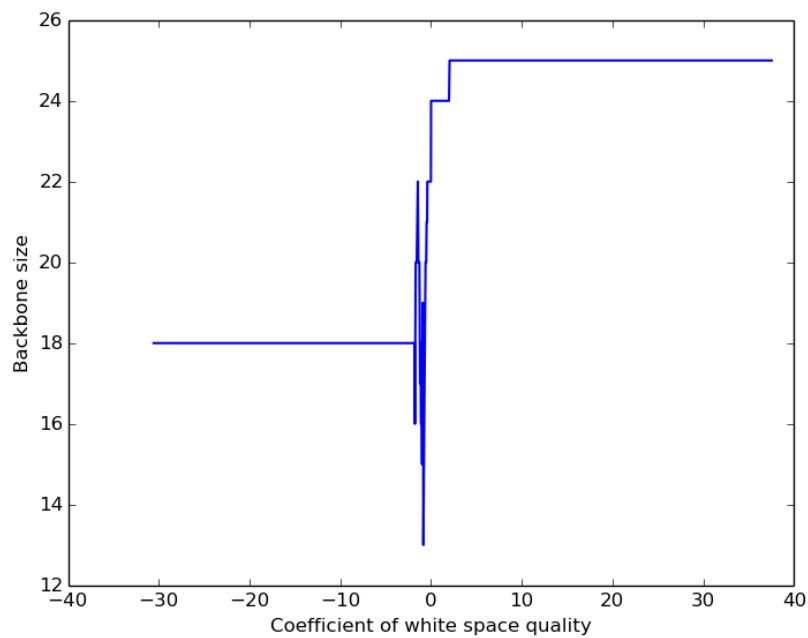
FIGURE 5.17: Impact of β_w on backbone size

trend as Figure 5.15, i.e., preference for the coefficient of white space diversity produced small backbone size. The smallest backbone size is achieved when the coefficient value negative and close to 0 and any increase in the value of the coefficient does not change the backbone size.
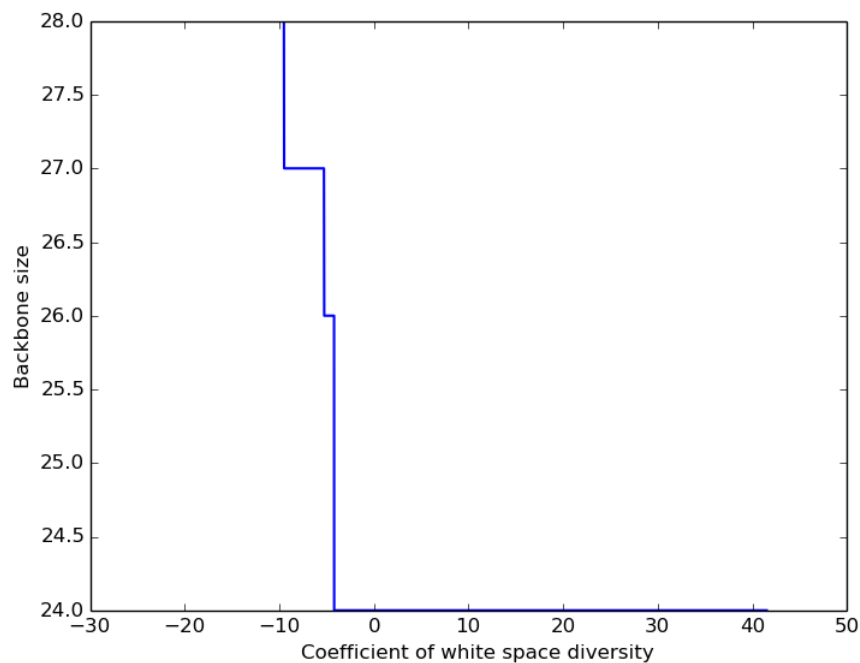
FIGURE 5.18: Impact of λ_w on backbone size

5.11 Chapter summary

In this chapter, design challenges that are expected to be met when designing mesh networks using opportunistic access to the white space spectrum, were explored and discussed. Dense network topology was highlighted as one of the design challenges that network planners and designers in white space frequencies will face, and the work in this chapter focused on addressing this challenge. A Link-based topology reduction algorithm has been developed to reduce a dense mesh network topology network, designed in white space frequencies, to a sparse mesh network topology, and a network optimization function, based on three metrics that determine the centrality measure of a node in a network graph, a concept borrowed from social network analysis, has been developed to generate a hierarchical backbone-based network topology from the sparse network topology. A performance evaluation on the designs was carried out and the results show that these designs can guide a network engineer to select the most relevant performance metrics, during a network feasibility study aimed at guiding the implementation process.

The next chapter summarise the thesis and discusses future research to follow the research work that has been done in this project.

Chapter 6

Conclusion and recommendations

6.1 Summary of the work

The aim of this thesis was to investigate and design a novel distributed network architecture for TV white space detection that is well adapted to Africa and the other parts of the developing world, where white space frequency usage is different from that in countries of the developed world. The background to the investigation was presented in Chapter 1 and it was motivated in Chapter 2 by the review of the related literature. The investigation and design of the framework was presented in Chapter 3. A cooperative spectrum sensing based network architecture for TVWS detection, based on real-time spectrum sensing data was designed. The framework does not use propagation models like those used in geo-location database based model, for detecting TVWS. The design choices incorporated in the architecture were documented, verified and validated in the same chapter. The verification and validation were performed through experimental measurements and simulations.

Following the design of the framework, the research focused on investigating a suitable mechanism for sharing/allocating the white space spectrum among potential white space users. A spectrum sharing/trading mechanism for short-time leasing of the TV white spaces was investigated and designed in Chapter 4. Its verification and validation were done through simulations and were presented in the same chapter. The background and motivation for this investigation was presented in Chapter 2.

The research also investigated the design of a mesh network in white space frequencies, which led to the development of a sparse network topology reduction algorithm and a novel network optimization function for creating a hierarchical backbone network topology in mesh networks designed in white space frequencies. Both the sparse network

117

topology reduction algorithm and the network optimization function were developed to guide network engineers during a network feasibility study done in TVWS frequencies, to select the most relevant performance metrics in the actual implementation process. The motivation for the development of these algorithms was presented in Chapter 5, and their verification and validation, done through simulations, were presented in the same chapter.

6.2 Revisiting the research aims

In Chapter 1 Section 1.10, it was stated that the aims of this research were three-fold: firstly, the research was aiming at investigating a white space network detection framework based on cooperative spectrum sensing; secondly, the research aimed at investigating a suitable spectrum sharing/trading mechanism for the short-term leasing of the TVWSs to potential white space users; and finally, the research aimed to investigate the design of a white space-aware network in white space frequencies. Each of the aims had been addressed by the end of the research.

6.2.1 White space network detection framework

A cooperative spectrum sensing-based framework for TVWS detection suitable for the developing world has been designed. The framework incorporates the cooperative spectrum sensing design, as a well-known proposed spectrum sensing design, for white space detection. This design mitigates the *hidden terminal problem* and some new proposed spectrum sensing designs for white space detection that addresses some of the very well-known spectrum sensing challenges met when used as a method for white space detection. The multi-threshold white space detection design is incorporated in the framework to mitigate the most likely result one would expect when single threshold white space detection design is used; too many false positives or too many false negatives. To mitigate further the *hidden terminal problem*, the framework incorporates the following designs: grouping of TV white spaces based on the threshold values used, virtual-pricing of the white spaces based on the signal strengths in the white space channels and sequential allocation of the white spaces to secondary users based on the probability that they will not cause interference to the spectrum incumbents. The framework also incorporates location clustering to reduce the implementation cost, making it more suitable for the developing world, where the cost of implementing a white space detection network could be a major factor in deciding which approach to adopt. Performance evaluation of the framework, that was done through experiments and simulations shows that the framework can detect the TVWSs accurately with minimal probability of causing interference

to the primary users resulting from false negatives. The framework has also shown that it can detect more white spaces than existing proposals, by reducing false positives.

6.2.2 Spectrum sharing/trading mechanism

An auction mechanism design for sharing/allocating TVWSs to secondary users, that meets specific requirements for a secondary spectrum market auction, has been designed. The design mimics a similar process employed in GA to maximise the spectrum allocation. To maximise the allocation profit, the design reduces the allocation problem to a 0-1 KP. The design uses a three-stage strategy to perform the allocation of the white spaces to secondary users. The first stage is called the *pre-candidate selection*, which removes any potential secondary white space user from the auction if it is violating the rules of the auction. The second stage is called *non-interfering bidder-grouping*, which groups potential secondary white space users into non-interfering groups. This stage is performed using a non-interfering buyer grouping strategy called Interference Graph-Complement, which derives the non-interfering buyer groups from the complement of the interference graph, to allow spectrum re-usability that leads to efficient spectrum utilization. The final stage is the *spectrum allocation* to the non-interfering groups of surviving potential secondary white space users; this is done by mimicking a similar process employed in GA and reducing the allocation problem to a 0-1 KP at each recursive step. Performance evaluation, that was performed through simulations on arbitrary heterogeneous buyer networks, shows that the auction mechanism design achieves high spectrum utilization, high spectrum efficiency and generates high profits to the white space owners.

6.2.3 White space-aware network design

Simulations of network design in TVWS frequencies reveal dense network topologies because of the improved signal propagation and penetration properties of the white space frequencies. Consequently, the design of networks in white space frequencies will require topology control to reduce packet collisions, protocol overhead, and interference. A link-based topology reduction algorithm has been developed in this thesis to guide network engineers during a network feasibility study done in white space frequencies, to select the most relevant performance metrics during the actual implementation process. In addition to this, a network optimisation function has been developed to introduce hierarchical backbone network topology from the sparse network topology. The network optimisation function uses the concept of centrality measure, borrowed from social

network analysis, to identify the most important nodes to include in a backbone topology using some of the centrality measure metrics. Performance evaluation on both the topology reduction algorithm and the network optimisation function show promising results, that will assist network engineers during network feasibility studies in white space frequencies.

6.3 Summary of contributions

A cooperative sensing-based framework for TVWS detection that includes a new concept called multi-threshold detection design where more than one detection threshold is used to detect the white spaces was proposed. To the best of the author's knowledge, the framework is the first of its kind to include multi-threshold detection design. Existing proposals use single-threshold detection design, where only one detection threshold is used to detect the white spaces. The proposed framework also includes a new concept called virtual pricing design, to rank the detected white spaces in terms of the probability to cause interference to the primary users. As a direct result of ranking the white spaces, the proposed framework includes a sequential allocation design of the white spaces to the secondary users, based on their probability to cause interference to the primary users. As far as the author's knowledge is concerned, these two designs have never been used before in any of the existing frameworks.

The work in this research proposed a spectrum auction mechanism design, that not only meets the economic properties that are essential for any auction mechanism design for selling merchandise, but also meets the complementary requirements that are specific for the secondary spectrum market auctions. While most of the existing spectrum auction mechanism designs meet the economic properties of any auction mechanism for selling merchandise, none meets all the complementary requirements specific to secondary spectrum market auctions.

The work in this research also proposed a new non-interference buyer-grouping strategy called the Interference Graph-Complement (IG-C) strategy, which extracts the non-interference buyer groups from the complement of the interference graph. The strategy produces optimal results, i.e., it produces a minimum number of non-interfering buyer groups leading to improved spectrum re-usability.

In this research, a network topology reduction algorithm has been developed that could guide network engineers, during network feasibility studies done in white space frequencies, to select the most relevant performance metrics in the actual implementation process. In addition, a network utility function, which takes relevant parameters, specific

to white space frequencies, into consideration, has been formulated for selecting mesh network nodes to be part of a hierarchical backbone mesh network topology, which is more scalable than a flat sparse mesh network topology. To the best of the author's knowledge, this work on network engineering in white space frequencies is the first of its kind.

6.4 Recommendations for future work

The work presented lays the foundation for the actual implementation of the TVWS detection network framework in one of the developing countries where it is well suited. The implementation will involve database implementation and white space resource allocation to network devices.

As far as the auction mechanism for the white space spectrum allocation is concerned, the pricing mechanisms that white space devices can adopt during the sharing of the while spaces in the auction setup were not studied. This is an area that requires further investigation to complement the auction mechanism design.

Another area for future research is to study and investigate white space network security. The security can be divided into two levels and investigated at each level: white space provider network security and white space user network security. The investigation will study the threats at both levels and the corresponding protection mechanisms.

Appendix A

Details about the measurement points and results

TABLE A.1: GPS coordinates of the police station and their HAAT

ID No	Police Station	Latitude	Longitude	HAAT (m)
0	Bellville	-33°54′05.6″	18°37′11.8″	227
1	Bellville South	-33°54′55.0″	18°38′40.3″	27
2	Parow	-33°54′16.4″	18°35′39.3″	-4
3	Ravensmead	-33°55′19.3″	18°35′45.0″	-26
4	Bishop Lavis	-33°56′45.7″	18°34′15.3″	-9
5	Belhar	-33°56′48.9″	18°38′54.9″	30
6	Saps-CT Int Airport	-33°58′08.0″	18°35′50.0″	-7
7	Kuils River	-33°55′56.4″	18°40′49.9″	-11
8	Brakenfell	-33°52′17.7″	18°40′50.7″	-22
9	Goodwood	-33°54′32.9″	18°33′35.2″	-14
10	Elsies River	-33°55′27.7″	18°33′46.5″	-19
11	Delft	-33°58′28.6″	18°38′24.5″	-9
12	Mfuleni	-34°00′10.7″	18°40′42.6″	227
13	Bothasig	-33°51′18.6″	18°32′36.6″	27
14	Durbanville	-33°50′01.2″	18°38′48.8″	-26
15	Kensington	-33°54′33.9″	18°30′33.4″	-22
16	Milnerton	-33°52′32.4″	18°30′00.1″	-22
17	Nyanga	-33°59′20.1″	18°34′54.3″	-7
18	Langa	-33°56′39.1″	18°31′27.4″	-14
19	Guguletu	-33°58′28.8″	18°33′42.7″	-9
20	Philippi	-34°00′2.4″	18°32′16.5″	-11
21	Khayelitsha	-34°1′28.6″	18°39′48.0″	227
22	Harare	-34°03′06.0″	18°40′01.4″	27

122

ID No	Police Station	Latitude	Longitude	HAAT (m)
23	Lingelthu West	-34°02′34.7″	18°39′28.2″	-4
24	Mitchells Plain	-34°02′51.0″	18°37′19.1″	-26
25	Athlone	-33°57′40.6″	18°30′20.0″	-22
26	Pinelands	-33°55′35.8″	18°29′55.8″	-14
27	Maitland	-33°55′24.9″	18°28′51.8″	-19
28	Sea Point	-33°54′20.4″	18°23′50.9″	-9
29	Table Bay Harbour	-33°54′35.8″	18°25′24.1″	-7
30	Port of Entry	-33°55′15.1″	18°26′18.0″	-9
31	Cape Town Central	-33°55′39.7″	18°25′16.2″	-9
32	Woodstock	-33°55′43.2″	18°26′48.1″	227
33	Mowbray	-33°57′00.5″	18°28′11.7″	27
34	Rondebosch	-33°57′45.7″	18°27′58.9″	-4
35	Claremont	-33°59′03.5″	18°28′14.6″	-26
36	Lansdowne	-33°59′25.5″	18°30′10.5″	30
37	Wynberg	-34°00′14.8″	18°27′45.7″	-19
38	Manenberg	-33°58′18.1″	18°33′12.8″	-19
39	Diep Rivier	-34°01′53.6″	18°27′46.9″	-14
40	Steenberg	-34°03′55.6″	18°28′27.5″	-9
41	Kirstenhof	-34°04′19.5″	18°27′10.7″	-9
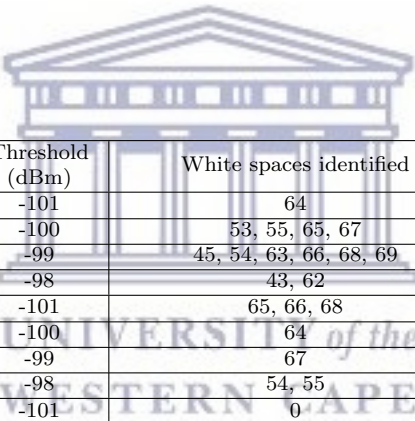
TABLE A.2: Averaged signal power of measured channels at each police station

ID No	Police Station	Av. Signal (dBm)	ID No	Police Station	Av. Signal (dBm)
0	Bellville	-91.6	21	Khayelitsha	-90.5
1	Bellville South	-90.5	22	Harare	-90.4
2	Parow	-87.4	23	Lingelthu West	-89.4
3	Ravensmead	-90.5	24	Mitchells Plain	-93.9
4	Bishop Lavis	-91.4	25	Athlone	-89.9
5	Belhar	-96.0	26	Pinelands	-92.8
6	Saps-CT Int Airport	-92.3	27	Maitland	-97.9
7	Kuils River	-94.4	28	Sea Point	-89.2
8	Brakenfell	-96.5	29	Table Bay Harbour	-95.4
9	Goodwood	-98.5	30	Port of Entry	-90.8
10	Elsies River	-92.7	31	Cape Town Central	-95.9
11	Delft	-90.0	32	Woodstock	-93.8
12	Mfuleni	-99.8	33	Mowbray	-91.1
13	Bothasig	-92.1	34	Rondebosch	-95.2
14	Durbanville	-94.6	35	Lansdowne	-89.6
15	Kensington	-85.5	36	Claremont	-101.1
16	Milnerton	-95.4	37	Wynberg	-100.3
17	Nyanga	-93.4	38	Manenberg	-86.7
18	Langa	-91.4	39	Diep Rivier	-96.7
19	Guguletu	-91.9	40	Steenberg	-98.8
20	Philippi	-92.8	41	Kirstenhof	-99.4

Appendix B

White spaces identified at each police station

ID No	SAPS Name	Threshold (dBm)	White spaces identified	Total	Largest contiguous white space width
0	Bellville	-101	64	13	8 channels
		-100	53, 55, 65, 67		
		-99	45, 54, 63, 66, 68, 69		
		-98	43, 62		
1	Bellville South	-101	65, 66, 68	7	5 channels
		-100	64		
		-99	67		
		-98	54, 55		
2	Parow	-101	0	0	None
		-100	0		
		-99	0		
		-98	0		
3	Ravensmead	-101	43-46, 54-56, 59, 62-69	24	9 channels
		-100	47, 49, 51, 52, 57, 61		
		-99	53		
		-98	33		
4	Bishop Lavis	-101	65, 66, 68, 69	8	5 channels
		-100	0		
		-99	43, 46, 63		
		-98	67		
5	Belhar	-101	46, 54, 55, 64-69	21	8 channels
		-100	45, 51-53		
		-99	43, 56, 57, 63		
		-98	44, 47-49		
6	SAPS-CT Int Airport	-101	65, 66, 68, 69	8	6 channels
		-100	0		
		-99	64, 67		
		-98	43, 46		
7	Kuilsriver	-101	43, 45, 55, 63-69	19	7 channels
		-100	0		
		-99	41, 54		
		-98	40, 49, 52, 53, 61		
8	Blackenfell	-101	41, 43, 45, 46, 54, 55, 57, 62-69	26	9 channels
		-100	49, 52, 53, 61		
		-99	44, 51, 56		
		-98	33, 47, 59		

124

ID No	SAPS Name	Threshold (dBm)	White spaces identified	Total	Largest contiguous white space width
9	Goodwood	-101	31-33, 40, 41, 44-47, 51-56, 62-69	36	9 channels
		-100	23, 35, 49, 57, 61		
		-99	21, 29, 58		
		-98	22, 25, 36, 48, 59		
10	Elsiesrivier	-101	64-66, 68, 69	14	8 channels
		-100	55, 67		
		-99	43, 45, 46, 49, 52, 62		
		-98	54		
11	Delft	-101	0	1	1 channel
		-100	0		
		-99	0		
		-98	65		
12	Mfuleni	-101	23-26, 31-36, 40, 41, 43-49, 53-56, 61-69	40	9 channels
		-100	21, 37, 57		
		-99	22, 27, 29, 58		
		-98	59		
13	Bothasig	-101	64, 66	13	7 channels
		-100	55, 67-69		
		-99	45, 54, 65		
		-98	63		
14	Durbanville	-101	63-69	16	9 channels
		-100	53-55		
		-99	41, 43, 45, 46, 62		
		-98	61		
15	Kensington	-101	0	0	None
		-100	0		
		-99	0		
		-98	0		
16	Milnerton	-101	54, 55, 64-69	19	8 channels
		-100	51, 56, 62		
		-99	43, 44, 48, 49, 53, 63		
		-98	46, 47		
17	Nyanga	-101	55, 64-68	13	7 channels
		-100	43, 63, 69		
		-99	45, 56		
		-98	41, 44		
18	Langa	-101	0	10	6 channels
		-100	65, 68		
		-99	64, 66, 69		
		-98	43, 46, 55, 65, 67		
19	Guguletu	-101	64, 65, 68, 69	10	3 channels
		-100	66		
		-99	46, 48		
		-98	43, 49, 55		
20	Philippi	-101	55, 63, 66-69	11	5 channels
		-100	52, 56		
		-99	0		
		-98	41, 44, 45		
21	Khayelitsha	-101	0	2	1 channel
		-100	0		
		-99	66, 68		
		-98	0		

ID No	SAPS Name	Threshold (dBm)	White spaces identified	Total	Largest contiguous white space width
22	Harare	-101	0	5	3 channels
		-100	0		
		-99	65, 66, 68, 69		
		-98	64		
23	Lingelethu	-101	0	4	2 channels
		-100	65, 66		
		-99	68, 69		
		-98	0		
24	Mitchels Plain	-101	55, 63-67	16	7 channels
		-100	41, 43, 54, 62		
		-99	52, 61		
		-98	44, 45, 49, 56		
25	Athlone	-101	0	0	None
		-100	0		
		-99	0		
		-98	0		
26	Pinelands	-101	64, 65, 68	14	8 channels
		-100	66		
		-99	54, 55, 67, 69		
		-98	43, 46, 53, 62, 63		
27	Maitland	-101	31-33, 43-47, 51, 53-55, 57-59, 61, 62, 64-69	28	6 channels
		-100	35, 49		
		-99	40		
		-98	21, 23		
28	Sea Point	-101	0	3	2 channels
		-100	0		
		-99	64, 65		
		-98	54		
29	Table Bay Harbour	-101	45, 46, 51, 53-55, 62, 65-69	19	5 channels
		-100	33, 43, 57, 59		
		-99	0		
		-98	23, 32, 47		
30	Port of Entry	-101	0	6	5 channels
		-100	64-66		
		-99	67, 68		
		-98	54		
31	Cape Town Central	-101	46, 49, 54, 55, 61-69	20	9 channels
		-100	43, 45, 53		
		-99	41, 44		
		-98	48, 52		
32	Woodstock	-101	64-66, 68	16	6 channels
		-100	53, 54, 67		
		-99	45, 46, 51, 55, 69		
		-98	43, 44, 48, 52		
33	Mowbray	-101	66	6	3 channels
		-100	64, 65		
		-99	0		
		-98	55, 62 68		
34	Rondebosch	-101	45, 46, 53-56, 64-69	19	8 channels
		-100	52, 62, 63		
		-99	43		
		-98	41, 44, 51		

ID No	SAPS Name	Threshold (dBm)	White spaces identified	Total	Largest contiguous white space width
35	Claremont	-101	23, 24, 29, 31, 33, 35, 36, 40, 41, 43-49, 53-56, 61-69	38	10 channels
		-100	22, 25, 27, 52, 58		
		-99	21, 26, 42, 57		
		-98	0		
36	Lansdowne	-101	66, 68	5	2 channels
		-100	65		
		-99	69		
		-98	55		
37	Wynberg	-101	31, 40-47, 49, 53-59, 61-69	34	10 channels
		-100	30, 33, 35, 52		
		-99	34		
		-98	23, 24, 48		
38	Manenberg	-101	0	0	None
		-100	0		
		-99	0		
		-98	0		
39	Diep Rivier	-101	45, 55, 56, 62-69	23	9 channels
		-100	41, 43, 44, 46, 57, 58, 61		
		-99	42, 54, 59		
		-98	49, 52		
40	Steenberg	-101	41-47, 54-58, 61-69	31	10 channels
		-100	49, 59		
		-99	31, 33, 52		
		-98	23, 30, 35, 48, 53		
41	Kirstenhof	-101	33, 41, 43-47, 49, 53-58, 61-69	33	10 Channels
		-100	35, 42, 59		
		-99	23, 24, 31, 36, 48, 52		
		-98	30		

Bibliography

[1] Ofcom Consultation. Digital dividend: cognitive access. *Statement on licence-exempting cognitive devices using interleaved spectrum*, 1, 2009. Date accessed: 2016-8-5.

[2] N. Hoven, R. Tandra, and A. Sahai. Some fundamental limits on cognitive radio. *Wireless Foundations EECS, Univ. of California, Berkeley*, 2005.

[3] C. Cordeiro and K. Challapali. Spectrum agile radios: utilization and sensing architectures. In *First IEEE International Symposium on New Frontiers in Dynamic Spectrum Access Networks, 2005. DySPAN 2005.*, pages 160–169. IEEE, 2005.

[4] X. Ying, J. Zhang, L. Yan, G. Zhang, M. Chen, and R. Chandra. Exploring indoor white spaces in metropolises. In *Proceedings of the 19th annual international conference on Mobile computing & networking*, pages 255–266. ACM, 2013.

[5] D. Liu, Z. Wu, F. Wu, Y. Zhang, and G. Chen. Fiwex: Compressive sensing based cost-efficient indoor white space exploration. In *Proceedings of the 16th ACM International Symposium on Mobile Ad Hoc Networking and Computing*, pages 17–26. ACM, 2015.

[6] T. Zhang, N. Leng, and S. Banerjee. A vehicle-based measurement framework for enhancing whitespace spectrum databases. In *Proceedings of the 20th annual international conference on Mobile computing and networking*, pages 17–28. ACM, 2014.

[7] J. Chebil, A.K. Lawas, and M.D. Islam. Comparison between measured and predicted path loss for mobile communication in malaysia. *World Applied Sciences Journal*, 21:123–128, 2013.

[8] J. Milanovic, S. Rimac-Drlje, and K. Bejuk. Comparison of propagation models accuracy for wimax on 3.5 ghz. In *Electronics, Circuits and Systems, 2007. ICECS 2007. 14th IEEE International Conference on*, pages 111–114. IEEE, 2007.

[9] J. Milanović, S. Rimac-Drlje, and I. Majerski. Radio wave propagation mechanisms and empirical models for fixed wireless access systems. *Tehnicki vjesnik/Technical Gazette*, 17(1), 2010.

[10] M.F. Iskander and Z. Yun. Propagation prediction models for wireless communication systems. *IEEE Transactions on microwave theory and techniques*, 50(3): 662–673, 2002.

[11] T. Yücek and H. Arslan. A survey of spectrum sensing algorithms for cognitive radio applications. *Communications Surveys & Tutorials, IEEE*, 11(1):116–130, 2009.

[12] I.F. Akyildiz, W. Lee, M.C. Vuran, and S. Mohanty. A survey on spectrum management in cognitive radio networks. *IEEE Communications magazine*, 46(4): 40–48, 2008.

[13] D.D. Ariananda, M.K. Lakshmanan, and H. Nikookar. A survey on spectrum sensing techniques for cognitive radio. In *Cognitive Radio and Advanced Spectrum Management, 2009. CogART 2009. Second International Workshop on*, pages 74–79. IEEE, 2009.

[14] S. Venkateswari and R. Muthaiah. An overview of cognitive radio architecture- a review. *Journal of Theoretical and Applied Information Technology*, 41(1):20–25, July 2012.

[15] A.V. Kulkarni and Y. Kulkarni. Spectrum sensing in cognitive radio. *International Journal of Advanced Engineering and Global Technology*, 1(5):309–316, December 2013.

[16] ICASA. Terestrial broadcasting frequency plan 2013. Technical report, Independent Communications Authority of South Africa, 2013.

[17] GSMA Mobile Spectrum. Data demand explained. Electronic, GSMA, http://www.gsma.com/spectrum/wp-content/uploads/2015/06/GSMA-Data-Demand-Explained-June-2015.pdf, June 2015. Date accessed: 2016-8-9.

[18] Y. Yuan, P. Bahl, R. Chandra, P.A. Chou, J.I. Ferrell, M. Moscibroda, S. Narlanka, and Y. Wu. Knows: Cognitive radio networks over white spaces. In *2007 2nd IEEE International Symposium on New Frontiers in Dynamic Spectrum Access Networks*, pages 416–427. IEEE, 2007.

[19] S.D. Barnes, P.J. Van VUURen, and B.T. Maharaj. Spectrum occupancy investigation: measurements in south africa. *Measurement*, 46(9):3098–3112, 2013.

[20] ET FCC. Docket no. 08-260,. *Second Report and Order and Memorandum Opinion and Order, Nov*, 2008.

[21] H.A.A. Garrido, M.E. Rivero-Angeles, and I.Y.O. Flores. Performance analysis of a wireless sensor network for seism reporting in an overlay cognitive radio system. In *2016 30th International Conference on Advanced Information Networking and Applications Workshops (WAINA)*, pages 565–570. IEEE, 2016.

[22] G. Naik, S. Singhal, A. Kumar, and A. Karandikar. Quantitative assessment of TV white space in India. In *Communications (NCC), 2014 Twentieth National Conference on*, pages 1–6. IEEE, February 2014.

[23] I.F. Akyildiz, W. Lee, M.C. Vuran, and S. Mohanty. Next generation/dynamic spectrum access/cognitive radio wireless networks: a survey. *Computer networks*, 50(13):2127–2159, 2006.

[24] R. Kaniezhil, C. Chandrasekar, and S. NithyaRekha. Performance evaluation of qos parameters in dynamic spectrum sharing for heterogeneous wireless communication networks. *arXiv preprint arXiv:1204.4550*, 2012.

[25] J. Carlson, N. Ntlatlapa, J. King, F. Mgwili-Sibanda, H. Hart, C. Geerdts, and S. Song. Studies on the use of television white spaces in south africa: Recommendations and learnings from the cape town television white space trial. Electronic, TENET, http://www.tenet.ac.za/tvws/recommendations-and-learnings-from-the-cape-town-tv-white-spaces-trial, October 2013. Date accessed: 2015-3-24.

[26] T.X. Brown, E. Pietrosemoli, M. Zennaro, A. Bagula, H. Mauwa, and S.M. Nleya. A survey of tv white space measurements. In *International Conference on e-Infrastructure and e-Services for Developing Countries*, pages 164–172. Springer, 2014.

[27] A. Marţian. Evaluation of spectrum occupancy in urban and rural environments of romania. 2014.

[28] R. Urban, T. Korinek, and P. Pechac. Broadband spectrum survey measurements for cognitive radio applications. *Radioengineering*, 21(4):1101–1109, 2012.

[29] A. Mancuso, S. Probasco, and B. Patil. Protocol to access white-space (paws) databases: Use cases and requirements. Technical report, 2013.

[30] R. Murty, R. Chandra, T. Moscibroda, and P. Bahl. Senseless: A database-driven white spaces network. *IEEE Transactions on Mobile Computing*, 11(2):189–203, 2012.

[31] N. Zurutuza. Cognitive radio and tv white space communications: Tv white space geo-location database system. 2011.

[32] ECC CEPT. Technical and operational requirements for the possible operation of cognitive radio systems in the white spaces of the frequency band 470–790 mhz. *ECC report*, 159, 2011.

[33] A.A. Ayeni, N. Faruk, L. Olawoyin, M.J. Muhammad, and M.I. Gumel. Comparative assessments of some selected existing radio propagation models: A study of kano city, nigeria. *European Journal of Scientific Research*, 70(1):120–127, 2012.

[34] White Space Database Administrator Group. Channel calculations for white spaces - guidelines (1.29). electronic, White Space Database Administrator Group, http://spectrumbridge.com/wp-content/uploads/2014/08/Database-Calculation-Consistency-Specification.pdf, June 2013. Date accessed: 2016-5-11.

[35] N. Hoven and A. Sahai. Power scaling for cognitive radio. In *2005 International Conference on Wireless Networks, Communications and Mobile Computing*, volume 1, pages 250–255. IEEE, 2005.

[36] K. Ruttik. Secondary spectrum usage in tv white space. 2011.

[37] H.L. Van Trees. *Detection, estimation, and modulation theory.* John Wiley & Sons, 2004.

[38] P.K. Varshney. Distributed bayesian detection: Parallel fusion network. In *Distributed Detection and Data Fusion*, pages 36–118. Springer, 1997.

[39] K. Koufos. Spectrum access in white spaces using spectrum sensing and geolocation databases. 2013.

[40] H. Urkowitz. Energy detection of unknown deterministic signals. *Proceedings of the IEEE*, 55(4):523–531, 1967.

[41] R. Tandra and A. Sahai. Snr walls for signal detection. *IEEE Journal of selected topics in Signal Processing*, 2(1):4–17, 2008.

[42] H. Kim and K.G. Shin. In-band spectrum sensing in cognitive radio networks: energy detection or feature detection? In *Proceedings of the 14th ACM international conference on Mobile computing and networking*, pages 14–25. ACM, 2008.

[43] R. Gill and A. Kansal. Comparative analysis of the spectrum sensing techniques energy detection and cyclostationary feature detection. *International Journal on Information Technologies & Security*, 7(3), 2015.

[44] D. Cabric, A. Tkachenko, and R.W. Brodersen. Spectrum sensing measurements of pilot, energy, and collaborative detection. In *MILCOM 2006-2006 IEEE Military Communications conference*, pages 1–7. IEEE, 2006.

[45] A. Ghasemi and E.S. Sousa. Optimization of spectrum sensing for opportunistic spectrum access in cognitive radio networks. In *2007 4th IEEE Consumer Communications and Networking Conference*, pages 1022–1026. IEEE, 2007.

[46] Przemyslaw Pawelczak, Gerard JM Janssen, and R Venkatesha Prasad. Wlc10-4: Performance measures of dynamic spectrum access networks. In *IEEE Globecom 2006*, pages 1–6. IEEE, 2006.

[47] J. Milanović, S. Rimac-Drlje, and I. Majerski. Radio wave propagation mechanisms and empirical models for fixed wireless access systems. *Tehnički vjesnik: znanstveno-stručni časopis tehničkih fakulteta Sveučilišta u Osijeku*, 17(1):43–52, 2010.

[48] M.A.K. Abdulsattar and Z.A. Hussein. Energy detector with baseband sampling for cognitive radio: Real-time implementation. *Wireless Engineering and Technology*, 3(04):229, 2012.

[49] P. Lingeswari, K.J. Prasanna Venkatesan, and V. Vijayarangan. Legacy user detection in ofdm based cognitive radio. *IJCA Proceedings on International Conference in Recent trends in Computational Methods, Communication and Controls (ICON3C 2012)*, ICON3C(7):23–27, April 2012.

[50] N. Yadav and S. Rathi. A comprehensive study of spectrum sensing techniques in cognitive radio. *International journal of Advances in engineering & technology*, 1 (3):85, 2011.

[51] Z. Sun. *Design and Implementation of Sequence Detection Algorithms for Dynamic Spectrum Access Networks*. PhD thesis, Citeseer, 2010.

[52] Y. Okumura, E. Ohmori, T. Kawano, and K. Fukuda. *Field strength and its variability in VHF and UHF land-mobile radio service*. Communication Channels: Characterization and Behaviour", Editor B. Goldberg, IEEE Press, 1976.

[53] M. Hata. Empirical formula for propagation loss in land mobile radio services. *IEEE transactions on Vehicular Technology*, 29(3):317–325, 1980.

[54] L. Yin, K. Wu, S. Yin, J. Li, S. Li, and L. M. Ni. Digital dividend capacity in China: A developing country's case study. In *Dynamic Spectrum Access Networks (DYSPAN), 2012 IEEE International Symposium on*, pages 121–130. IEEE, October 2012.

[55] E. Damosso and L.M. Correia. Urban transmission loss models for mobile radio in the 900 and 1800 mhz bands. *The Hague, Sep*, 1991.

[56] T. Zhang, N. Leng, and S. Banerjee. A vehicle-based measurement framework for enhancing whitespace spectrum databases. In *Proceedings of the 20th annual international conference on Mobile computing and networking*, pages 17–28. ACM, September 2014.

[57] S.M. Mishra and A. Sahai. How much white space has the FCC opened up? *IEEE Communication Letters*, 2010.

[58] WG802.11 Wireless LAN Working Group. 802.11af - ieee standard for information technology - telecommunications and information exchange between systems - local and metropolitan area networks. Electronic, IEEE Standards Association, http://standards.ieee.org/getieee802/download/802.11af-2013.pdf, 2013. Date accessed: 2016-8-8.

[59] Federal Communications Commission et al. Second memorandum opinion and order in the matter of unlicensed operation in the tv broadcast bands and additional spectrum for unlicensed devices below 900 mhz and in the 3 ghz band. *Washington, September*, 2010.

[60] Ofcom. Implementing tv white spaces. Electronic, Ofcom, http://stakeholders.ofcom.org.uk/consultations/white-space-coexistence/statement, February 2015. Date accessed: 2016-8-7.

[61] V. Gonçalves and S. Pollin. The value of sensing for TV white spaces. In *New Frontiers in Dynamic Spectrum Access Networks (DySPAN), 2011 IEEE Symposium on*, pages 231–241. IEEE, 2011.

[62] N. Faruk, A. Ayeni, and Y.A. Adediran. On the study of empirical path loss models for accurate prediction of tv signal for secondary users. *Progress In Electromagnetics Research B*, 49:155–176, 2013.

[63] E. Pietrosemoli and M. Zennaro. *TV White Spaces. A pragmatic approach*, volume 1, chapter 4, pages 35–40. ISTB, December 2013.

[64] Ofcom. Decision to make the wireless telegraphy (white space devices) (exemption) regulations 2015. Electronic, Ofcom, http://stakeholders.ofcom.org.uk/spectrum/tv-white-spaces/consultations-statements/tvws-regulations-2015/, 12 2015. Date accessed: 2016-8-7.

[65] G. Iosifidis and I. Koutsopoulos. Challenges in auction theory driven spectrum management. *IEEE Communications Magazine*, 49(8), 2011.

[66] J. Su, J. Wang, and W. Wu. A truthful bilateral multiunit auction for heterogeneous cognitive radio networks. *International Journal of Distributed Sensor Networks*, 2011, 2011.

[67] P. Cui, Y. Dong, H. Liu, D. Rajan, E. Olinick, and J. Camp. Whitemesh: Leveraging white spaces in wireless mesh networks. volume 14 of *14th International Symposium on Modeling and Optimization in Mobile, Ad Hoc, and Wireless Networks (WiOpt)*, pages 100–106, http://ieeexplore.ieee.org/document/7492910/, May 2016. IEEE, IEEE Xplore.

[68] Federal Communications Commission et al. In the matter of unlicensed operation in the tv broadcast bands (et docket no. 04-186) and additional spectrum for unucensed devices below 900 mhz and in the 3 ghz band (et docket no. 02-380): Notice of proposed rulemaking. *Federal Communications Commission, Washington, DC, USA, Tech. Rep. ET Docket*, (04-113), 2004.

[69] CSIR. Csir tv white space database. Technical report, CSIR, Meraka Institute, http://whitespaces.meraka.csir.co.za/about˙page.jsp, 2013.

[70] A.A. Moret, A. Sathiaseelan, M. Zenaro, F. Rondon, E. Pietrosemoli, and D. Johnson. Open and regionalised spectrum repositories for emerging countries. In *Proceedings of the 2016 workshop on Global Access to the Internet for All*, pages 13–18. ACM, 2016.

[71] M. Marco, M. Zennaro, and E. Pietrosemoli. Rftrack: a tool for efficient spectrum usage advocacy in developing countries. In *Proceedings of the Eighth International Conference on Information and Communication Technologies and Development*, page 34. ACM, 2016.

[72] S. Roberts, P. Garnett, and R. Chandra. Connecting africa using the tv white spaces: From research to real world deployments. In *Local and Metropolitan Area Networks (LANMAN), 2015 IEEE International Workshop on*, pages 1–6. IEEE, 2015.

[73] Ofcom. Digital dividend review. Electronic, Ofcom, http://stakeholders.ofcom.org.uk/consultations/ddr/statement/, December 2007. Date accessed: 2016-8-5.

[74] Ofcom. Digital dividend: cognitive access. Electronic, Ofcom, http://stakeholders.ofcom.org.uk/consultations/cognitive/, February 2009. Date accessed: 2016-8-5.

[75] Ofcom. Digital dividend: Geolocation for cognitive access. Electronic, Ofcom, http://stakeholders.ofcom.org.uk/consultations/cogaccess/, November 2009. Date accessed:2016-8-6.

[76] Ofcom. Implementing geolocation-ofcom proposals on how to successfully launch white space technology and how new devices will be made available to consumers without the need for a licence. Electronic, Ofcom, http://stakeholders.ofcom.org.uk/consultations/geolocation/, November 2010. Date accessed: 2016-8-6.

[77] Ofcom. Tv white spaces - a consultation on white space device requirements. Electronic, Ofcom, http://stakeholders.ofcom.org.uk/consultations/whitespaces/, 11 2012. Date accessed: 2016-8-6.

[78] Ofcom. Implementing geolocation - summary of consultation responses and next steps. Electronic, Ofcom, http://stakeholders.ofcom.org.uk/consultations/geolocation/statement/, September 2011. Date accessed: 2016-8-6.

[79] Ofcom. Tv white spaces: Pmse coexistence tests. Electronic, Ofcom, http://stakeholders.ofcom.org.uk/market-data-research/other/technology-research/2014/tvws-pmse-coexistence, November 2014. Date accessed: 2016-8-7.

[80] Ofcom. Tv white spaces: Dtt coexistence tests. Electronic, Ofcom, http://stakeholders.ofcom.org.uk/market-data-research/other/technology-research/2014/tvws-coexistence-tests/, December 2014. Date accessed: 2016-8-7.

[81] IEEE 802.22 Working Group on Wireless Regional Area Networks. Enabling broadband wireless access using cognitive radio technology and spectrum sharing in white spaces-ieee 802-22. Electronic, IEEE Standards Association, http://standards.ieee.org/getieee802/download/802.22-2011.pdf, 2011.

[82] A.N. Mody and G. Chouinard. Ieee 802.22 wireless regional area networks. *Enabling Rural Broadband Wireless Access Using Cognitive Radio Technology*, 2010.

[83] A.B. Flores, R.E. Guerra, E.W. Knightly, P. Ecclesine, and S. Pandey. Ieee 802.11 af: a standard for tv white space spectrum sharing. *IEEE Communications Magazine*, 51(10):92–100, 2013.

[84] D. Lekomtcev and R. Maršálek. Comparison of 802.11 af and 802.22 standards– physical layer and cognitive functionality. *Elektro Revue*, 3(2):12–18, 2012.

[85] C. Ghosh, S. Roy, and D. Cavalcanti. Coexistence challenges for heterogeneous cognitive wireless networks in tv white spaces. *IEEE Wireless Communications*, 18(4):22–31, 2011.

[86] Y. Zeng, Y. Liang, A. Hoang, and R. Zhang. A review on spectrum sensing for cognitive radio: challenges and solutions. *EURASIP Journal on Advances in Signal Processing*, 2010(1):1, 2010.

[87] P.G. Scholar. An overview of cognitive radio architecture. *Journal of Theoretical and Applied Information Technology*, 41(1), 2012.

[88] X. Liu and N.S. Shankar. Sensing-based opportunistic channel access. *Mobile Networks and Applications*, 11(4):577–591, 2006.

[89] A. Kataria. *Cognitive Radios–Spectrum Sensing Issues*. PhD thesis, Citeseer, 2007.

[90] P. Kolodzy. Next generation communications: Kickoff meeting. In *Proc. DARPA*, volume 10, 2001.

[91] V. Krishna. *Auction theory*. Academic press, 2009.

[92] X. Zhou and H. Zheng. Trust: A general framework for truthful double spectrum auctions. In *INFOCOM 2009, IEEE*, pages 999–1007. IEEE, 2009.

[93] Y. Chen and Q. Zhang. *Dynamic Spectrum Auction in Wireless Communication*. Springer, 2015.

[94] X. Zhou, S. Gandhi, S. Suri, and H. Zheng. ebay in the sky: strategy-proof wireless spectrum auctions. In *Proceedings of the 14th ACM international conference on Mobile computing and networking*, pages 2–13. ACM, 2008.

[95] A.P. Subramanian, M. Al-Ayyoub, H. Gupta, S.R. Das, and M.M. Buddhikot. Near-optimal dynamic spectrum allocation in cellular networks. In *New Frontiers in Dynamic Spectrum Access Networks, 2008. DySPAN 2008. 3rd IEEE Symposium on*, pages 1–11. IEEE, 2008.

[96] L. Yu, C. Liu, Z. Liu, and W. Hu. Heuristic spectrum assignment algorithm in distributed cognitive networks. In *2010 6th International Conference on Wireless Communications Networking and Mobile Computing (WiCOM)*, pages 1–5. IEEE, 2010.

[97] Y. Chen, J. Zhang, K. Wu, and Q. Zhang. Tames: A truthful double auction for multi-demand heterogeneous spectrums. *IEEE Transactions on Parallel and Distributed Systems*, 25(11):3012–3024, 2014.

[98] M. Parzy and H. Bogucka. Non-identical objects auction for spectrum sharing in tv white spacesthe perspective of service providers as secondary users. In *New Frontiers in Dynamic Spectrum Access Networks (DySPAN), 2011 IEEE Symposium on*, pages 389–398. IEEE, 2011.

[99] M. Parzy and H. Bogucka. On-line spectrum auctions in tv white spaces for supporting mobile servicesa practical manual. *Telecommunications Policy*, 37(2): 219–230, 2013.

[100] P. Lin, X. Feng, and Q. Zhang. Flexauc: Serving dynamic demands in spectrum trading markets with flexible auction. In *IEEE INFOCOM 2014-IEEE Conference on Computer Communications*, pages 2265–2273. IEEE, 2014.

[101] M. Lopez-Benitez and F. Casadevall. Spectrum usage in cognitive radio networks: from field measurements to empirical models. *IEICE Transactions on Communications*, 97(2):242–250, 2014.

[102] M. Zennaro, E. Pietrosemoli, J.S.P. Mlatho, M. Thodi, and C. Mikeka. An assessment study on white spaces in malawi using affordable tools. In *Global Humanitarian Technology Conference (GHTC), 2013 IEEE*, pages 265–269. IEEE, 2013.

[103] Federal Communications Commission et al. Antenna height above average terrain (haat) calculator. *Online, Retrieved*, 4(7):16, 2016.

[104] S. Ramanathan. A unified framework and algorithm for channel assignment in wireless networks. *Wireless Networks*, 5(2):81–94, 1999.

[105] R. Peeters. *On coloring j-unit sphere graphs.*

[106] A.P. Subramanian, H. Gupta, S.R. Das, and M.M. Buddhikot. Fast spectrum allocation in coordinated dynamic spectrum access based cellular networks. In *2007 2nd IEEE International Symposium on New Frontiers in Dynamic Spectrum Access Networks*, pages 320–330. IEEE, 2007.

[107] A. Gräf, M. Stumpf, and G. Weißenfels. On coloring unit disk graphs. *Algorithmica*, 20(3):277–293, 1998.

[108] M. Hristakeva and D. Shrestha. Solving the 0-1 knapsack problem with genetic algorithms. In *Midwest Instruction and Computing Symposium*, 2004.

[109] R. Coudé. *Radio Mobile - RF propagation simulation software.* http://radiomobile.pe1mew.nl/, 1998.

[110] A. Vázquez-Rodas and L.J. de la Cruz Llopis. Topology control for wireless mesh networks based on centrality metrics. In *Proceedings of the 10th ACM symposium on Performance evaluation of wireless ad hoc, sensor, & ubiquitous networks*, pages 25–32. ACM, 2013.

[111] M. Newman. Networks: an introduction. *United Slates: Oxford University Press Inc., New York*, pages 1–2, 2010.

[112] J. Zhao, H. Zheng, and G. Yang. Distributed coordination in dynamic spectrum allocation networks. In *New Frontiers in Dynamic Spectrum Access Networks, 2005. DySPAN 2005. 2005 First IEEE International Symposium on*, pages 259–268. IEEE, 2005.

[113] P.H. Pathak and R. Dutta. *Designing for network and service continuity in wireless mesh networks.* Springer Science & Business Media, 2012.

[114] H. Karl and A. Willig. *Protocols and architectures for wireless sensor networks.* John Wiley & Sons, 2007.

[115] F. Zhao and L.J. Guibas. *Wireless sensor networks: an information processing approach.* Morgan Kaufmann, 2004.

[116] M.A. McHenry, K. Steadman, and M. Lofquist. Determination of detection thresholds to allow safe operation of television band" white space" devices. In *New Frontiers in Dynamic Spectrum Access Networks, 2008. DySPAN 2008. 3rd IEEE Symposium on*, pages 1–12. IEEE, 2008.

[117] D. Makris, G. Gardikis, and A. Kourtis. Quantifying tv white space capacity: quantifying tv white space capacity. *IEEE Communications Magazine*, 50(9):145–152, 2012.

[118] M. Iwamura, K. Etemad, M. Fong, R. Nory, and R. Love. Carrier aggregation framework in 3gpp lte-advanced [wimax/lte update]. *IEEE Communications Magazine*, 48(8), 2010.

[119] K.I. Pedersen, F. Frederiksen, C. Rosa, H. Nguyen, L.G.U. Garcia, and Y. Wang. Carrier aggregation for lte-advanced: functionality and performance aspects. *IEEE Communications Magazine*, 49(6), 2011.

[120] G. Yuan, X. Zhang, W. Wang, and Y. Yang. Carrier aggregation for lte-advanced mobile communication systems. *IEEE Communications Magazine*, 48(2), 2010.

[121] H. Mauwa, A. Bagula, and M. Zennaro. Exploring tv white spaces for use in campus networks. In *International Conference on e-Infrastructure and e-Services for Developing Countries*, pages 14–25. Springer, 2015.

[122] N. Li, J.C. Hou, and L. Sha. Design and analysis of an mst-based topology control algorithm. *IEEE Transactions on Wireless Communications*, 4(3):1195–1206, 2005.

[123] P.M.W. Rojas. Topology control in wireless sensor networks. 2010.

[124] K. Sohraby, D. Minoli, and T. Znati. *Wireless sensor networks: technology, protocols, and applications.* John Wiley & Sons, 2007.

[125] D. Katsaros, N. Dimokas, and L. Tassiulas. Social network analysis concepts in the design of wireless ad hoc network protocols. *IEEE network*, 24(6), 2010.

[126] L.C. Freeman. Centrality in social networks conceptual clarification. *Social networks*, 1(3):215–239, 1978.

[127] G. Sabidussi. The centrality index of a graph. *Psychometrika*, 31(4):581–603, 1966.

[128] M.A. Beauchamp. An improved index of centrality. *Behavioral science*, 10(2): 161–163, 1965.

[129] A. Cuzzocrea, A. Papadimitriou, D. Katsaros, and Y. Manolopoulos. Edge betweenness centrality: A novel algorithm for qos-based topology control over wireless sensor networks. *Journal of Network and Computer Applications*, 35(4):1210–1217, 2012.

[130] E. Stai, V. Karyotis, and S. Papavassiliou. Topology enhancements in wireless multihop networks: a top-down approach. *IEEE Transactions on Parallel and Distributed Systems*, 23(7):1344–1357, 2012.

[131] C.K. Verma, B.R. Tamma, B.S. Manoj, and R. Rao. A realistic small-world model for wireless mesh networks. *IEEE Communications Letters*, 15(4):455–457, 2011.

[132] M. Kas, S. Appala, C. Wang, K.M. Carley, L.R. Carley, and O.K. Tonguz. What if wireless routers were social? approaching wireless mesh networks from a social networks perspective. *IEEE Wireless Communications*, 19(6), 2012.

[133] E.M. Daly and M. Haahr. Social network analysis for routing in disconnected delay-tolerant manets. In *Proceedings of the 8th ACM international symposium on Mobile ad hoc networking and computing*, pages 32–40. ACM, 2007.

[134] A.B. Bagula and A.E. Krzesinski. Traffic engineering label switched paths in ip networks using a pre-planned flow optimization model. In *Modeling, Analysis and Simulation of Computer and Telecommunication Systems, 2001. Proceedings. Ninth International Symposium on*, pages 70–77. IEEE, 2001.

[135] J. Yu, N. Wang, G. Wang, and D. Yu. Connected dominating sets in wireless ad hoc and sensor networks–a comprehensive survey. *Computer Communications*, 36 (2):121–134, 2013.

[136] F. Dai and J. Wu. On constructing k-connected k-dominating set in wireless ad hoc and sensor networks. *Journal of parallel and distributed computing*, 66(7): 947–958, 2006.

[137] S. Kutten and D. Peleg. Fast distributed construction of k-dominating sets and applications. In *Proceedings of the fourteenth annual ACM symposium on Principles of distributed computing*, pages 238–251. ACM, 1995.