KWAME NKRUMAH UNIVERSITY OF SCIENCE AND TECHNOLOGY

MEASUREMENT OF TELEVISION WHITE SPACE SPECTRUM IN THE CENTRAL REGION OF GHANA

BY

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DECLARATION

I hereby declare that this submission is my own work towards the conferment of Master of Philosophy Degree in Information Technology and that, to the best of my knowledge, it contains no material previously published by another person, nor material which has been accepted for the award of any other degree of the University, except where due acknowledgement has been made in the text.

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DEDICATION

I dedicate this thesis to God Almighty for His abundance of grace, guidance and provision throughout the period of my pursuit of this Master of Philosophy Programme.

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ABSTRACT

Recent studies on efficient TV frequency spectrum used have proven that TV frequency spectrum in most geographical areas (*especially the rural areas*) are underutilized. These significant researches have shown that, the amount of frequency spectrum which is under-utilized in the TV bands is much larger than the spectrum available for use by current unlicensed user applications and services. TV White Space is an emerging concept of technology that has emanated while studying the effective utilisation and efficient management of the TV spectrum in various regions of the world. Studies have also shown that the actual unutilized frequency spectrum available varies significantly from one geographical area to another spatially as well as temporally. For this reason, TV white space estimation has been done in countries like the United States (US), the United Kingdom (UK), Europe, and Japan but unfortunately in Ghana, to the best of the authors' knowledge no such work has been done. This thesis presents the very first effort of estimation of the amount of available TV white spaces in the Central Region of Ghana. In this study, TVWS is used as a tool for effective utilisation and efficient management of frequency spectrum. The very first localized geolocation database for TVWS in Central Region of Ghana is presented. Comparative analysis of Wi-Fi and TVWS networks revealed that Wi-Fi in the absence of strong interference from its environment works better in LoS networks while TVWS works better in the NLoS network mode. Also signal strength tests performed has shown that geographical features of a location and weather elements can have significant effect on the quality of signal strength. Finally, a proposed hybrid method for the protection of incumbent spectrum users and WSD from interference is demonstrated.

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AM	-	Amplitude Modulation
AP	-	Access Point
BS	-	Base Station
BSS	-	Basic Service Set
CBS	-	Cognitive Base Station
CDMA	-	Code Division Multiple Access
CR	-	Cognitive Radio
CRS	-	Cognitive Radio System
CS dB	-	Cooperative Sensing deci-
dBm	-	Bel deci-Belmilli-watt
dBu	-	deci-Belunit
DSA	-	Dynamic Spectrum Access
DTV	-	Digital Television
DTT	-	Digital Terrestrial Television
DYSPAN	-	Dynamic Spectrum Access Networks
ECC	-	Electronics Communications Committee
EIRP	-	Equivalent Isotropically Radiated Power
ETSI	-	European Telecommunications Standards Institute
FCC	-	Federal Communications Commission
FDMA	-	Frequency Division Multiple Access
FH	-	Frequency Hopping
FM	-	Frequency Modulation
FSA	-	Fixed Spectrum Access
GDB	-	Geolocation Database
GHz	-	Giga Hertz
GPS	-	Global Positioning System
HTTPS	-	Hyper Text Transfer Protocol Secure
ICT	-	Information and Communications Technology
IEEE	-	Institution of Electrical and Electronic Engineers
IETF	-	Internet Engineering Task Force
	-	

ISM	-	Instrumentation, Scientific, and Medical
ITU	-	International Telecommunications Union
LAN	-	Local Area Network
LGDB	-	Localised Geolocation Database
LoS	-	Line-of-Sight
LTDS	-	Localised TVWS database
MHz	-	server Mega Hertz milliWatt
mW	-	National Communications Authority
NCA	-	Non-Line-of-Sight
NLoS	-	Opportunistic Spectrum Access
OSA	-	Protocol to access White-Space
PAWS	-	Physical Layer
PHY	-	Program Making and Special Events
PMSE	-	Registered Location Secure Server
RLSS	-	Return on Investment
RoI	-	Received Signal Strength Indicator
RSSI	-	Software Defined Radio
SDR	-	Signal-to-Noise-Ratio
SNR	-	Time Division Multiple Access
TDMA	-	Television White Spaces
TVWS	-	Ultra-High Frequency
UHF	-	United Kingdom
UK	-	United States
US	-	Ultra-Wide Band
UWB	-	Very High Frequency
VHF	-	Wireless Fidelity
Wi-Fi	-	White Space
WS	-	White-Space Device
WSD	-	White-Space Database
WSDB	-	

CHAPTER ONE

INTRODUCTION

1.0 Background

Wireless network connectivity has never been in great demand as it is seen now. This demand has been driven by advances in telecommunication technology and devices which render access to new services in such a way that seemed not possible to previous generations (Pahlavan & Levesque, 2005). In the forefront are mobile broadband and wireless access to the Internet, but there is also a wide range of other applications making great demands for wireless connectivity. For this reason, there is a great burden on current network infrastructure due to the increasing freedom of wireless access which consumers now expect. In view of that network operators are working very hard to bring optical fibre closer to customers, to deliver superfast broadband access (Frangoudis et al., 2011). The introduction of new technologies and the use of cellular networks have helped to improve the performance of wireless networks by making judicious use of existing spectrum allocations (Wang et al., 2014). Notwithstanding, there is still the need to work out for new opportunities to free up spectrum from older technologies, to be used by new wireless networks. Regulators have scoured the bands for opportunities to do exactly that. Unfortunately, this work has been very slow and cost intensive.

In order to overcome this challenge, another approach that has recently gained support is the sharing of spectrum through dynamic spectrum access techniques. Dynamic spectrum access would enable wireless network access to a wide range of applications which might otherwise struggle to have access to spectrum (Brown et al., 2014).

Dynamic Spectrum Access uses location-aware devices and online databases to deliver cost effective and efficient broadband access and other forms of network connectivity to consumers. This approach is based on the idea that devices with greater knowledge about their environment can opportunistically utilize available radio spectrum that are temporary unoccupied by their primary users (Wang et al., 2011). These unoccupied TV broadcast channels can be found in nearly every location in the world. These unused channels or blocks of spectrum known as “white spaces” have been proven to be a key part of the future; not just for the provision of universal broadband access but also the solution for the explosion of devices connecting the Internet (Stevenson et al., 2009). Television White Spaces provide an excellent opportunity to demonstrate the power of this new spectrum sharing technology, based on the use of cognitive radio techniques.

TVWS which was originally conceived of as a technology that could take advantage of the guard bands also known as white spaces (*frequency gabs that were left between television channels to prevent interference*) have now emerged as a secondary spectrum technology which is capable of utilizing unused television spectrum in a dynamic manner (Zennaro & Pietrosemoli, 2013). Television White Space (TVWS) is an emerging technology in the field of Information Technology that offers new economic benefits and provides an opportunity to improve Internet services to the remote parts of the world. These TVWSs have recently been of great interest to industry and spectrum regulators because, TV broadcasting is not making use of some allocated frequencies in certain geographic areas and hence created coverage holes (Nekovee, 2010). Several studies have shown that most of the TV frequency bands in urban, sub-urban and especially the rural areas are under-utilized. It is therefore clear that the amount of spectrum which is under-utilized is much larger than that which is available for the implementation of current unlicensed applications (Pietrosemoli & Zennaro, 2013). This eventually has resulted in the ineffective use and inefficient management of TV frequency spectrum with about eighty percent (80%) of allocated spectrum not being used, thereby creating an artificial spectrum scarcity (Akyildiz et al., 2006; Kaniezhil, 2012). However, this artificial spectrum scarcity has been created due to strict regulatory policies governing the use of frequency spectrum by various regulatory bodies. Because these rigid regulations governing the use and management of spectrum have impaired innovations, all stakeholders are urging for a paradigm shift in the old regulatory regime to address the growing demand of spectrum (Yucek & Arslan, 2009). This therefore, has resulted in many regulators showing their willingness to allow secondary opportunistic access to the licensed spectrum bands (Bayileyegn, 2012).

But contrary to the conventional static spectrum allocations, these TVWS frequencies will still be needed by these license users (*Primary Users*) and therefore cannot be leased for permanent use by the unlicensed users (*Secondary users*) (Bayileyegn, 2012). The new unlicensed user can only use these TVWS spectrum at a time when there is no transmission by the primary user. This dynamic frequency spectrum access scheme needs a new enabling technology such as Cognitive Radio (CR), a radio which is capable of changing its transmission parameters based on its location. Cognitive radio technique has been the proposed technology to ensure that the TV white space devices do not cause any harmful interference to the incumbent services provided by the primary users operating in the occupied TV bands (Rayal, 2010) (Jones & Thomas, 2007). The operation of TV white space devices (WSD) is on the condition that these devices do not cause any harmful interference to the licensed services in the TV bands ((Pietrosemoli & Zennaro, 2013). Television White Space (TVWS) technology therefore, uses cognitive radio technique to address this spectrum deficiency problem. TV white spaces (TVWS) also known as interleaved spectrum are “portions of spectrum left unused by TV broadcasters. TVWS also referred to as portions of spectrum that are currently unoccupied in the terrestrial television frequency bands in both VHF and UHF TV spectrum be it analogue or digital (ITU, 2013). These unlicensed and unused frequencies found in the allocated and unallocated portions in the VHF and UHF TV spectrum (*especially white spaces in the UHF TV bands*) have been of much interest due to their superior propagation characteristics as a wireless backhaul with an excellent Non-Line-of-Sight (NLoS) network coverage. In view of that, these TV white spaces have been investigated and identified to be the next potential immediate solution to spectrum scarcity for emerging wireless services (Bayileyegn, 2012).

Since the amount of TV white space spectrum available varies with geographical location and time, measurement of TV white space has been done in countries like the United States (US), the United Kingdom (UK), Europe, Japan and India (Mishra & Sahai, 2009), (Nekovee, 2009), (van de Beek et al., 2012), (Shimomura et al., 2012) but unfortunately in Ghana, to the best of the authors' knowledge, no such work has been done. This thesis presents the very first effort to estimate the amount of available TV white spaces that have excellent propagation characteristics in a comprehensive manner in the rural communities in the Central Region of Ghana. In this work, a detailed quantitative assessment and estimates of these available TV white spaces and propagation characteristics of these frequencies are presented. TVWS is used as a tool for effective utilisation and efficient management of frequency spectrum. In this thesis, the development of the first localised geolocation TVWS database for the rural communities in the Central Region of Ghana is presented. This is because, though, there exist some form of data from the NCA on the available TV White Spaces, no active geolocation database is available for the protection of the terrestrial TV broadcast receivers and the coexistence of secondary TVWS devices.

It must also be noted that, the so-called “white spaces” are in fact not so “white” as the name suggests. They are not completely clean bands since they naturally suffer from “pollution” due to residual power signals emanating from neighbouring DTV transmitters. Although these signals may be too weak to be decoded, they are still considered a potential source of interference for TVWS devices (Harrison et al., 2010). To ensure a very high tolerable co-channel interference levels and error-free operation, a hybrid method for protection of incumbent frequency spectrum users and secondary TVWS devices from interference is demonstrated.

In conclusion, the exploitation of these TV white spaces has been a major challenge not for only manufacturers but also for spectrum regulators. This is because the idea of secondary use of TV spectrum bands is quite novel and presents several challenges when it comes to regulation (Makris et al., 2012). Regulators have the mandate to ensure that primary spectrum users (licensed TV broadcasters) are absolutely protected against potential interference and at the same time, sufficient freedom given to secondary users to exploit the available underutilised spectrum. In view of that, analysis of the various methods for accessing available TVWS spectrum is done and a suitable method for the spectra ecosystem of Ghana proposed.

1.2 Problem statement

Reliable access and cost-effectiveness are key challenges facing the provision of Internet connectivity in most rural communities in Ghana. This is due to lack of adequate infrastructure and high cost of network connectivity especially in the rural areas (Achampong, 2012). It is very expensive to lay fibre or cable in these rural areas due to their geographical make-up and low population density, except for satellite connectivity where even cost-effective and low latency solutions are still under development. In this case, wireless access becomes the only practical solution. But traditional Wi-Fi technologies have not been able to provide a reliable wide area network coverage under non-line-of-sight (NLoS) condition due to the geographical features of these rural communities.

Television White Space (TVWS) is an emerging wireless technology that can offer a reliable long-range non-line-of-sight (NLoS) network coverage and at the same time provide efficient use of Radio Frequency spectrum. Studies have shown that these TVWSs vary significantly from one geographical area to another spatially as well as temporally. Thus, adequate information on their existence is very vital to their utilisation. For this reason, TV white space estimation has been done in countries like the United States (US), the United Kingdom (UK), Europe, and Japan but unfortunately in Ghana, to the best of the authors' knowledge no such work has been done. It is against this background that television white space (TVWS) in the rural communities in the Central Region of Ghana be measured.

1.3 Research objective

Investigate the existence of television white space (TVWS) and utilize it as a network backhaul for the provision of Internet access to rural communities in the Central Region of Ghana.

1.3.1 Specific Objectives

1. To find out how much of TVWS spectrum is available in rural Ghana.
2. To develop a localised geo-location database of available TVWS frequency spectrum.
3. To compare the propagation characteristics of TVWS network to Wi-Fi.
4. Propose a hybrid method for access and protection of incumbent frequency spectrum users and White Space Device from interference.

1.4 Research questions

During the study, we shall be able to find or give answers to these very pertinent questions:

1. How much of TVWS spectrum is available in rural Ghana?
2. How do we develop a localised geo-location database for available TVWS frequency spectrum?
3. What are the propagation characteristics of TVWS network compared to Wi-Fi?
4. How do we ensure that incumbent spectrum users and White Space Devices (WSD) are protected from interference?

1.5 Significance of the study

The availability of TVWS presents a great opportunity for the provision of a network backhaul for the rural communities in Central Region of Ghana because of the following reasons: Since, TVWS is a secondary-spectrum-use technology, its utilisation does not need a re-allocation of spectrum in order to regulate its use. This is because regulators are not committed to give away a spectrum band to a user for specific number of years. Also, the government will not be exposed to the challenges that emanate from spectrum auctions which sometimes end in stalled process as seen from the experience in South Africa. TVWS used will also help to deal with the widespread corruption associated with the auctioning of spectrum bands as seen in India (Naik et al., 2014). Again, TVWS spectrum measurement and use will help deal with the major challenge faced by communication network operators in the provision of network access in the rural areas (*which is the economic viability for the installation and maintenance of mobile base stations*). TVWS has specific advantages that makes it a suitable complementary network access technology for rural communities. Thus, it offers a very long-range coverage translating into lower cost for high bandwidth networks and reduction in the complexity of wireless communications network setup and maintenance. It also has an excellent vegetation and in-building penetration, guaranteeing a very strong signal Non-Line-of-Sight (NLoS) network connection. Finally, the rising demand for licensed spectrum has raised the bar for market entry so high that small entrepreneurs find it very difficult to get involve. But contrary to the above-mentioned challenge, TVWS technology is projected to open up rural broadband service delivery to a new breed of entrepreneurs who are interested in providing local competitive broadband Internet services.

1.6 Scope of the Study

This study is on TVWS utilisation which is an emerging area in the field of computer networking. The study focused on quantitative analysis of available TVWS spectrum in the Central Region of Ghana. But due to time and resource constraint, the study was done only in Cape Coast and its' surrounding villages. TVWS and Wi-Fi point-tomultipoint networks were setup. The performance of the networks is tested using parameters such as throughput, latency and RSSI and results compared. Furthermore, the study proposes a hybrid method of protection as an appropriate technique for controlling frequency interference to incumbent spectrum users and WSD.

1.7 Research organization

This thesis is organized into five chapters as follows: Chapter One, consist of the background of the thesis work. Chapter Two, enumerates on related works that have been done by some researchers on TVWS utilisation and also discusses how TWVS is deploy as a cost effective and efficient technology for long distance NLoS wireless network backhaul in the rural communities in the Central Region of Ghana. Chapter Three covers the methodology. In this chapter, a discussion on how low-cost radio sensing devices are used in the assessment of the availability of TVWS is presented.

Also, Carlson's RuralConnect WSD is used in the implementation of TWVS as a network backhaul for the provision of Internet access to rural communities in Central Region of Ghana. Chapter Four covers the analysis and results of a quantitative assessment of the availability of TVWS in rural Ghana. A comparative assessment and results of the propagation characteristics TVWS and Wi-fi is presented. A qualitative analysis of the various methods for accessing TVWS spectrum and protection of primary TV spectrum users and WSDs from interference is presented.

Finally, the performance of the proposed Hybrid method for access and protection of incumbent TV spectrum users and WSDs is demonstrated. Chapter Five covers the conclusion of the thesis and recommendation. It also proposes a future study which could be done in this area.

CHAPTER TWO

RELATED LITERATURE

2.0 Introduction

This chapter gives a short overview on spectrum access and enumerates on related works that have been done by some researchers on TVWS utilisation in some parts of the developed and developing world. It also highlights the features and the fundamental concepts of cognitive radio techniques in the protection of incumbent spectrum users from interference. This part also discusses how dynamic spectrum access is used as a tool for effective utilisation and management of radio frequency spectrum. A comparison between TVWS and traditional Wi-Fi networks is discussed. The need for hybrid method for the protection of primary spectrum users and TVWS devices from interference is also presented. Finally, it also discusses how TWVS could be deployed as a cost effective and efficient technology for long distance NLoS wireless network backhaul for the provision of Internet in rural communities in the Central Region of Ghana.

2.1 Spectrum Access

Until recently, transmission of radio signals has been done by accessing spectrum using what is known as fixed spectrum access (FSA). In this spectrum access mode, fixed radio frequency slots are dedicated to specific services in specific regions. Thus, the assigned frequency band cannot be changed during the license validity. In contrast, in Frequency Hopping (FH) systems, the carrier frequency varies, but only within the assigned band. Current Frequency Allocation Tables in Radio Regulations set precisely such a mode of operation. Though special methods have been developed to use optimally spectrum resources in this mode, these methods have not proven to be effective as expected (Leese, 2002).

DSA which may be seen as a generalization of FH systems, is a concept in which not only the carrier frequency can vary, but also the assigned frequency band. This liberates radio systems from the constraint to function on a fixed radio frequency dedicated to a specific service at a specific region. Since in FSA spectrum users operate on fixed frequency bands assigned to them by regulators, they are able to set up static coexistence conditions for the compatibility of existing and new regulations.

This has been the solution to the co-existence of earth satellite stations and terrestrial radio-relay links which share frequency spectrum. However, FSA conditions may not be applicable and the priori sharing conditions insufficient, should there be changes in signal power and direction of arrival. In such case, the Dynamic Spectrum Access concept has to be applied systems (Pietrosemoli & Zennaro, 2013). This is because Dynamic Spectrum Access Systems are capable of switching automatically from one frequency band to another. In this way, the spectrum previously allocated for exclusive use can be shared at a given time in a particular region. This is done under the condition that the potential interference cause by the new user are kept within acceptable limits. Such a mode of operation requires that existing technical, legal, and other aspects of spectrum management fit the actual local conditions.

2.2 Dynamic spectrum access (DSA)

Dynamic spectrum access also known as opportunistic spectrum access (OSA) which uses cognitive radio techniques for effective usage and efficient management of frequency spectrum may look daunting, but the technical challenges it poses create the opportunity to try new technologies such as TVWS (Hossain et al., 2009). This if carefully investigated, can help to potentially harvest the untapped capacity of spectrum more efficiently than traditional licence-based approaches have been able to do so far. This traditional licence-based approaches have resulted in a digital divide, existing between developed and developing countries (countries who are far behind in terms of infrastructure and resources). Essentially these countries are being excluded from the current global technological exchange of information. This situation tends to be worse even within developing countries, where there is also a further divide between urban and rural areas. This problem therefore, opens the door for possible utilisation of these unoccupied spectrums opportunistically (Ghasemi & Sousa, 2005). Hence, the ability to detect and utilise this unoccupied frequency spectrum and using them opportunistically forms the foundation for the thesis.

2.2.1 Classification of Dynamic Spectrum Access

Dynamic Spectrum Access can be categorised into three categories with dynamic exclusive use and hierarchical access models subdivided into two as shown in Figure 2.0.

2.2.1.1 Dynamic exclusive use model

This model still maintains the basic structure of static spectrum allocation policy. In this model spectrum bands are licensed for exclusive use by operators, services and technologies, but putting in place flexible measures has helped to optimize the spectrum efficiency. This model is subdivided in two models:

- **Spectrum property rights:** In this model, the economy and market play a very vital role in ensuring a profitable use of spectrum. Licensed users have the liberty to sell and lease some portions of their licensed spectrum and to choose a suitable technology to deploy as well as the service to be delivered in that licensed spectrum band. It should be noted that this spectrum sharing approach is not mandated by regulatory policy, though licensed users can sell or lease some of their spectrum for economic profit. (Zhao & Swami, 2007).
- **Dynamic spectrum allocation**: This method enables two or more networks of a converged radio system to share a band of spectrum by adapting to either

temporal or spatial variations. Bandwidth reservation results in inefficient use of spectrum in large geographical areas for long periods of time. Hence, exploitation of spatial and temporal traffic variations of different services could be used to improve spectrum efficiency (Hatfield & Weiser 2005).

2.2.1.2 Open sharing model

This model is also known as spectrum commons. It looks at open sharing of spectrum band among peer users as the basis for managing a spectral region. Open sharing model adopts a similar approach use in the management of wireless services operating in the unlicensed Industrial, Scientific, and Medical (ISM) band. Advocates of this model believe that regulation of wireless transmissions could be done by baseline rules enabling users to avoiding interference, coordinate their deployment, and preventing congestion **(**Leaves, 2004**).**

2.2.1.3 Hierarchical access model

This is a hybrid model built upon a hierarchical access structure that distinguishes between licensed and license exempt users. It uses a combination of some features of the dynamic exclusive use and open sharing models. The basic idea behind it, is to open licensed spectrum to secondary users by limiting the interference perceived by primary users. This model uses two approaches in sharing spectrum between primary and secondary users:

- **Spectrum underlay:** This mode uses technologies such as Code Division Multiple Access (CDMA) or Ultra-Wide Band (UWB) to spread secondary transmissions over a wide frequency band. Thus, enabling overlapping of transmissions from secondary users by the imposition of severe restrictions on their transmission power; ensuring they operate below the noise floor of primary users. By this approach, activities of primary users do not need to be tracked while secondary users can potentially obtain high data rates with extremely low transmission power. The greatest challenge with this approach is its low transmission power which limits its implementation in short-range applications (Lehr & Crowcroft, 2005).

- **Spectrum overlay:** Unlike spectrum underlay this model is characterized by severe restriction on when and where secondary users may transmit rather than the transmission power. The basic idea of this approach is to define spatial and temporal spectrum gaps (white spaces) not occupied by primary users and exploit them in an opportunistic and nonintrusive way. Hence, this approach is also known as Opportunistic Spectrum Access (OSA) (Santivanez et al., 2006).

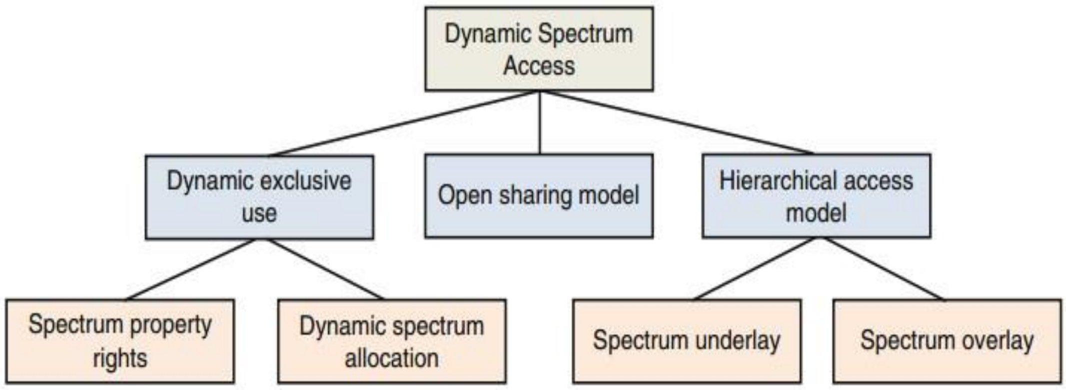

Figure 2. 0: Classification of the dynamic spectrum access models (Source: Santivanez et al., 2006)

2.3 Cognitive Radio System

According to ITU, Cognitive Radio System (CRS) can be define as a radio system that employs technology which allow the system to obtain knowledge of its operational and geographical environment, established policies and its internal state; to dynamically and autonomously adjust its operational parameters and protocols according to its obtained knowledge in order to achieve predefined objectives; and to learn from the results obtained (ITU, 2009). CRs have the capability to learn about their environment and dynamically reconfigure their operational parameters in accordance to their usage. CRs are similar to software-defined radios which have the ability to change a wide range of their characteristics such as frequency of operation, bandwidth, waveforms, and protocol stacks etc. (Nychis et al., 2009). However, cognitive behaviour can span a wide variety of techniques. One example of cognitive radio by virtue of its designed, is capable of detecting dynamically changing conditions of spectrum quality and thereby automatically choosing the best available channels in its operating environment (Sun, 2013).

Because of the above-mentioned features, CR technique has been proposed as an effective solution to the dilemma presented by the quick growth of wireless communications and the scarcity of spectrum resources. It is therefore seen as a future solution for the increasing demand for radio spectrum. Thus, CR allows increasing spectrum efficiency and increased number of radio services in operation in the same place and/or time by using Dynamic Spectrum Access (DSA) techniques. This is accomplished by means of spectrum sensing, in which research is still ongoing towards the development of better algorithms for spectrum sensing, both in narrow and wide band (Sun, 2013). However, while sensing is one tool enabling cognitive behaviour, its effectiveness is limited in some scenarios. (*involve widely dispersed operation, lack of coverage, and non-reciprocal use cases*). In the same vein, at the policy level, some obstacles to practical operation of autonomous cognitive radios must eventually be addressed. There should be modifications on existing regulations regarding the frequencies used by such radios. Cognitive radio technologies can also be permitted through the use of database-directed spectrum allocation schemes and database-assisted policy control. This can also be implemented by using intelligent network management, where individual radios are made aware of spectrum opportunities through network assistance. These individual approaches notwithstanding, the limitations they present has pushed for the proposal of a cooperation between them in order to offer a synergistic advantage when used together.

2.4 Spectrum Assessment

Spectrum occupancy has recently become a very interesting issue as the quest for effective utilisation and efficient management of radio spectrum continue. This has been evidenced by some empirical measurements conducted in the radio environment in a bid to ascertain the spectrum usage by different wireless services. Majority of these researches reach a common conclusion on the need for a further measurement of spectrum occupancy at different locations over varied periods. This therefore motivates the need for spectrum occupancy measurement in the rural communities in the Central region of Ghana. On concluding their investigations, some authors affirm that, the major challenges of spectrum occupancy measurements in multiple geographic locations are the high-cost of radio frequency measuring equipment and also the time it takes for the deployment of these equipment (Vo Nguyen Quoc Bao et al., 2011). That is why in this project RF Explore Spectrum Analyser, a low-cost handheld radio spectrum analysing device designed to be intuitive and easy to use to identify and geo-tag RF spectrum in the sub band of 15-2700MHz and 4850-6100MHz has been adopted.

2.5 How to identify TVWS

The exploitation of TVWS has been a major challenge not only for manufacturers but also for spectrum regulators. This is because the utilisation of these licensed but unused or unlicensed TV spectrum bands in a secondary use mode is quite novel and for that matter presents several regulation difficulties (Makris et al., 2012). It must be noted that, the successful implementation of a TVWS network is on the condition that primary users (licensed TV broadcasters) are absolutely protected against potential interference and, at the same time, sufficient freedom given to the secondary users to exploit available frequency spectrum. In order to achieve this aim, three methods have been proposed by experts in the field for the exploitation of TVWSs. These are beaconing (pilot channel), spectrum sensing, and geolocation database. But the reality is that each of these methods has its pros and cons depending on the geographical area.

Beaconing (Pilot channel)

Beaconing has been identified as one of the possible solutions for protection of the incumbent spectrum users from interferences that may be caused by WSDs. In this method of protection, a dedicated channel is used to broadcast information about free channels that are available and current spectrum usage to every WSD. The major problem with this method is finding a common regional-wide or world-wide frequency allocation that would be used for such special pilot channel (Pietrosemoli, 2013). This due to the differences in frequency allocations in different countries. Even when it is decided that each country could separately allocate a channel as a pilot channel, in that case many pilot frequency bands would be operating around the World and that could further complicate the current wireless market. Also, device standardization would be difficult to achieve. At the same time, different interference problems between stations that are transmitting beacons in different regions would have to be mitigated. Due to the challenges mentioned above, the beaconing has been met with limited success so far because of the complexities involved in its implementation. Hence, alternative methods of protection such as spectrum sensing and geolocation databases seem to be more promising.

Spectrum sensing

Spectrum sensing by the CRS devices is considered the natural solution for learning about the existence of other incumbent radio services and controlling of emission parameters of device. It uses an approach known as "listen before talk". WSDs listen (scan) for a wireless signal transmission to determine whether a TV channel is vacant or occupied. Measurement of the energy level in a spectrum band is performed and compared to that of a set threshold value. If the energy level is above the threshold value, then a transmission signal by a primary user is considered present otherwise the spectrum band is considered vacant. This measurement is done either by energy detection or feature extraction. The energy detection (*commonly proposed method due to its simplicity*) is done with a spectrum analyser while feature extraction which is more sensitive and also more complex, is based on specific characteristics of the type of signal to be detected (Brown et al., 2014).

Spectrum sensing means the current spectrum condition of the spectral environment must be constantly detected and learned by the CRS devices in order to determine current spectrum usage. This method however, is still under research because of the following reasons: First of all, there is "hidden node" problem - where due to obstruction (*hills, high-rise buildings, impenetrable vegetation, etc.*) the sensing device is unable to sense primary signals on the receiving path. In such condition, a false declaration of spectrum as free and available for use could occur, when in reality it is occupied and unavailable or otherwise. Thus, eventually creating a spectrum prediction error (Gomez, 2013).

In order to overcome this problem (*hidden node*), cooperative Sensing (CS) has been proposed. CS uses multiple devices together, instead of a single device for sensing the spectrum and share the information that they have accumulated (Lavaux, 2010). Though CS has the potential to solve the hidden node problem, it is a very complicated solution. This is because it cannot be used without recurring to additional protection mechanism and does not also work in the protection of receive-only services, such as radio astronomy. It is for this reason; a hybrid method of incumbent spectrum protection is proposed.

Geolocation Databases.

Currently, geolocation database is considered as the most promising solution to incumbent services because it offers a one-off simple solution to many of the problems (*the hidden node problem, protection of reception-only devices and sensing level etc.*). GD is suitable for all types of transmissions and frequency ranges. This is because every regulatory provision for any radio system can be registered along with the rules that will determine the availability of White Space Spectrum in a controlled database. With GD method of protection, the WS device must be able to determine its location with the aid of a GPS, send its geographical coordinates to an online database and queries it either directly or via a Master device as shown in Figure 2.1. This queries request for available channels under specific conditions (such as transmission power, antenna height, mode of operation, etc.) (Doyle, 2009).

The information in the geolocation database is use to predict which frequencies are available at different locations by using the details of primary transmitters and radio propagation models. It must be noted that the quality of the propagation model used in the prediction of the signal coverage and reliability of the database information determine the accuracy of available TV signal at a given location (Brown et al., 2014). This content of the database can easily be modified which makes spectrum usage and protection of incumbent channels more flexible. The GD also contains "safe harbour" channels that are forbidden for CRS. This is because these channels are reserved for special applications such as Program Making and Special Events (PMSE) channels. With the support of the GD, a real-time on-line spectrum-related operation can be performed. This is necessary to ensure protection of primary users from WS CR devices that have access to channels for just a limited time.

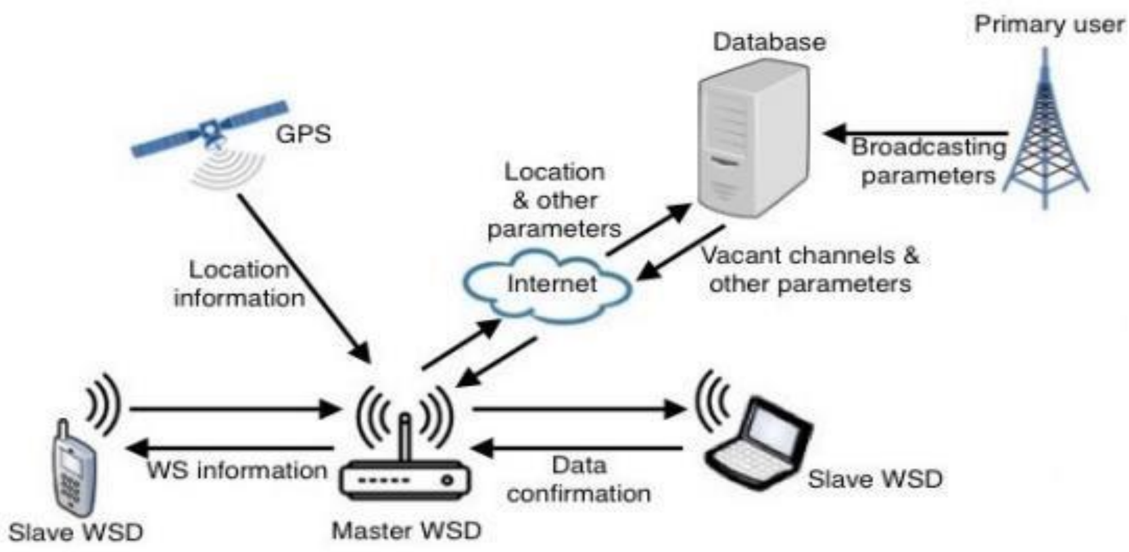

Figure 2. 1: Frame work for Geolocation Database

Source: (Zennaro, 2016)

2.5.1 Protocol to Access White Space Database (PAWS)

In order to achieve the requirements of white space geolocation database access, the Protocol to Access White-Space Database (PAWS) has been designed by a collaboration between the following companies: Google, Huawei and iconectiv. This protocol (PAWS) except for the avoidance between secondary users, has four important characteristics: Spectrum agnostic, Interface agnostic, globally applicable, and Flexible and extensible data structures. PAWS is an application-layer transport protocols and a common message interface between WSDs and database. White Space devices (WSDs) either wired or wireless are able to query the WSDB through the common message interface of PAWS. PAWS can be used in any spectrum and it is capable of supporting different device characteristics and databases that operate in different countries by different regulators (Hsieh, 2014). PAWS as shown in Figure 2.2 specifies the interaction between master devices and WSDBs. The master WSD establishes an HTTPS session with the WSDB. It then goes through a procedure to get the available frequency spectrum to operate in. All registered master WSDs that have registered with WSDBs can get access to available spectrum and operating parameters through the computation of WSDBs in order to avoid interference with each other in same location and primary TV transmitters. Interactions between master and slave WSDs are done in accordance with IEEE 802.11af, also referred to as White-Fi and

Super Wi-Fi (IDA Singapore, 2014).

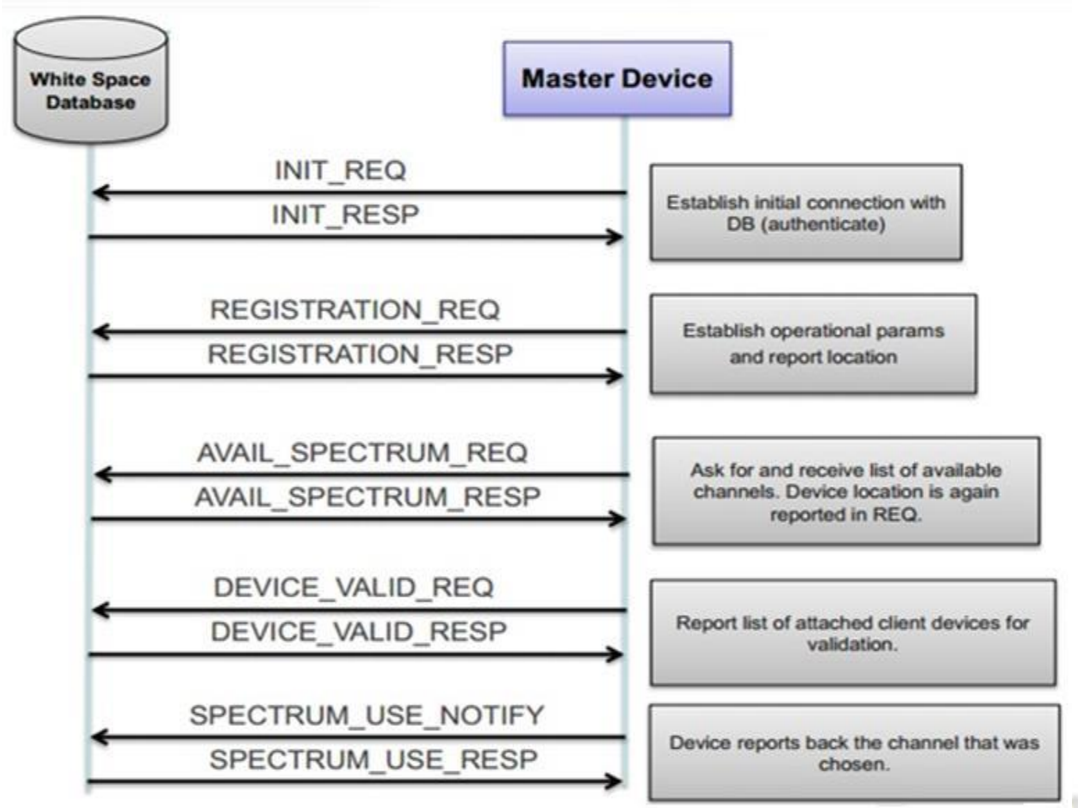

Figure 2. 2: Protocol to Access White Space Database (PAWS)

2.5.2 Standards for Use of TV Band White Spaces

Many works are on-going by International Standards Development Organizations aimed at creating a wide variety of specifications and inter-operable standards for the utilisation of white spaces in TV Band. The Institute of Electronics and Electrical Engineers (IEEE) 802 LAN MAN Standards Committee 28 is one of such organisations which is currently leading the consensus with industry standards body to produces standards for wireless networking devices. These include wireless regional area networks ("WRANs"), wireless metropolitan area networks ("Wireless MANs"), wireless local area networks (WLANs), and wireless personal area networks (WPANs). The group's current focus is on the development of standards for Wireless

Coexistence in TVWS networks. Table 2.1 shows the standards and specification that have been developed so far (Châtaignier et al., 2014; Mody, 2013; Flynn, 2013; Mlinarsky, 2010).

Table 2. 0 Standards for Use of TVWS

Standards	Specifications
IEEE 1900.1	Standard Definitions and Concepts for Spectrum Management and Advanced Radio System Technologies
IEEE 1900.2	Recommended Practice for Interference and Coexistence Analysis
IEEE 1900.4	Standard for Architectural building blocks enabling network-device distributed decision making for optimized radio resource usage in heterogeneous wireless access networks.
IEEE 1900.5	Standard on Policy Language and Policy Architectures for Managing Cognitive Radio for Dynamic Spectrum Access Applications
IEEE 1900.6	Standard on interfaces and data structures for exchanging spectrum sensing information for dynamic spectrum access systems
IEEE 1900.7	Standard on radio interface for white space dynamic spectrum access radio systems supporting fixed and mobile operation.

2.5.3 How to compute available TVWS in Geographical Area

TVWS can emanate at any given location in different ways. Thus, the amount of spectrum available as TVWS vary significantly across different geographical locations and this depend on several factors which include:

- geographical features of the location
- frequency guard channels used for interference avoidance
- the height of the TVWS transmission site and also height of its antenna in relation to the reception of a surrounding TV broadcast coverage
- the geographical areas outside the reach of current TV coverage. That is areas where no broadcasting signal is present currently.
- Unutilized licensed TV frequencies: licensed TV channels that are not

currently in use.

With reference to the factors mentioned above, three (3) methods for the computation of TVWS available in a geographical area at particular time have been proposed in literature (Naik et al., 2014). These are the protection view point, pollution view point and the FCC rules methods for TVWS computation. In order to get accurate results for the quantitative assessment of available TVWS in the areas of interest, all the three methods have been adopted and the results compared. The three methods are discussed as follows:

2.5.3.1 TVWS computation by Protection viewpoint

The pollution and protection viewpoints used for calculating TV white space was introduced by Mishra and Sahai (Mishra & Sahai, 2009). In the protection viewpoint, the secondary user of spectrum band must ensure that its operation does not cause any harmful interference to the primary receivers in its location. As shown in Figure2.3, three (3) key parameters significantly influence the accuracy of spectrum detection:

- **Distance from Transmitter**: This is the distance of the nearest TV transmitter operating in a given channel. This is a very important parameter because the geolocation database should be able to envisage whether the nearest transmitter is too close or too far from the location of WSD. When the transmitter is too close the geolocation database will report channel not available and when to far channel available.
- **Modelled Power:** This is a representation of the estimated power received for a given channel as predicted by the FCC F-Curve Model.
- **LOS Obstruction Length:** This is the portion of the ‘line-of-sight’ from the closest TV transmitter at the specific channel that is ‘obstructed’ due to terrain

irregularity. To determine it, an imaginary straight line is constructed from the antenna of the transmitter to the WSD location.

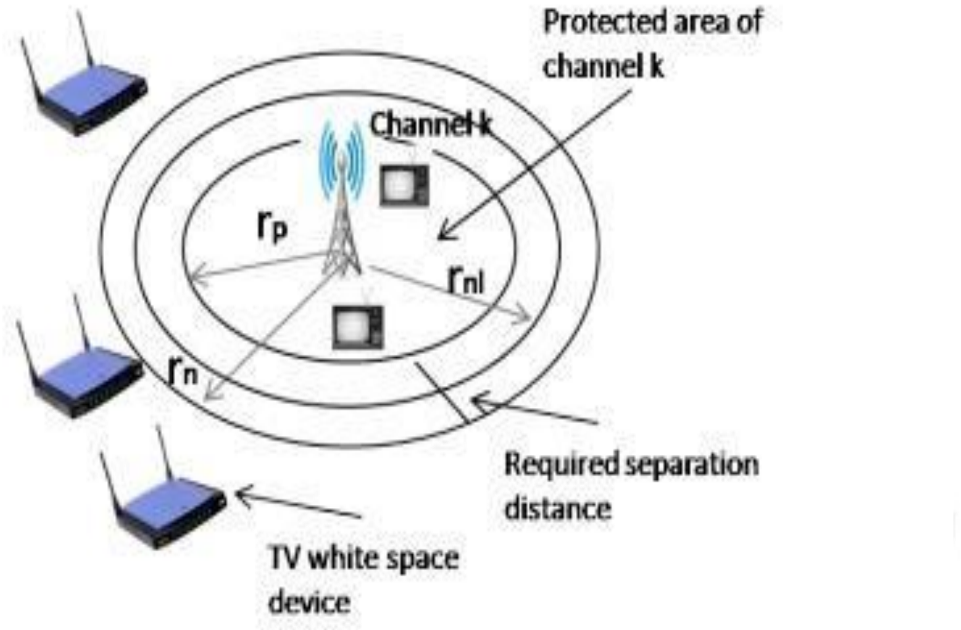

Figure 2. 3: Protection radius, separation distance and no-talk radius
Source: (Nekovee, 2009)

From Figure 2.3, the protected area could be determined by using the following SNR equations:

$P_t - PL(r_p) - N_o = \Delta$ -------- equation (1) (Nekovee, 2009)

Where Pt is the transmit power of primary transmitter in dBm, P L(r) the path-loss in dB at a radial distance r *(*$r = r_n$ *in Figure2.3)* from the transmitter, N_o is the thermal noise in dBm, Δ the threshold SNR in dBm and r_p the protection radius as shown in Figure 2.3. Since radio equipment, including TVWS devices, suffer from residual power signals emitted from other radio frequency devices, spectrum masks suffer from power “leakage” to adjacent channels. For this reason, the probability that a WSD operating at channel N could cause interference to nearby TV sets tuned to ATV or DTV signals at channels N±1 is high. In order to absolutely protect primary users, an additional margin (Ψ) to account for the signal interference is provided. This suggests that at any given geographic location, for a secondary network to operate in channel N, not only channel (N) but also its adjacent (N+1, N-1) must be locally unused (Nekovee, 2009). Thus, equation (1) is modified as:

$P_s - PL\ (r_n - r_p) = \Psi$ ---------- equation (2) (Nekovee, 2009)

Where, *Ps* is the secondary transmitter power in dBm, *rn* is the no-talk radius. No-talk radius is the distance from the transmitter up to the point which no secondary user can transmit. The difference $r_n - r_p$ is calculated such that if a secondary device transmits at a distance of $r_n - r_p$ from the TV band receiver located at r_p, *(as shown in Figure 2.3)* then the SINR at the TV band receiver within a radius r_n does not fall below Δ (McHenry et. al., 2006). Thus, in the protection viewpoint, the protection radius in the adjacent channel is considered to be the same as in co-channel. Since, the TV receiver can tolerate more adjacent channel interference than co-channel interference, FCC regulations set a margin of 27dB more than co-channel fading (*Ψ*) (FCC, 2009).

2.5.3.2 TVWS computation by Pollution viewpoint

Whereas in the protection viewpoint the main concern is prevention of interference to the primary users, in the pollution viewpoint, TV white space computations are looked at, from the secondary users’ point of view (Mishra & Sahai, 2009). The pollution viewpoint takes into consideration the fact that, interference cause by primary transmitter to secondary receiver might be higher than the tolerable interference level, even though the region could be used by a secondary device. Thus, if ʒ is the interference the secondary receiver can tolerate, then pollution radius, r_{pol} is given by,

$P_t - PL\ (r_{pol}) = N_o +$ ʒ, ----- Equation (3) (Naik et al., 2014).

It should be noted that, there are also adjacent channel conditions such as leakage of primary transmitter's power in the adjacent channel in this viewpoint, as in the protection viewpoint. It is therefore, assumed that the secondary device, when operating in the adjacent channels can tolerate up to 45dB of interference. In this case, the available TV white space spectrum is given by the intersection of the white space determined from both the pollution and protection viewpoints (Naik et al., 2014).

2.5.3.1 TVWS computation by FCC rules

In the FCC's definition of TV white space, the protection radius is same in the Grade B contour (rb) (Mishra & Sahai, 2009; FCC, 2009). In the UHF band, rb is given as the distance from the TV tower where the field strength of the primary signal falls to a signal level of 41dBu. Since the transmission power is measured in dBm, the required field strength is converted from dBu to dBm using the FCC conversion formula *(equation 4).*

$$P(\text{dBm}) = E(\text{dBu}) - 130.8 + 20\log_{10}\left(\frac{1230}{f_H + f_L}\right),$$

------ Equation (4) (FCC, 2004)

Where, P (dBm) is the transmission power in dBm, E(dBu) is the signal field strength in dBu, fH and fL are the upper and lower frequency-limits of the channel respectively. To calculate the distance of separation that is distance beyond rb where no secondary device can transmit, we calculate the distance r_n - rb such that the signal from the secondary device at r_n results in a signal level of E_{rb} - 23dBu at the TV receiver located at rb (FCC, 2004).

2.6 Comparison of TVWS and Wi-Fi

The expansion of network access in rural communities has been accomplished by the use of a mix of commercial mobile technologies, satellite radio and licence-free WiFi backhaul networks (Kretschmer et al., 2011). But recent research on expansion of rural network access has been focused on the use of unlicensed and unutilised frequency spectrum. Wi-fi and TVWS technology fall under this category. However, there has not been any investigation to establish whether TVWS performs better or worse than Wi-Fi in a line-of-sight (LoS) and non-line-of-sight (NLoS) scenarios (*in the absence or presence of interferences caused by environmental and geographical factors*). Because both technologies have different advantages and disadvantages, the decision to make a choice between them is not always obvious. It is assumed that in the absence of interference in LoS scenario, Wi-Fi would perform better than TVWS, while TVWS will usually perform better than Wi-Fi where there is not clear line-of-sight. This work seeks to either approved or disproved this assertion.

Wireless Fidelity (Wi-fi) is an IEEE 802.11 standards technology for the connection of wireless local area networks. Wi-Fi mostly make use of the 2.4 GHz UHF and 5.8 GHz SHF ISM radio bands. It is a mature and well-known technology that can readily be connected with high gain Wi-fi antenna of up to about 30 dBi. Wi-Fi has a shorter propagation range, higher sensitivity to obstacles and makes it subject to any less interference. But the consequence of this is that more wireless access points (WAP) per unit area is required and also a line-of-sight will be needed for optimal operation.

In contrast, TVWS is an emerging technology with an obvious technical advantage of wider network coverage of up to 30 km in NLoS situation, which means fewer WSDs will be required per unit area compared that of Wi-Fi making TVWS suitable for rural network backhaul (Henkel et al., 2011). Because TVWS can only use spectrum not used by TV broadcasters, its network performance is largely linked to the amount of available spectrum. TV White spaces is capable of offering many of the low-cost benefits of Wi-Fi but with improved coverage properties. TVWS has been proposed for setting up wireless networks in mountainous areas and areas with vegetation that require very high masts in the case of Wi-Fi to achieve a line-of-sight. But since the performance of Wi-Fi and TVWS network is linked to the amount of spectrum available, interference levels to a specific chosen channel, the propagation environment, and the type of antennae used, there are various shades in-between these extremes (Ab-Hamid et al., 2011).

2.7 Proposed Hybrid Method of identification and Protection

Current literature on TVWS identification methods have been little bias by placing much emphasis on the limitations of the spectrum-sensing approach. This may have been the case because the idea of TV white space (TVWS) utilisation originated from the developed world, where most of the trials and experiments have been based mainly on research conducted in such environments (Goncalves & Pollin, 2011). In the same vein, literature has also discussed clearly the critical performance requirements that each of the techniques requires to perform well. Which suggests that the performance of each technique could potentially be affected by the presence or absence of these requirements in a particular region. For this reason, this section presents an exploration of both spectrum sensing and geolocation database approaches by looking at the factors that can affect their performance. Also, the impact of these factors when each of these techniques are used either in the environment of a developed or developing region are explored. Figures 2.4 and 2.5 give an overview of some of the factors that contribute to the optimal performance of the spectrum sensing and geo-location database approaches respectively.

Performance Requirements for Geolocation Database approach in a region

It could be seen from Figure 2.4 that, for geolocation database approach to perform optimally in a region, the following factors must be ensured:

- Accurate propagation models should be used.
- A reliable telecommunication infrastructure that will provide an Internet backbone to facilitate efficient and frequent communication between the geolocation database, a master WSD and a slave WSD.
- The existence of a centralised up-to-date database on existing TV spectrum information in the area of interest.
- The cost of database implementation and maintenance can also affect the performance.

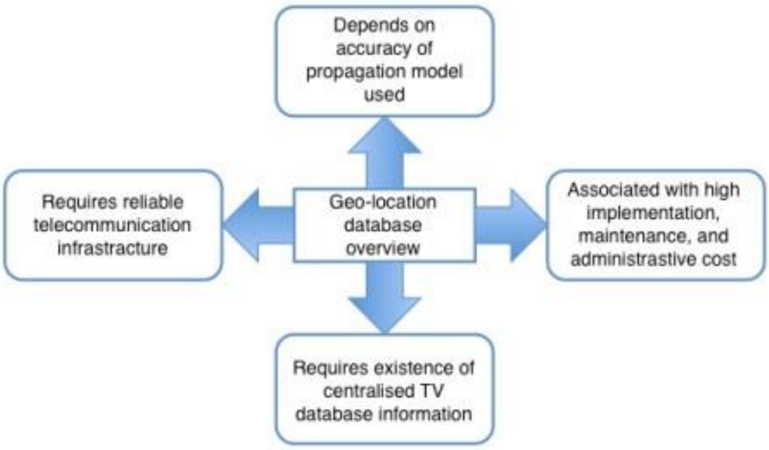

Figure 2. 4: Performance Requirements for Geolocation Database approach
Source: (Zennaro, 2016)

Performance Requirements for Spectrum Sensing approach in a region For optimal performance of spectrum sensing approach, the following factors must be present, as shown in Figure 2.4:

- A detection threshold value that is optimal such that there is no harmful interference to the primary users or any missed opportunities by secondary users.
- Hidden user problem should be avoided by ensuring a minimal to no multipath fading and shadowing of large blocks of TVWSs in the area of interest.
- The antenna type and height could also affect optimal performance.
- Large blocks of white spaces are required for optimal performance.

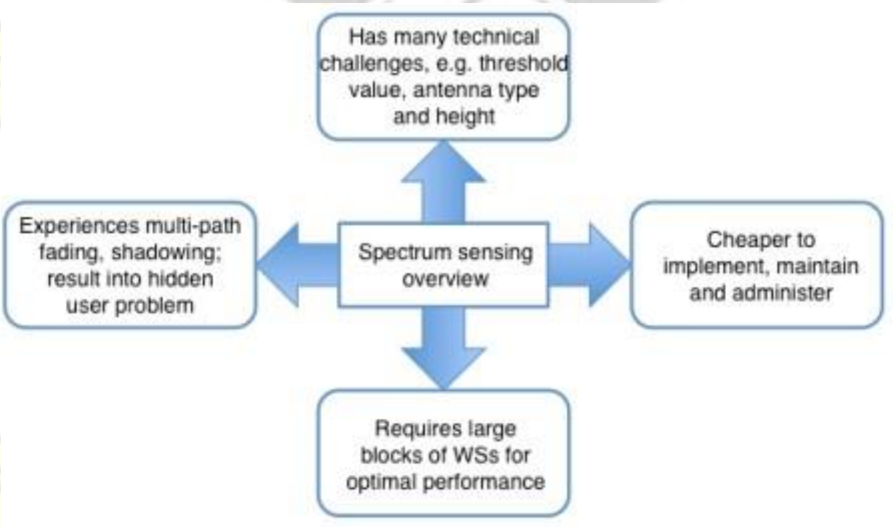

Figure 2. 5: Performance Requirements for Spectrum Sensing approach Source: (Zennaro, 2016)

2.7.1 The need for Hybrid Method of identification and Protection

This section, presents a broader assessment of these two approaches by looking at the factors that can affect the optimal performance of each of these approaches and also look at how the absence or presence of these factors could affect their performance in both developed and developing regions. Starting with Geolocation Database approach, our assessment reveals in most developing regions of the world, especially in the rural areas, the information on TV spectrum needed for the creation of geolocation database is not readily available and at the same time, telecommunication infrastructure needed for optimal performance does not exist. This will eventually affect the performance of geolocation database approach in the developing regions, since WSDs would have to query the GD via the Internet. Also, considering the implementation, maintenance and administrative cost, geolocation database approach will not be most appropriate. Spectrum sensing may also not be appropriate for the developed world due to the severity of fading, shadowing and hidden user problem. This is because these regions are characterised with a lot of high-rise buildings, hence primary TV signals may be difficult to accurately detect by spectrum sensing alone. This could eventually result in harmful interference, thus the performance of spectrum sensing been low.

Contrary to the developed regions, most areas of developing regions especially the rural areas are sparsely populated with small isolated traditional building structures, which are unlikely to cause considerable fading, shadowing or bring about the hidden user problem. But since spectrum sensing approach, uses extremely low detection thresholds, usually there is a heavy under-estimation of the actual white space in a particular location. This is because very weak DTV signals coming from distant transmitters can still be detected and the associated channels are ruled out, although practically no DTV receiver in that location can actually demodulate and decode them. Thus, leading to waste of valuable spectrum due to overestimation of protected areas (Gurney et al., 2008). Because most of these developing regions have vast tracts of unused spectrum in the ultra-high frequency (UHF) band (Pietrosemoli & Zennaro, 2013), cooperative spectrum sensing has been proposed to be a favourable alternative to geolocation database (Zennaro, 2016). But given the complexity of the implementation of cooperative spectrum sensing and the limited literature on this approach, we propose a hybrid approach which is easy to implement and maintain with a lower cost. This method uses a combination of both geolocation database and spectrum sensing with an introduction of a localised TVWS database server (LTDS) and a dedicated spectrum sensing device which enables a real-time update of the database of LTDS. A further discussion on how this hybrid approach works is discussed in the chapter three of this thesis.

2.8 Impact of current regulatory framework on TVWS Implementation

In radio network propagation, spectrum is a very important but limited resource. For this reason, it is very important to explore new ways of unlocking its potential, and at the same time ensuring a balance in the needs of all the different users of this valuable but limited resource (Lopez-Benitez et al., 2009). Also, according to Wiecek (2011) since the quantity of TVWS spectrum available in a geographical area at a given time, depends on the methodology, propagation models, and the data used for its assessment (this may differ from country to country), thus the introduction of DSA systems in a country may require some changes in national regulatory policy in the licensed frequency bands (Shimomura et al., 2012).

Currently, most countries operate on the existence of a fixed frequency assignments. But for DSA to be operational it requires a new kind of license that allows for dynamic change of the frequency band within a given period and could be shared by a number of users simultaneously in a dynamic way. Such is a newly proposed method for an effective utilisation and efficient spectrum management and this will require some advance radio technologies such as cognitive radio and a review of the current regulatory regime (Haykin, 2005). For example, this method may need a real-time access to geolocation databases controlled by the Administration or by spectrum brokers. These geolocation databases would include the geographical locations, frequency channels, radiated power, etc. of the existing or future licensed spectrum users. Also, a precise technical coexistence conditions must be defined and a relevant non-interference requirement be determined in real-time. Change in signal parameters should be automatically established and enforced by the Administrations (ECC, 2013). Finally, the legal consequences of possible errors that will emanate from these geolocation databases would have to be carefully dealt with.

The challenge is that though the utilisation of cognitive radio signal processing techniques may enable an effective and efficient spectrum usage, the rigid regulations under the current existing spectrum management framework (*command-and-control approach*) makes it difficult to achieve. The current fixed spectrum allocation scheme has resulted in underutilisation of frequency spectrum. Measurements performed at various locations worldwide indicates actual spectrum utilisation to be about 5% to 15%. There is therefore a worldwide recognition that these spectrum management methods have reached their limit and are no longer effective and efficient (Bourdena et al., 2012). To break away from the inflexibility and inefficiencies of these rigid methods of spectrum management, the adoption of a new spectrum policy that will permit the use of CR techniques in the implementation of these wireless networks is very vital.

In the current regulatory framework, all primary services are protected and any transmission that could interfere (harmfully) with primary users is not allowed. If a new service is to be introduced in the country (or in neighbouring countries), detailed protection conditions of the existing primary services have to be established to assure their adequate protection and keep interference levels safely below harmful limits. Currently it can take months (or even in some cases years) to negotiate and agree on detailed technical conditions of such spectrum sharing issues with neighbouring countries. Even this aimed at a situation where new (non-CRS) services have fixed frequency range and near-fixed technical characteristics. In the case of CRS, however, it is even more complicated and that frequency ranges can change dynamically on both sides of the border. This could eventually lead to the situation where it is difficult to coordinate different CRS standards and systems implemented by the different Administrations. In such case, common technical CRS standards or coexistence technical standards (or at least common database settings) could help the Administrations involved (Pietrosemoli & Zennaro, 2013).

2.8.1 Spectrum Management

When the first generation of mobile operators were granted licenses to use wireless spectrum to build their networks, they were simply given the spectrum at no charge. The availability of spectrum exceeded demand. Today, popular frequency bands are auctioned for large amounts of money, often running into the billions of dollars (Zennaro et al., 2013). Because so much money is now at stake concerning spectrum, the process of making new spectrum available has become very complex. It is increasingly becoming hard to ensure that spectrum is made available in a timely manner and to the entities that are most likely to serve a country's strategic interest. In many of the developing countries, governments and regulators are caught between the increasing demand for more spectrum by the broadcasting market and also the need for more human and financial resources to manage the complex nature of issues in the field, such as spectrum auctions, technological advances and regional harmonisation (Pietrosemoli & Zennaro, 2013).

This may also be compounded by the fact that decisions about spectrum are likely to have serious consequences on the spectrum market and are capable of lasting for a generation or more. That notwithstanding, the intensity of investment, evolving of technical standards, and administrative complexity also tend to slow down decisionmaking in this environment. This means that, it does not only take a longer period to introduce new spectrum regulation but also any strategic errors in regulation can take several years to be corrected (Borth et al., 2008). In order to deal with this problem, it is important to contrast this traditional licensed spectrum approaches with the rapid uptake of technologies based on dynamic unlicensed spectrum usage. This is because though dynamic unlicensed spectrum is regulated, it is done through technical specifications imposed on the devices operating within a designated unlicensed spectrum band instead of being managed through a licensing process which normally takes a long time. Traditionally, spectrum management are based on the following general principles:

- The spectrum resources are public and for that matter, it uses is based on the common administrative regulations and allocations of frequency bands that are set through the mechanism of international consultations, negotiations, and consensus.
- Every country has an equitable and free access to spectrum resources and that no fee mechanism has been envisaged on the international scene for it use.
- National sovereignty is a "sacred" principle in the ITU thus, each country decides on the use of available spectrum freely, as long as it respects the existing international regulations and agreements (Pietrosemoli & Zennaro, 2013).

2.8.1.1 The need for radio spectrum management

Because radio spectrum is a finite resource, there is definitely the need to manage to ensure an effective and efficient usage by all Stakeholders. Spectrum management also helps: to conform to the ITU recommendations and international best practices of spectrum usage, avoid interference of spectrum waves and last but not least curb illegal use of the spectrum.

Some benefits of Spectrum management

- Spectrum management protects the consumer from interference problems.
- Spectrum management helps regulators to manage conflicts or interferences of the waves.

- Spectrum management serves as employments opportunity for the people of the country, and also generates income or economic benefit for the nation.

2.8.1.2 Why Spectrum Management is a Difficult Task

Spectrum Management is a daunting issue to address because of its multi-dimensional complexity. It requires technical, economic, and legal expertise in order to address it efficiently. Stated below are some of the main reasons why spectrum management is a difficult task:

Technical complexity.

What we understand about wireless spectrum is in flux. About a decade ago, the only way spectrum management was done was by giving an exclusive right to a spectrum holder. Also, regulators ensured that significant gaps (guard bands) existed between spectrum holders in order to prevent interference. Television transmitters were obliged to transmit signals at relatively high-power output in order to reach the comparatively unintelligent receiver devices. But today, wireless communication technology continues to increase in efficiency and in its ability to mitigate interference. There are limits to this, however, the understanding of how to maximise the efficient use of spectrum is an ongoing technical challenge which attracts a lot of R&D investment. It must be noted that the complexity of understanding the trends and changes in spectrum technology is essential to understanding how to regulate it (ITU, 2013; Pietrosemoli & Zennaro, 2013).

Money and Corruption.

In recent times, an increasing premium has been put on spectrum access. This is happening because the telecommunication industry has become more of a lucrative business. As a result, regulators find themselves managing a valuable but limited resource worth millions of dollars to interested parties. With all these huge sums of money on the table, ensuring a fair play that takes into consideration the national strategic interest can be very challenging. This has resulted in the emergence of spectrum auctioning as the de facto mechanism for dealing with licensed spectrum. But even with that, an effective auction design and execution is still a challenge even in well-resourced regulatory environments. In order to ensure success in this area, experts in the field have advocated an optimal spectrum auction environment be designed and well-organised and disciplined spectrum auction process that guarantee a fair play (corruption free auction) which will help to avoid legal challenges which is capable of halting the entire auction process from disgruntled parties (Pietrosemoli & Zennaro, 2013).

Spectrum usage dependency on technology

In the past, spectrum allocations have been done by tying a particular spectrum band to a particular technology. Thus, spectrum usage has been solely dependent on having technology capable of using a given set of frequencies. Which suggests that the effective utilisation and efficient management of spectrum depended on manufacturers' ability to produce transmitters and receivers for those available frequencies. However, the unfortunate situation is that, the manufacturing industry could not follow the path that regulators expected hence, this has led to chunks of spectrum lying fallow. Thus, many new technologies only become practical as and when manufacturers scale up their commitment to meet new regulatory requirements to support specific standards and frequencies. But today, the situation is different; there is an increasing emphasis on technological neutrality in the allocation of frequency spectrum. But even with that there is still a challenge to overcome, because some technologies require spectrum allocations to be organised in a specific mode.

For example, some technologies require paired spectrum utilisation which are dependent on spectrum allocations being organised in a specific mode (Shellhammer, 2009).

Lack of Institutional Capacity

In order to achieve effective regulation of spectrum, there is a clear need for technical, administrative, economic, and legal capacity within the regulatory body of individual countries to address the issues mentioned above effectively. But for many developing countries, this is often not the case. Most of the communication regulators of this countries are typically under-resourced and are plague with lack of sufficient independence of state and industry alike. Because huge sums of money are at stake, these communication regulators are often outmatched by their wealthy industry counterparts. Governments and communication regulators are therefore torn between the growing market demand for more spectrum and the need for more human and financial resources to manage the increasingly complexity of the issues. This is compounded by the fact that decisions about spectrum auctions, regional harmonisation, and technological advances can have serious consequences that can last a generation or more if not handled with care (ITU, 2013).

Challenges with the pace of international coordination

Prior to the advent of mobile telephony and wireless broadband technologies, the available radio spectrum exceeded demand. And because incentives to coordinate spectrum allocation existed but were often trumped by local or regional priorities, this has led to the creation of critical variances in the details of broader coordination in general areas of spectrum use. This eventually has led to the need for mobile phones that operate in three, four, or more spectrum bands in order to provide a working service internationally. For this reason, regulators find themselves in a difficult situation where they recognise the need to harmonise spectrum use but are tempted to act individually because the of the seemly slow pace of international coordination (Pietrosemoli & Zennaro, 2013).

The interplay of investment, evolving technical standards, and administrative complexity tends to make this a very slow-moving decision-making environment. This means that not only does it take a long time to introduce new spectrum regulation but also any strategic errors in regulation can take many years to undo. South Africa is a good example of how challenging it can be to carry out a spectrum regulation change. In May 2010, the South African communication regulator, ICASA, announced an auction of spectrum in the 2.6 GHz and 3.5 GHz bands. This auction was plagued with many problems and was ultimately withdrawn (Carlson et al., 2013).

2.9 Spectrum Regulatory Frameworks

The spectrum available to a system ultimately determines the capacity a communication system provides. Currently, there is quite a great number of radio systems in operation worldwide and this continues to increase. Most of the suitable frequencies on the radio spectrum have already been occupied and in some geographical regions there is no place for new radio systems. Spectrum occupation has further increase with the advent of cloud-based applications, which exchange data back and forth with distant datacentres instead of storing them locally. To help solve this spectrum problems, many organizations such as International Telecommunication Union (ITU), FCC and ECC have employed thousands of experts. These experts are of the view that, public policy might be better served, if we moved to an environment of minimal (near zero) regulation. Baran and Noam in their separate work both argued against zero regulation but supported a minimal regulation that allow an open access spectrum system. In this system, there is neither license requirement nor an up-front auction. Instead, all users are required to pay a spectrum band access fee that is continuously and automatically determined by the existing congestion in various frequency bands (Baran, 1995; Noam, 1995). In such an environment, freedom of spectrum use is guaranteed, without the barriers to entry that impair true innovation in the spectral eco-system.

But the question some experts in the field are asking is, whether this laissez faire form of regulation can lead to chaos or not? Possibly, the answer may be no. This is because of how, the many millions of Bluetooth devices, cordless telephones, burglar alarms, and other wireless house controllers have operated within a minute portion of the spectrum with limited interference to one another. Though these are very low powered ’dumb devices’ compared to current CR equipment that are able to change their frequencies and minimize radiated power to suite their environment in order to avoid interference to themselves and to others. The success story of the Internet, also provides an instructive model for the future of spectrum regulations. With the Internet, there is no central node, but a minimal centralized management structure. This model permits the Internet to be responsive to a very large unregulated constituency and at the same time allow explosive growth with an increase in its usefulness to its users. This approach can also work for radio spectrum regulation with the aid of CR which are capable of listening and then automatically choose preferred frequencies to avoid interference to other signals in the band. Thus, it been said, it is just a matter of being a good neighbour (Pietrosemoli & Zennaro, 2013).

2.9.1 Unlicensed versus licensed spectrum

About two decades ago, unlicensed spectrum use was simply illegal in most countries and even for some others a daring exception to the norm of licensed services. But now, due to the successful implementation of the ISM band especially the global acceptance of Wi-Fi and RFID's, most countries have license-free bands. In the US and few places in Europe, license exemption or unlicensed use is increasingly recognized as the new norm, while the licensed radio services part of the wireless ecosystem is shrinking gradually ((Ntuli et al., 2014). But the story is different in most developing countries with Ghana not exempted. In Ghana, the spectral ecosystem is dominated by the traditional method of assigning spectrum through an exclusive-use where licensedusers are entitled to a spectrum band.

For unlicensed spectrum to be operational, radios that are smart enough to manage their own frequency use while minimizing interference should be developed. Else, the existing institutional framework will not be change by lawmakers. Though these types of radios are already being produced for military operations, they are being done at higher cost and more investment is needed for its production in large volumes to bring down cost. Also, more testing is needed to convince sceptics about its viability. Contrary to this traditional method of spectrum allocation, in the world of unlicensed spectrum use, spectrum regulation is done differently. In this environment, spectrum regulation is done through the technical specifications imposed on devices operating in spectrum designated as unlicensed. Typically, this means that devices that are supposed to operate in this environment are required to have a power output which is much lower than that found in the licensed environments (Deb et al., 2009). Figure 2.5 gives a summary of the various spectrum regulatory approaches discussed in this section.

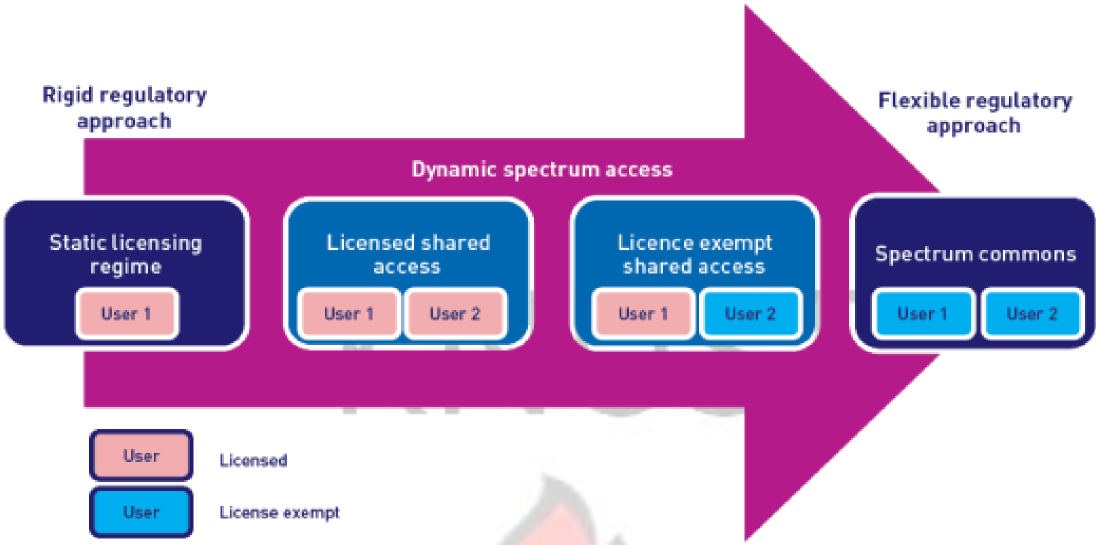

Figure 2. 6: Spectrum regulation approaches

2.9.2 Regulatory Bodies

The regulation of radio spectrum is done at three distinct levels and this are: the international, regional and national. The international and regional governing bodies have the mandate of standardizing the most optimal spectrum management techniques and also to ensure a worldwide harmony in radio spectrum regulation. This if well done eases technological challenges and global market access. Market confidence of wireless device manufacturers is boosted. Standardisation of radio spectrum use also creates a good environment that makes the whole sector highly competitive and more innovative. There has been an increasing trend of centralizing the standardization efforts in the telecom sector as the global economy becomes more dependent on one another. In view of that, regulators at the international level have become more involved in drafting a more suitable spectrum allocation scheme. However, national regulators at the national level still have a reasonable freedom to identify the models that best suit their interests, provided they don't go beyond their responsibilities (Nekovee et al., 2012).

At the international level is the International Telecommunications Union (ITU), a specialized agency of the United Nations (UN), which has the regulatory mandate at the international level. The ITU, uses its World Radio Communication Conferences (WRC) to achieve this mandate. The Radio Communication Sector of the International Telecommunication Union (ITU-R) plays a very important role in the harmonization of spectrum management worldwide (QUASAR, 2010).

The regional level has the Electronic Communications Committee (ECC) of the European Conference of Postal and Telecommunications Administration (CEPT) playing the regional regulatory role for Europe, which in many ways reflect European interests in the ITU. The ECC also works to formulate regulatory procedures and mutually optimal spectrum policies across Europe, Africa and Asia (Nekovee, 2009).

Each member state of ITU also has its own National Regulatory Authorities (NRA) which can exercise power at the national level based on the recommendations and guidelines from the EC. Article 3 of the Common Regulatory Framework Directive (European Commission, 2000) mandates each member state to ensure an effective liberalization of the telecommunication sector by putting in place a structurally independent and impartial NRA. It explains that: “Member States shall guarantee the independence of national regulatory authorities by ensuring that they are legally distinct from and functionally independent of all organizations providing electronic communications networks, equipment or services.” In Ghana, this role is played by the National Communication Authority of Ghana.

2.9.3 The State of TVWS implementation in Ghana

Currently, a draft of an interim framework for TVWS regulations and usage in Ghana has been adopted by NCA. This follows the successful trials of pilot TVWS projects in Ghana. These projects have been partnered by DSA members of the Kofi Annan AITI and Spectra Wireless and 6Harmonics (*Meltwater and Koforidua pilots*) trials, and also Public Consultations by NCA on proposed TV White Spaces (TVWS) Spectrum usage. This drafted Regulatory Framework has been done in the light of the USA's Federal Communications Commission (FCC), UK Ofcom's and Singapore's IDA decisions on the implementation of TV white space technology. The successful trials of these pilot projects have resulted in both Spectra Wireless and Microsoft 4Afrika the decision to launch a TVWS-based broadband commercial service in Ghana (this been the first in Africa). This service will allow university students to purchase fast and affordable Internet bundles.

This move by NCA to grant a commercial license which will allow the use of TV spectrum band frequencies on a secondary basis in as much as no interference is caused TV transmitters, has been welcomed and applauded by Dynamic Spectrum Alliance (DSA). The DSA noted that this if implemented would enable efficient use of TV spectrum bands in Ghana. The NCA, by allowing access to TVWS spectrum, will enable more efficient and effective utilisation of finite spectrum resources and also support facilitation of key priority policy such as bridging the digital divide and sustainable economic development. According to the DSA, they truly appreciate the leadership of NCA in the development of these rules for license-exempt access to vacant television channels (white space). The DSA is also of the view that, the proposal of Ghana's NCA through their consultation to endorse the adoption of a new

Regulatory Framework, which will enable widespread deployment of TVWS-based network platforms, is a step the in right direction that will ensure the successful trial of TVWS networks in Ghana (Nwana, 2014).

According to NCA, their aim for opening the market to TVWS technology use, is to facilitate a cost-effective and faster access to wireless broadband Internet backhaul mainly for the rural communities of Ghana. The NCA believes that this drafted Regulatory Framework for TVWS access, when it is formally adopted, could serve as the foundation for widespread deployment of this technology in Ghana and across other African countries. Due to the above-mentioned successes the NCA of Ghana has been adjudged one of the most effective telecom regulatory agencies in the region. Notwithstanding, despite the successful deployment of these pilot projects on TVWS, no work has been done on the creation of a national TVWS geolocation database for Ghana (Nwana, 2014).

2.9.4 Overview of TVWS Trials in Africa and Other parts of the world

This section presents an overview of successful trials of TVWS in other parts of Africa and the world at large.

Kenya

In Kenya's TVWS network trial, TVWS technology and solar-powered base stations were used to deliver broadband Internet access. While creating new opportunities for education, healthcare delivery, commerce, and provision of government services. The focus of Kenyan trial has been on the commercial feasibility of TVWS technology in delivering low-cost broadband Internet connectivity in communities that are currently lacking access to both reliable electricity and robust network backhaul. This trial project has the following partners: Microsoft, Indigo Telecom Kenya's Ministry of Information and Communications, Adaptrum and 6Harmonics. The network covered a geographical area of approximately 108 km^2 having Nanyuki as its seat and spanning through Kenya's Laikipia County. It also provided network coverage to about 20,000 people. Thus, providing broadband Internet access to three schools: Gakawa Secondary School, Male Primary and Secondary School. Two healthcare clinics: The Burguret Health Dispensary and the Red Cross Office in Nanyuki and also two local businesses (Carlson et al., 2013).

Tanzania

The trials in Tanzania focused on the provision of a broadband internet connection in some urban areas and also delivering of an integrated device, service and internet connectivity solutions to some tertiary institutions. This initiative by the Tanzanian Government was announced at the World Economic Forum on Africa in May 2013. The project had the following as partners: The Tanzania Commission for Science and Technology (COSTECH), Microsoft, and UhuruOne a local ISP. This pilot's project targeted four universities in Dares Salaam with a combined student population of about 74,000 (Carlson et al., 2013; Microsoft, 2013).

Malawi

In Malawi TVWS trial, Carlson Wireless' RuralConnect TVWS radios were used to connect hospitals and schools in the southern parts of the country. The aim of the trial was to test the use of white space devices in ISM bands72. The Malawi Communications Regulatory Authority (MACRA), University of Malawi, and the Marconi Wireless Lab (T/ICT4D) at the International Centre for

Theoretical Physics (ICTP) were the partners of this project (Mikeka et al., 2014; Zennaro et al., 2013).

United States

The idea of TVWS utilisation started in the US when the FCC conducted extensive laboratory and field tests of prototype devices in 2007 and 2008. These trials informed the FCC's final rules for TVWS use as amended. In the US there have been several successful trials of TVWS networks with a number of commercial deployments in place including a city wide TVWS network coverage in Wilmington, NC .77 78 (Carlson et al., 2013).

United Kingdom

In the UK, a consortium of partners in June 2011 launched a TWVS trial, which was designed to evaluate both the technical abilities of the technology as well as potential end user applications and scenarios. This trial which was done in Cambridge, England, tested several different applications of TVWS. In the trial a city-wide coverage was provided by establishing base stations in four pubs and a theatre. This provided widespread coverage including "pop-up" Wi-Fi hotspots. The trials showed that TVWS could be utilised to extend broadband internet access thereby offloading some mobile broadband data traffic. With these hotspots, users were able to enjoy datadriven services such as live video streaming during peak traffic periods (Carlson et al., 2013).

Finland

In Finland the TVWS trial was initiated by issuance of a test radio license for cognitive radio devices on the TV White Space frequencies to Turku University of Applied

Sciences on August 27, 2012 by the Finnish Communications Regulatory Authority (FICORA). The licence covered the 470-790 MHz frequency. This project was supported by the Turku University of Applied Sciences, Aalto University, Nokia, the WISE consortium, Digita, Fairspectrum, and Ficora. The test licence was issued for one-year period and covered a geometrical area of $40km^2$ around Turku (Carlson et al., 2013).

Singapore

In Singapore, there are eight projects that were aim at demonstrating a diversity of commercial services that could be deployed using TVWS spectrum technology. For this reason, in April 2012, the Singapore White Spaces Pilot Group (SWSPG) was established. This group had eighteen members participating and has supported a number of varied application trials which include WLANs, machine-to-machine communications, and security networks (Carlson et al., 2013).

The Philippines

The Philippine trial targeted its fishing communities and other remote areas. The project targeted five municipal areas: Bien Unido, Talibon, Ubay, Trinidad, and Carlos P Garcia. Partners of this project included: The Philippines Department of Science and Technology's Information and Communication Technology Office (DOST-ICT Office), United States Agency for International Development (USAID), Department of Agriculture's Bureau of Fisheries and Aquatic Resources (DA-BFAR), and Microsoft (Carlson et al., 2013).

CHAPTER THREE

RESEARCH METHODOLOGY

3.0 Overview

This chapter discusses how a quantitative assessment of TV white space in rural Ghana is addressed with emphasis on TVWS in the rural areas of the Central Region. The chapter starts by given a detail description of the tool used to investigate the existence of television white space (TVWS) in these areas of interest. It continues to discuss how this device is used to scan for frequency spectrum that are available as TVWS. In this chapter, actual available TVWS is computed using all the three (3) methods discussed in the chapter two (2) of this thesis and results compared. Comparative analysis of the impact of distance, signal interference by environmental factors such as weather conditions and interference from other radio frequency devices on TVWS and Wi-Fi signals is discussed. Signal attenuation and path loss in both TVWS and Wi-Fi signal propagation due obstruction from mountainous regions, vegetation and high-rise buildings is compared. The chapter also discusses how the proposed hybrid method for accessing and protecting TV spectrum could help minimise signal interference while ensuring a robust network. The chapter ends by discussing how TVWS is utilize as a network backhaul for the provision of Internet connectivity in three rural communities in the Central Region.

3.1 Radio Spectrum Sensing Device

Traditionally, spectrum sensing and analysis are done with high-end commercial spectrum analysers and these are very expensive devices that cost thousands of dollars and at the same time bulky. A person may also need to be an expert to use these devices (Pietrosemoli & Zennaro, 2013). Due to resource constraint, RF Explorer Spectrum Analyser device which is a low-cost radio spectrum analyser was adopted for the current work. This is because, the RF Explorer Spectrum Analyser is capable of offering about 90% of the functionality that high-end commercial spectrum analyser unit will do for a given RF band at a little cost (*about 5% of the cost of high-end commercial spectrum analysers*). Additionally, it is very portable and can work efficiently outdoors for hours with a single battery charge (Rainone et al., 2015).

3.1.1 RF Explorer Spectrum Analyser Device

This device is an affordable Handheld Radio Spectrum Analyser which is designed to be intuitive and easy to use for spectrum sensing and measurement (refer to Figure3.0). It is compatible with US FCC regulation 47 CFR Part 15.103(c) and also certified for CE compliance under regulations EN/IEC61236 and EN/IEC61000. The RF Explorer Spectrum Analyser runs on an embedded firmware which is copyrighted by Ariel Rocholl, 2010-2017. This device is capable of displaying full frequency spectrum in a radio spectrum band including the carrier and modulated shape. It also displays the Spread Spectrum activity if that exist, and shows bandwidth to monitor collisions and frequency deviation from an expected tone. The model adopted for this work is capable of covering wider bands with a full coverage of 15-2700MHz and 48506100MHz in the same unit. It has an excellent dynamic range and many important features. Though other USB-Key radio devices always depend on a PC connection, and that makes them very inconvenient for outdoor work, RF Explorer Spectrum Analyser is a fully functional independent unit. An optional PC connection can be done for additional features and display of quality images.

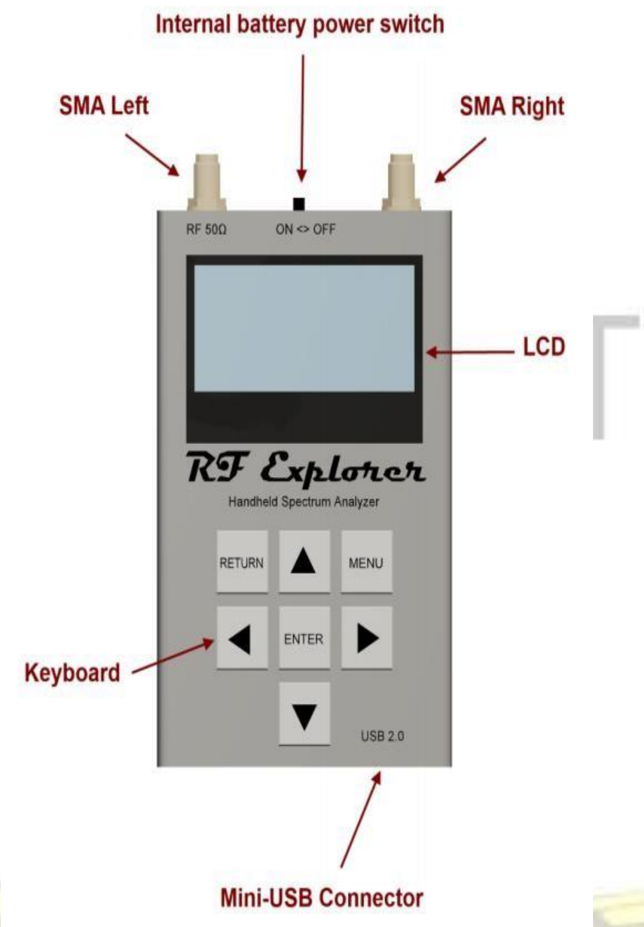

Figure 3. 0: Parts of RF Explorer Spectrum Analyser Source: (RF Explorer Handheld Analyser User Manual)

Keyboard: this is use for menu navigation and entering of data.

SMA Left & Right: antennae connection

Mini-USB Connector: for establishing a connection with a computer and for charging of internal battery.

Internal battery power switch: this is used to power-on and off the device.

LCD Screen: displays information on scanned frequency spectrum.

Table 3.0 gives detail features of features of RF Explorer Spectrum Analyzer. This device is capable of monitoring continuous radio frequency wave (CW) and temporary transmissions in specific ISM band. It can also determine whether a device is transmitting in the frequency and with the power it is expected to operate. It also helps to check the impact of an antenna or amplifier change on power, orientation and noise level. It functions as RF signal generator with tracking capabilities for full SNA test, testing of RF link and presents spectrum data in Normal, Average and Peak Maximum calculator modes. Open source PC client software for Windows and Mac OSX, guarantees unlimited data capture and post-processing storage. Figure 3.1 shows a Labelled Display of RF Explorer Spectrum Analyser.

Table 3. 0: Features of RF Explorer Spectrum Analyser

Features	Specifications
Frequency Range	15 — 2700 MHz
Sensitivity f	typ. ± 10 ppm
Sensitivity level	typ. ± 3 dBm
Resolution f	min. Bandbreite/112 typ.
Resolution level	0.5 dBm typ.
Setting accuracy f	1 kHz
Broadband displayed	112 kHz — 600 MHz
Antenna jack	2x SMA
Antenna impedance	50 Ω
Display	LCD with background light, 128x64 px
Dynamic range	-115 — 0 dBm typ.
Noise floor	-115 dBm typ.
Max. input level	+5 dBm
Weight	185 g
Dimension without antennas	113 x 70 x 25 mm

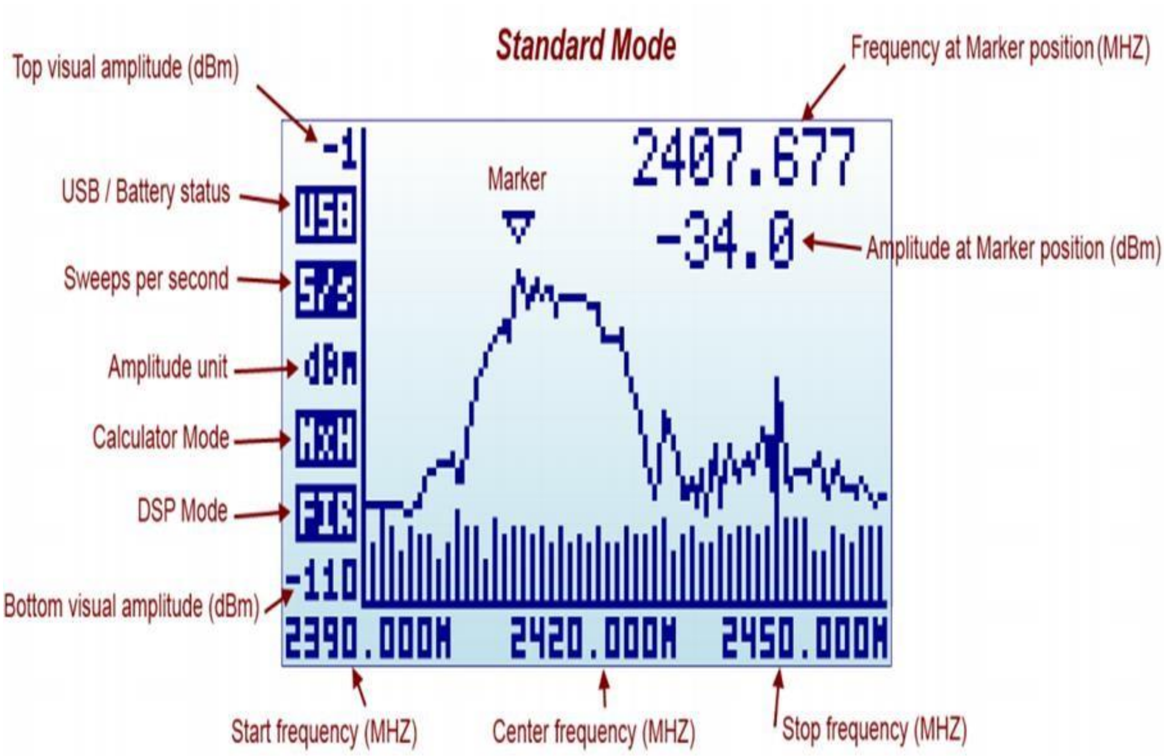

Figure 3. 1: Labelled Display of RF Explorer Spectrum Analyser
Source: (RF Explorer Handheld Analyser User Manual)

3.1.1.1 The Menus on the RF Explorer Spectrum Analyser

The RF Explorer Spectrum Analyser has several menus which are organized on different screens that can be iterated through by using the "*Menu*" button. Thus, clicking the *Menu* button multiple times, will take you through every one of them and back to the default. The Right and Left buttons can optionally be used to move from one screen to another while the Return button is used to exit from a menu. The *Up* and *Down* buttons are used to select the desired mode and the Enter button is clicked to activate it. Frequency Menu opens the first time you click on *Menu* button. But this may change because after the device has been used and data saved, the next time you click on Menu button, the last menu you were working with actually re-opens from Spectrum Analyzer main screen. This has been done in order to save time by not having to navigate through all the menus to move the same menus used preciously.

Operational Mode menu

RF Explorer Spectrum Analyser has the Spectrum Analyser as its default mode. Spectrum Analyzer, Wi-Fi Analyser, RF Connections, Battery information and About the device are other menus in the operational mode as shown in Figure 3.2.

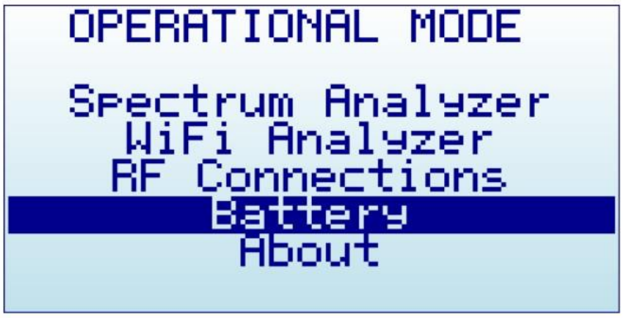

Figure 3.2: Operational Mode menu of RF Explorer Spectrum Analyser

Frequency menu

This menu has Center frequency, Frequency span or range, Start Frequency **(for** lower frequency range), Stop Frequency (*for higher frequency range*) and the Module (for activation of a selected RF module) all in Mega Hertz (MHz) as shown Figure 3.3.

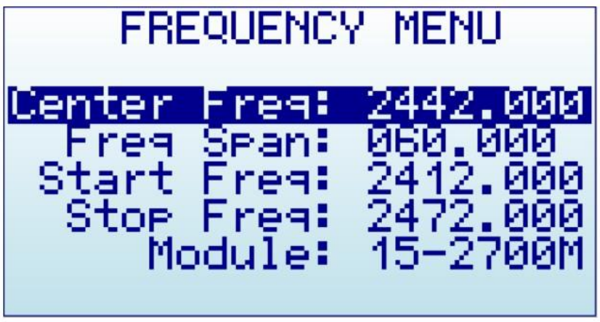

Figure 3. 3: Frequency menu of RF Explorer Spectrum Analyser

Attenuator Menu

This menu comprises Calculator (for internal DSP calculator mode), the Top dB and Bottom dB menu lists for determining visual maximum and minimum amplitude on screen, Iterations for internal DSP calculator iterations, Offset dB for external dB attenuation or gain value compensation and also Units which indicates the unit of signal measurement in dBm or dBuV as shown in Figure 3.4.

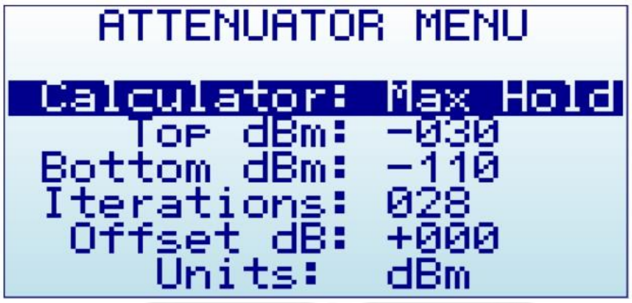

Figure 3. 4: Attenuator menu of RF Explorer Spectrum Analyser

3.2 TVWS Spectrum Measurements

TVWS measurements were done in sixteen (16) different locations in the Central Region of Ghana. This includes areas around the Cape Coast Teaching Hospital and fifteen other villages in and around the Cape Coast Metropolis. These locations were selected purposefully, taking into consideration their distance from BS, geographical make-up in terms of vegetation, mountainous regions, and high-rise buildings. Also, interference by environmental factors such as weather conditions and interference from other radio frequency devices were considered.

TVWS measurements were done for five (5) days at different times of the day at the various locations of interest. These measurements were done in the morning, afternoon and evening at 6am – 10am, 12 noon - 4pm and 6pm -10pm respectively. The RF Spectrum Explorer Analyser device model WSUB1G was used during these times to take a radio frequency spectrum scan to ascertain which of the radio frequencies in a particular spectrum are unutilised and could be used as TVWS. This device was connected with a wide band telescopic antenna, Nagoya NA-77. This is because Nagoya NA-77 provides a wide frequency band measurement capability.

Radio frequency scan was done by using both Vehicular and Stationary scans. This was done for both UHF and VHF spectrums. The Vehicular scan was done in order to enable the authors to estimate potential TVWS in the locations of interest. This was done by driving through the location of interest at a speed of ten kilometres per hour (10Km/h) in a radius of one (1) to Two (2) kilometres and frequency spectrum scan taken by the RF Spectrum Explorer Analyser. The Stationary scan was done by situating the RF Spectrum Explorer Analyser at the premises where the TVWS base station was setup and also the community centres where the slave WSD would be mounted. This was necessary in order to be able to determine which frequency spectrum will guarantee minimal interference or interference free signal propagation. NB: the two-hour intervals between the periods of measurement was to enable the RF Spectrum Explorer Analyser to be recharged before the next frequency spectrum scan. Average values of the measurements obtained from the radio frequency scan was calculated and the protection view, pollution view and FCC rules methods for TVWS space computation used to compute the actual TVWSs that are available in these areas of interest. This is because, the fact that a frequency or channel is unutilised does not make it a white space.

3.2.1 Computation of Available TVWS

Computation of TVWSs available at the various locations of interest started by using Google Maps to establish the geographical coordinates. Google Maps is an Internet base mapping service developed by Google. This application offers satellite imagery, street maps, 360° panoramic views of streets, real-time traffic conditions, and route planning for traveling. It also allows users to measure distance, find the coordinates of a location, create maps, set routes, share location etc. Geographical coordinate measurements were done on different times of the day (morning, afternoon and evening) for three (3) days and average values used. This was done in order to accommodate errors that may arise as a result of the rotation of the earth. These measurements had been necessitated by the fact that the Geolocation Database should be able to determine the location of WSD in order to determine the appropriate TVWS frequency to operate in. Table 3.1 shows the geographical positioning system (GPS) coordinates of the sixteen (16) locations where TVWS spectrum scan were done and their distances away from the BS transmitter. The table also shows the height above sea level (HASL) of the areas under consideration which were generated by Google Maps.

Table 3. 1: GPS coordinates, HASL and distances from BS transmitter

Site	Area	Distance (*d*) (Km)	Latitude (º)	Longitude (º)	HASL (m)
1.	Cape Coast Teaching Hospital	3.07	5º 7′ 53.44″	1º 16′ 46.11″	20.32
2.	Nkanfoa	3.32	5º 7′ 53.43″	1º 16′ 46.10″	30.05
3.	Ekon	3.45	5º 7′ 53.46″	1º 16′ 46.12″	28.67
4.	Amosima	3.33	5º 7′ 53.45″	1º 16′ 46.14″	19.43
5.	Duakor	5.50	5º 7′ 53.38″	1º 16′ 46.13″	-20.34
6.	Akotokyir	6.11	5º 7′ 53.41″	1º 16′ 46.15″	5.43
7.	Kwawprow	6.33	5º 7′ 53.39″	1º 16′ 46.09″	6.22
8.	Amamoma	6.98	5º 7′ 53.40″	1º 16′ 46.08″	3.37
9.	Yomransa	7.25	5º 7′ 53.35″	1º 16′ 46.17″	4.67
10.	Moree	8.60	5º 7′ 53.47″	1º 16′ 46.16″	3.23
11.	Simir	13.1	5º 7′ 53.33″	1º 16′ 46.07″	-1.45
12.	Biriwa	16.00	5º 7′ 53.48″	1º 16′ 46.20″	2.54
13.	Jukwa	20.00	5º 7′ 53.42″	1º 16′ 46.18″	-8.34
14.	Egya	21.70	5º 7′ 53.49″	1º 16′ 46.04″	10.89
15.	Kormantse	25.50	5º 7′ 53.50″	1º 16′ 46.19″	12.86
16.	Asebu	26.70	5º 7′ 53.30″	1º 16′ 46.05″	15.45

Table 3.2 shows the average signal power measurements attained at each location of measurement by the spectrum analyser and the corresponding antenna input power.

Table 3. 2: Measured Signal Power and Antenna input power

Site	Area	Distance (*d*) (Km)	Signal Power (dBm)	Antenna input Power (dBm)
1.	CCTH	3.07	-84.65	-23.75
2.	Nkanfoa	3.32	-96.58	-38.76
3.	Ekon	3.45	-95.34	-35.45
4.	Amosima	3.93	-93.23	-29.91
5.	Duakor	5.50	-93.34	-36.93
6.	Akotokyir	6.11	-86.45	-38.75
7.	Kwawprow	6.33	-97.30	-35.08
8.	Amamoma	6.98	-94.52	-39.94
9.	Yomransa	7.25	-91.61	-35.38
10.	Moree	8.60	-91.77	-39.95
11.	Ankaful	13.1	-96.33	-37.85
12.	Biriwa	16.00	-97.75	-37.53
13.	Jukwa	20.00	-95.34	-36.98
14.	Egya	21.7	-89.56	-39.78
15.	Kormantse	25.5	-92.25	-37.18
16.	Asebu	26.7	-90.40	-38.66

Table 3.3 shows measurements of signal power at each measurement location from the BS. The average value was calculated and taken as the signal power received. The average value

of the signal power measured at the closest distance to the BS was used as the base for calculating the power received at longer distances along the same approximate radial by using Friis transmission equation. This equation has been used because it is universally accepted and able to accurately determine the signal power with respect to distance along the approximate radial.

$$Pr(d) = Pr(d_o) + 20 * log(d_o/d)$$ ---- Equation (6)

(Rao, 2007).

Where *Pr(d)* is the received power at distance *d*, d_o is the close-in-reference-distance and *Pr(d_o)* is signal power received at a close-in-reference-distance.

Table 3. 3: Change in signal power with respect to distance

Site	Area	Distance (*d*) (Km)	Signal Power (dBm)	Power Output (dBm)	Signal Power Change (dBm)
1.	CCTH	d_o = 3.07	*Pr(d_o)* = -84.65	Ref. power	-
2.	Nkanfoa	3.32	-96.58	-85.34	-11.24
3.	Ekon	3.45	-95.34	-86.35	-8.99
4.	Amosima	3.93	-93.23	-85.51	-7.72
5.	Duakor	5.50	-93.34	-89.72	-3.62
6.	Akotokyir	6.11	-86.45	-90.63	4.18
7.	Kwawprow	6.33	-97.30	-90.94	-6.36
8.	Amamoma	6.98	-94.52	-91.78	-2.74
9.	Yomransa	7.25	-91.61	-92.11	0.5
10.	Moree	8.60	-91.77	-93.60	1.83
11.	Ankaful	13.1	-96.33	-97.25	0.92
12.	Biriwa	16.00	-97.75	-98.99	1.24
13.	Jukwa	20.00	-95.34	-100.93	5.59
14.	Egya	21.7	-89.56	-101.64	12.08
15.	Kormantse	25.5	-92.25	-103.04	10.79
16	Asebu	26.7	-90.40	-103.44	13.04

3.2.1.1 TVWS by Protection, Pollution and FCC methods

In the TV frequency spectrum scan, GBC TV tower located at Radio Central was considered. Secondary data from the NCA on the tower indicates it operates in the VHF band III (174-230 MHz) and UHF V (582-682 MHz) at 100m tower height above sea level and transmission power of 20 KW (80dBm). By using the pollution viewpoint, for a tolerable signal interference of 15dB in UHF V (582-682 MHz), the pollution radius for the tower was calculated to be 35.45 km, and for a tolerable interference of 45dB in the adjacent channel, the pollution radius was 5:23km. This implies the interference level was above the allowable limit for a secondary device in a region of 35.45km in UHF V (582-682 MHz) and 5.23km in the adjacent channels around the tower. Assuming a fading margin of 1dB then the protection radius = 32.52 Km and no-talk radius = 33.52km. The no talk radius in the adjacent channel was then calculated as 32.52 Km by considering an additional fading margin of 27dB in the adjacent band. What this means is that, the primary user receiving at UHF V (582-682 MHz) will be subjected to some interference if there is a secondary device which operates within a distance of 32.52km and 33.52km in adjacent channels in the same band. In this case using Protection Point of View, WSD operating within the frequency range of 582-682 MHz must be installed outside a distance radius of 33.52Km in order to prevent signal interference from nearby transmitters. Scanning of frequencies available that could be used as white space was conducted from a frequency range of 49.5 MHz (VHF) to 950.5 MHz (UHF). In order to minimise interferences influenced by random noise, frequency scans have been separated by an interleave channel margin of 8 MHz corresponding to the licensed TV frequency channels. Each channel is represented by an average value of a number of different frequency scans at different times of the day. Table 3.4a and 3.4b show the average number of channels available as TVWS in the spectrum bands 49.5 MHz (VHF) to 950.5 MHz (UHF) in the sixteen locations per the assessment method *(Pollution and Protection View Point and FCC Rules)* used. In computing for the available white spaces, the following parameters were used.

- **Pollution Point of view**
    1. Maximum tolerable interference by secondary is between 5dB – 15dB (specified for 802.11g systems).
    2. Maximum tolerable interference by secondary for adjacent channel is 45dB.
    3. Noise in 8MHz band (*No)* is -104.97 dBm.

- **Protection Point** of **View**
    1. Target fading margin is 0.1 dB to 1dB specified by FCC
    2. Additional fading margin in adjacent channel is 27dB specified by FCC
    3. Required signal-to-Noise- Ratio for primary receiver is 45dB 4. Transmission power of secondary device 36dBm

Table 3. 4a: Average TVWS by Protection, Pollution and FCC methods

Method	Period	Area								STDV
		CCTH	Kwawprow	Akotokyir	Duakor	Amamoma	Nkanfoa	Biriwa	Moree	
Protection Point View (PrPV)	6 - 10am	39.94	42.93	44.33	45.32	45.15	44.23	45.98	45.24	**1.81**
	12 - 4pm	38.52	41.20	44.13	45.36	45.47	45.34	45.43	45.51	**2.45**
	6 - 10pm	40.23	43.07	43.73	45.34	45.98	45.76	45.65	45.78	**1.88**
	Average	**39.56**	**42.40**	**44.06**	**45.34**	**45.53**	**45.11**	**45.69**	**45.51**	**2.02**
Pollution View Point (PoPV)	6 - 10am	39.99	43.74	45.47	45.47	45.58	45.36	45.65	45.51	**1.84**
	12 - 4pm	42.87	43.38	45.45	45.23	45.66	45.55	45.34	45.53	**1.03**
	6 - 10pm	42.97	43.65	45.24	45.24	45.46	45.40	45.88	45.56	**0.97**
	Average	**41.94**	**43.59**	**45.39**	**45.31**	**45.57**	**45.44**	**45.62**	**45.53**	**1.25**
FCC Regulations	6 - 10am	42.99	43.94	45.79	45.77	45.86	45.86	45.89	45.87	**1.06**
	12 - 4pm	41.05	40.78	44.98	45.12	44.98	45.05	45.56	45.15	**1.84**
	6 - 10pm	41.96	43.85	45.56	45.67	45.98	45.58	45.98	45.98	**1.35**
	Average	**42.00**	**42.86**	**45.44**	**45.52**	**45.61**	**45.50**	**45.81**	**45.67**	**1.39**

Table 3. 4b: Average TVWS by Protection, Pollution and FCC methods

Method	Period	Area								STDV
		Simir	Kormantse	Amosima	Ekon	Yomransa	Egya	Jukwa	Asebu	
Protection Point View (PrPV)	6 - 10am	45.35	45.54	46.65	45.54	44.73	45.47	46.38	45.94	**0.57**
	12 - 4pm	38.52	43.56	45.78	45.04	45.12	45.23	45.24	45.14	**2.23**
	6 - 10pm	45.45	45.43	46.87	45.55	45.23	45.89	45.28	45.58	**0.50**
	Average	**43.11**	**44.84**	**46.43**	**45.38**	**45.03**	**45.53**	**45.63**	**45.55**	0.90
Pollution View Point (PoPV)	6 - 10am	45.43	45.53	46.57	45.69	45.65	45.84	45.43	46.67	**0.46**
	12 - 4pm	45.32	45.42	45.56	45.62	45.76	45.45	45.67	46.69	**0.40**
	6 - 10pm	42.97	43.65	45.24	45.24	45.46	45.40	45.88	46.46	**1.08**
	Average	**44.57**	**44.87**	**45.79**	**45.52**	**45.62**	**45.56**	**45.66**	**46.61**	0.57
FCC Regulations	6 - 10am	45.77	45.88	45.39	45.98	45.86	45.99	45.98	45.95	**0.19**
	12 - 4pm	43.25	41.48	45.08	45.42	43.78	45.80	45.86	45.45	**1.45**
	6 - 10pm	45.87	45.84	45.43	45.54	45.98	45.79	46.05	46.08	**0.22**
	Average	**44.96**	**44.40**	**45.30**	**45.65**	**45.21**	**45.86**	**45.96**	**45.83**	0.50

Table 3.5 presents the percentage channels/ frequencies which could be used as white spaces at the various locations where TVWS frequency scan was conducted.

Table 3. 5: Percentage of Available Channel per Method Used (%)

		Percentage of Available Channels per Method Used (%)		
Site	**Area**	**Protection View Point**	**Pollution View Point**	**FCC Regulations**
1.	CCTH	77.57	82.24	82.35
2.	Nkanfoa	88.45	89.10	89.22
3.	Ekon	88.98	89.25	89.51
4.	Amosima	91.04	89.78	88.82
5.	Duakor	88.90	88.84	89.25
6.	Akotokyir	86.39	89.00	89.10
7.	Kwawprow	83.14	85.47	84.04
8.	Amamoma	89.27	89.35	89.43
9.	Yomransa	88.29	89.45	88.65
10.	Moree	89.24	89.27	89.55
11.	Simir	84.53	87.39	88.16
12.	Biriwa	89.45	89.45	89.82
13.	Jukwa	89.47	89.53	90.12
14.	Egya	89.27	89.33	89.92
15.	Kormantse	87.22	87.98	87.06
16.	Asebu	89.31	91.39	89.86
	Mean	**87.53**	**88.55**	**88.43**

Table 3.6 presents the channels that are available as TVWS in the spectrum bands 49.5 MHz (VHF) to 950.5 MHz (UHF) in the sixteen locations. In this table the channel number and corresponding frequency are shown.

Table 3.6: TVWS Channels and Corresponding Radio Frequencies

Channel	Channel Number and Corresponding Frequency													
VHF	3	4	5	6	7	8	10	11	12					
Frequency (MHz)	57.5	64.5	177.5	184.5	191.5	198.5	212.5	219.5	226.5					
UHF	21	22	23	24	25	26	30	31	32	33	34	35	36	40
Frequency (MHz)	474	482	490	498	506	514	546	554	562	570	578	586	594	626
UHF	42	44	46	47	52	53	54	55	56	57	58	59	60	61
Frequency (MHz)	642	658	674	682	722	730	738	746	754	762	770	778	786	794
UHF	62	63	64	65	66	67	68	69						
Frequency (MHz)	802	810	818	826	834	842	850	858						

3.3 Residual DTT Signal Interference

In considering the co-existence between WSDs and DTT, much of the focus till date has been on the extent to which DTT reception might be affected by the transmissions of WSDs. However, the extent to which DTT signals from TV transmitters might impinge upon white space channels has not been given much attention. But it is very important to note that when permission is given for a white space channel in a particular location to be used, there is no guarantee that it will be free from potential interference from DTT signal transmissions. For this reason, signal interference from residual DTT signal strength to estimated TVWS available in each of the locations has been calculated. This will help to determine the quality of TVWS spectrum available at the locations under consideration. Residual DTT signal power was measured by using the RF Explorer Spectrum Analyser. The results obtained from measurement of residual signal power of DTT is presented in Table 3.7.

Table 3.7: Residual DTT Signal Power at the various locations

Site	Area	Residual Signal Power (dBμV/m)
1.	CCTH	45
2.	Nkanfoa	38
3.	Ekon	37
4.	Amosima	38
5.	Duakor	37
6.	Akotokyir	36
7.	Kwawprow	37
8.	Amamoma	39
9.	Yomransa	38
10.	Moree	39
11.	Simir	36
12.	Biriwa	37
13.	Jukwa	36
14.	Egya	38
15.	Kormantse	35
16.	Asebu	34

3.4 Creation of TVWS Database

The creation of a national TVWS geo-location database requires the decision on the technical data needed for WSD to operate. This data basically includes, at least spectrum masks and full technical specifications/standards. Since WSDs operate on CR techniques and considering the nature of CR and mandatory protection of all incumbent services, the data in the databases cannot be technically neutral; due to the fact that protection of incumbent services from interference caused by WSDs depends on detailed technical data of the CRS used. For this reason, some regulators may wish to implement only some selected technical CRS standards in specific regions. Others may also wish to accept all CRS devices that fit the spectrum mask and other general parameters. This assures flexibility of spectrum use and neutrality in technology. However, allowing different types of radio transmission means that special attention has to be given to the adjacent frequency bands. Thus, the geo-location database should contain up-to-date detailed information on TV transmitter characteristics and specific propagation models to estimate the TV signal power at any given location. It is for this reason that, this thesis adopted the hybrid method of spectrum user protection which assures a real-time database update with the help of radio sensing devices.

3.4.1 Database ER-model diagram

MySQL database management was used in the implementation of the WSDB system. This is because MySQL is a relational database system in which data is organized in different related tables with different attributes. Figure 3.5 shows the ER-model diagram of the designed TV white space database. With reference to FCC Regulations the proposed TVWS database is made up of fourteen related tables/entities with variety of attributes containing data on different entity groups as discussed as follows:

Regulators Table

This table stores information about the rules that governs the operation of white space devices and WSDBs. This information is defined and registered by the region's regulatory authority such as in NCA in Ghana, ECC in UK and FCC in USA. But since Ghana currently, does not have any regulatory policy in place for the use of available TV white Spaces, the FCC regulatory policy has been adopted in this work.

In this table, the following identified key attributes of the entity are described: the transmission power of WSDs, the pixel size of regulator's domain, TV towers, and other users, the maximum duration between requests for available spectrum in seconds, and the max coverage distance of the white space device.

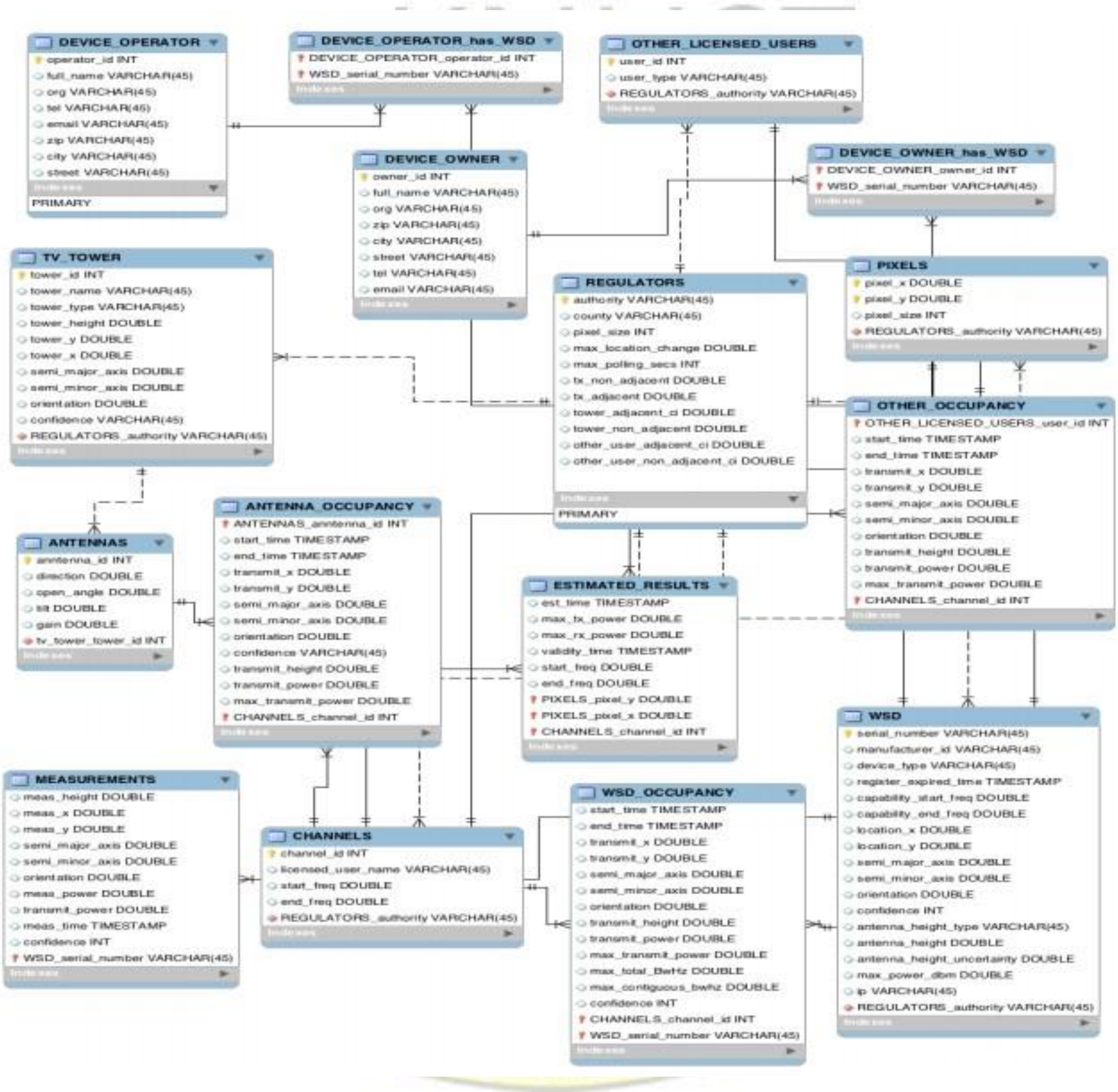

Figure 3.5: ER-Model diagram of Localised TVWS Database

WSD Table

This table contains information about WSDs that have registered to the WSDB. The attributes contain in this table are mainly used for identification and authentication and also enable the control of WSDs that make use of the system.

Device Operator Table or Device Owner

This table contains information on the owner and operator of WDSs. This includes their detailed contact information that will make contacting them very easy.

TV Towers Table

This table stores information on TV Towers such as name, type, location and height. This information enables the computation of the scope of TV signal transmission. This table has Tower ID as its' identified (primary) key and Regulator authority as a foreign key.

WSD, Antennas Occupancy and Other-Licensed Users Table

These tables are used to store information about occupancy and coverage of radio frequency transmitters. This includes detailed information on the antennas WSDs and other spectrum users. This information is used to identify all the transmitters, the different transmission channels and frequencies for each location and moment. The attributes of these table stores data on the transmission duration (*the start time and end time*). It also contains information on the height of the white space device above an average level, the permissible power and the coordinate of transmission during the occupancy time of the given channel.

Antenna Table

Because a TV Tower may have more than one antenna mounted on it, the antenna table stores information about each antenna such as the direction, open angle, tilt, and signal power gain. This information enables simulation of the scope of transmission of TV signal and also help to increase the interference protection of transmitters.

Pixels Table

The Pixels Table has the Pixel ID as its primary (identified) key and stores information about the pixels. The attributes of this table indicate the height and user-defined coordinates of the pixel. It has a foreign key to match the regulator, because different regulator may have the different pixel size.

Channels Table

This table stores information about the different channels. This enables protection on TV channels that are regulator defined and allows the extension of service to other frequencies.

TV Towers Table

This table stores the information on TV Towers such as the name, location, type and height. This information is used for the computation of the scope of TV signal transmission. Its primary key is the Tower ID, and it has a foreign key which is the Regulator authority.

Measurement Table

This table contains the sensing results of the registered sensing node. These results can increase the accuracy of computation of the WSDB system and also enable the WSDB to provide more trustable results to white space devices, thus reducing the possibility of interference occurrence.

Estimated Result Table

This is used to save the result of the calculations/computations of the white space database system. Computation of available channels for each pixel is done according to the content of Occupancy and Measurement. When a request is made by an incumbent spectrum user or a query by white space device to the database to get the available channels for a certain location, the database gives a response in accordance with the content of this table for the given location.

3.5 Frame work for Hybrid Method of Incumbent User Protection

In this section, the proposed hybrid method of accessing and protection of TV spectrum is discussed. This method is termed hybrid because it uses a combination of both geolocation database and spectrum sensing with an introduction of a localised TVWS database server (LTDS) and a dedicated spectrum sensing device which enables a real-time update of the geolocation database of LTDS as shown in Figure 3.6. Since the amount of available TVWS is unique for a given geographical location, the LGDS will contain information on all TV Channels operating in that geographical area and also the available channels that could be used as white spaces. At the same time, the LGDS is linked to a nationwide (regional) online TVWS geolocation database through the internet for regular update of its content. In this case, the master WSD would contact the GPS in order to know its geographical location and then query the LGDS instead of the online geolocation database. This enables the WSDs to work without causing harmful interference to primary users even when Internet connectivity is lost.

But the question one may ask is, what happens when there is a change in transmission parameters of TV channels operating in that particular geographical area of the TVWS broadcast? The work of the spectrum sensing device (SSD) is to do a continuous spectrum sensing and real-time update of the localised geolocation database in order to handle any changes in transmission parameters thereby avoiding any harmful interference to primary users. Since spectrum sensing is done by the SSD, the problem of network complexity associated with cooperative spectrum sensing is overcome. At the same time, the fading, shadowing or the hidden user problem of spectrum sensing is dealt with. This is because whenever the master or the Slave WSD is not sure of the availability of a particular channel it will query the LGDS. In this case, the WSD will not just assume the channel is occupied or free to be used as white space. Even when there is a break in Internet connection between the Localised and online GD, the network can still work effectively because the SSD together with the localised GD would continuously be assisting the WSDs to be operating on the most suitable frequency until the time Internet connection is re-establish and the localised GD is updated. Another advantage about this setup is that, without the SSD and the localised database, the WDSs will continue to operate on a single frequency even when there is a change in the spectra conditions of that geographic location until the update of WDSs information by a re-establishment of Internet connection between the WSDs and online TVWS GD.

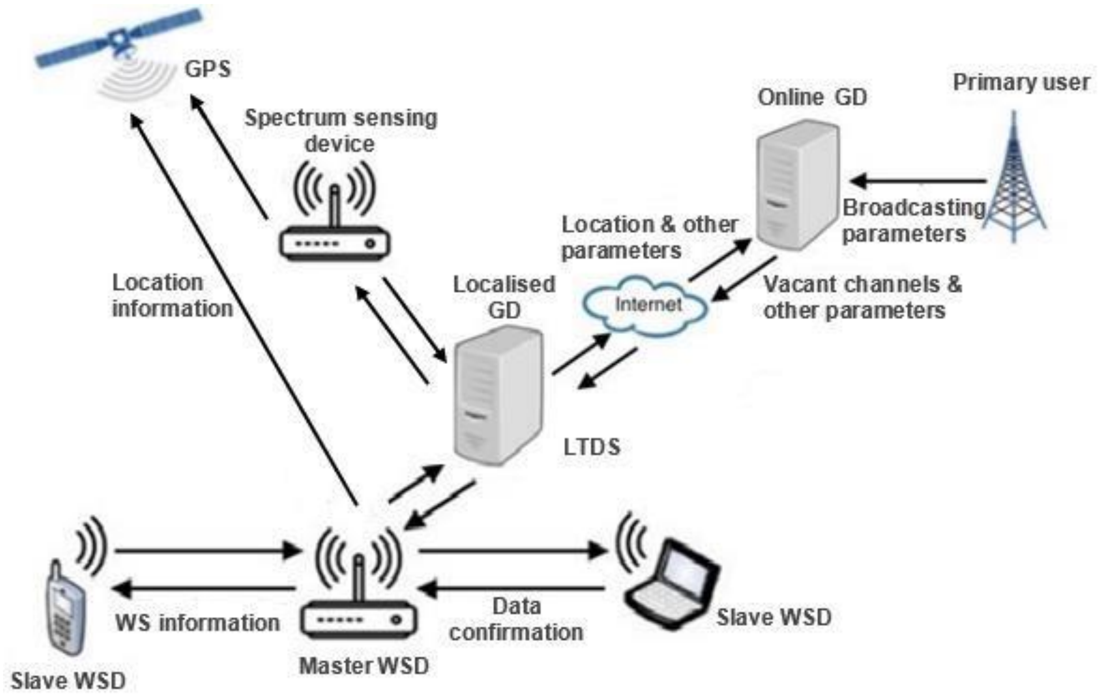

Figure 3.6: Hybrid Method of Incumbent User of Protection

3.6 Architecture for TVWS Network

A point-to-multipoint TVWS network was setup to link the Clinical Teaching Centre of the School of Medical Sciences at the Cape Coast Teach Hospital (CTC SMS CCTH) and four (4) other community Centres as shown in Figure 3.7. A master TVWS device was setup at the TVWS Base Station and Slave TVWS devices were used to link the various community centres to the CTC SMS CCTH. Internet connectivity was provided by EMCEE Satellite, a private Internet service provider (ISP) based in Cape Coast. In this case information in the form of text documents, images, and videos could be transmitted from the CTC SMS CCTH to the community centres and vice versa. Real-time video communication was also possible since the TVWS network provided a very good latency and a high data throughput. The results of the analysis of the TVWS network performance is discussed in the chapter four of this thesis. From Figure 3.6, the Localised TVWS geolocation spectrum database (L) is housed on a localised TVWS database server (LTDS) and this server is connected to an online

TVWS geolocation spectrum database through the internet. This enable an automatic update of the database on the LTDS thus ensuring an up-to-date information hence avoiding interference due to false declaration of free channels. The master TVWS device is connected to the LTDS and GPS to enable it get information on its geographical location. All slave WDSs are connected to the master device thus creating a point-to-multipoint network as shown Figure 3.7.

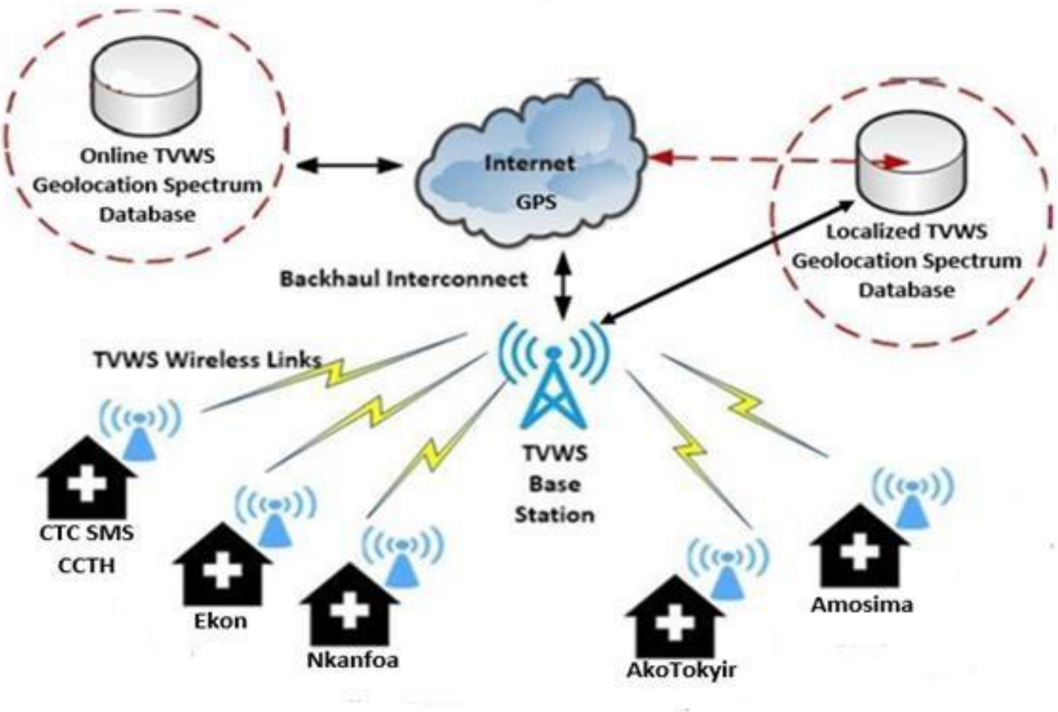

Figure 3. 7: Point-to-Multipoint TVWS Network Architecture

3.6.1 Network Performance Measurements

In order to measure the performance of Wi-Fi and TVWS networks, two separate Point-to-Multipoint networks. Each network had four sectors with each sector location chosen on purpose. One sector guaranteed a clear LoS connection with the other three sectors having the geographical features: mountainous obstructions, Obstruction by vegetation and structural obstruction (high-rise building). The Wi-Fi network was setup up by using a RADWIN 5000 and Carlson's Gen3 RuralConnect TV White Space System for the TVWS network. RADWIN 5000 is an excellent high-capacity Point-to-Multipoint (HPMP) Wi-Fi network device that is capable of delivering both LoS and NLoS network backhaul solution with an outstanding performance of up to 25 Mbps per sector. Table 3.8 give a description of the features of RADWIN 3000 and Gen3 RuralConnect.

Table 3.8: Features of RADWIN HBS 5025 and Gen3 RuralConnect

	Network Device	
Features	**RADWIN HBS 5025**	**Carlson RuralConnect**
Range	25 Km	25 Km
Sensitivity	-98 dBm	-94.7 dBm
Antenna Power	11dBi	5dBi
Latency	4 – 20 ms	25 – 35 ms
Bandwidth	25 Mbps	24 Mbps
Frequency	4.9 t0 6.4 GHz	470 – 698 MHz
Data Throughput	Up-to 100 Mbps	Up-to 72 Mbps
Power Tx	25 dBm	24 dBm
Standardization	IEEE 802.3af	IEEE 802.11af
Connector	RJ45 POE	RJ45 POE

Before network performance measurements were carried out, frequency scans were carried out in the UHF band and also the 5 GHz Wi-Fi band. Wi-Fi and TVWS radio frequencies which resulted in the lowest noise level or lowest level of interference were selected for the network setup. Performance of the networks was also tested at different channel widths (5, 10, 20 MHz) in order to ascertain if interference from adjacent channels will have any impact on network performance. Network performance test was measured in terms of the following parameters: data throughput, latency and RSSI.

Throughput: it is the amount of information successfully delivered per unit time over a network. It is controlled by the network bandwidth, the available signal-to-noise ratio and also limitations of the hardware used. While bandwidth is the maximum amount of data that can be transmitted on channel, throughput gives the actual amount of data that travel through the channel. It is usually measured in bits per second (bps), but sometimes expressed in data packets per second (pps). The throughput of a network can be calculated using the Shannon's equation of channel capacity for a communication link as shown in the equation below (Shannon, 1949).

$$C = B\log_2\left(1 + \frac{S}{N}\right)$$

Where B is the bandwidth, S the average signal power received and N the average noise power. Table 3.9 presents data throughput measurements recorded for both Wi-Fi and TVWS networks at different channel widths (5, 10, 20 MHz).

Table 3.9: Data throughput measurements for Wi-Fi and TVWS networks

Channel Width (MHz)	LoS Network Throughput (Mbps)		NLoS Network Throughput (Mbps)	
	Wi-Fi (5180 MHz)	TVWS (575 MHz)	Wi-Fi (5180 MHz)	TVWS (575 MHz)
	Min /Avg /Max	Min /Avg /Max	Min /Avg /Max	Min /Avg /Max
5	2.5 /6.2 /8.5	1.8/ 5.4/ 6.1	2.0 / 4.5/ 5.5	1.8 /5.2 /5.8
10	6.4 /8.5 /8.7	4.4 /6.3 /7.3	4.2 /6.4 /7.5	4.1/ 6.1 /7.0
20	8.5 /9.1 /10.2	6.5 /7.3 /8.2	6.5 /8.3 /8.8	6.1 /6.8 /8.1

Latency: it is the measure of the time it takes for a packet of data to be transferred from one destination to another. It is used to indicate the amount of delay in a network. It is determined by but not limited to the following: the communication medium used, the distance between the source and destinations of packets and router. The latency of a network can be tested either by using ping or traceroute tool. In this work, the Microsoft Ping utility software has been used in the measurement of the latency. The results of the Wi-Fi and TVWS network performance in terms of latency is shown in Table 3.10.

Table 3.10: Latency measurements for Wi-Fi and TVWS networks

Channel Width (MHz)	LoS Network Latency (ms)		NLoS Network Latency (ms)	
	Wi-Fi (5180 MHz)	TVWS (575 MHz)	Wi-Fi (5180 MHz)	TVWS (575 MHz)
	Min /Avg /Max	Min /Avg /Max	Min /Avg /Max	Min /Avg /Max
5	1 / 4 /10	10 / 12 /17	10/ 20/ 25	10 /15 /20
10	1 / 3 /10	10/ 12 /15	12 /18 /23	10/ 15/18
20	1 / 2 /5	10 /11 /13	10 /15 /20	10/ 12 /16

3.6.2 Propagation Analysis of Measured TVWS Signals

Comparative analysis of signal propagation characteristics of Wi-Fi and TVWS was done by measuring the attenuation levels over a distance and signal resistance to interference caused by a noise signal. The impact of geographical location terrain and some weather elements such as temperature and atmospheric humidity on RSSI was also tested.

3.6.2.1 Signal Path Loss (Attenuation)

Signal attenuation measurements were taken for both the Wi-Fi and TVWS networks by measuring the signal power at the transmission site and signal power at the receiving site. Attenuation *(signal loss)* is a natural consequence in the transmission of signals over long distances. This can occur in either digital or analogue signal transmission and is usually expressed in decibels (dBs) which is the unit for measuring signal power loss. Signal path loss was measured in both LoS and NLoS signal propagations. Path loss in free space range (LoS) was determined by using the Friis free space equation for Free Space Path Loss (ITU-R, 1994). This equation has been chosen because it a universally accepted formula for calculating signal path loss in LoS scenario. Also, signal path loss depends mainly on two important parameters and these parameters are captured, thus making the equation very flexible to work with.

$PL_{FreeSpace} = 20log(d) + 20\ log(f) + 32.4$ ----- Equation (7) (ITU-R, 1994)

Where *d* is the distance in meters (m) and *f* is the frequency in Giga Hertz (GHz) Table 3.11 shows the average signal path loss for both Wi-Fi and TVWS signal at various distances.

Table 3.11: Line-of-Sight Signal Path Loss for Wi-Fi and TVWS Networks

	Line-of-Sight Signal Path Loss (dBm)	
Distance Km	**Wi-Fi**	**TVWS**
Below 1	100.57	81.61
1 – 2	112.95	93.66
STDV	**6.19**	**6.03**

3.6.2.2 Signal Path Loss in NLoS Network

Non-line-of-sight signal path loss for both Wi-Fi and TVWS networks were determined by using three different path loss formulae. This is because research of literature on how to determine signal path loss for non-line-of-sight networks revealed that no single formula is able to accurately do that. For this reason, this study adopted the following formulae: Hata, Ericsson, and Stanford University Interim models.

Average values of these equations have been used to determine the difference in the NLoS signal path loss for both Wi-Fi and TVWS networks. Table 3.12 shows the results obtained from NLoS signal path loss calculations and averages values.

Table 3.12: Signal Path loss in NLoS Wi-Fi and TVWS Networks

	Non-Line-of-Sight Signal Path Loss (dBm)							
	Hata		Ericson		SUI		Average	
Distance (Km)	Wi-Fi	TVWS	Wi-Fi	TVWS	Wi-Fi	TVWS	Wi-Fi	TVWS
Below 1	101.23	81.62	118.39	105.24	121.83	103.18	**113.82**	**96.68**
1 – 2.5	113.28	93.66	177.13	165.86	155.25	136.59	**148.55**	**132.04**
3 – 4.5	116.80	97.1	194.86	183.60	165.02	146.37	**158.89**	**142.36**
5 – 6.5	121.23	101.62	217.20	205.94	177.33	158.68	**171.92**	**155.41**
7 – 8.5	124.16	104.54	231.91	220.65	185.44	166.79	**180.50**	**163.99**
9 – 10.5	126.34	106.73	242.90	231.64	191.44	172.85	**553.56**	**170.41**
11 – 12.5	128.08	108.47	251.68	240.42	196.33	177.68	**192.03**	**175.52**
13 – 14.5	129.53	109.92	258.99	247.72	200.36	181.71	**196.29**	**179.78**
15 & Above	131.86	112.25	270.72	259.46	206.83	185.16	**203.14**	**185.62**
							P= 0.899	**P= 0.894**

3.6.2.3 The effect of Geographical Terrain on RSSI

RSSI is the relative received signal strength in a wireless environment, in arbitrary units. It indicates the power level of a signal being received by a wireless device after antenna and possible cable loss. Received signal strength is represented either as the quality of signal in percentage, or an RSSI value in decibels (dB). But it is usually expressed in dB which is the power ratio of the measured power referenced to one milliwatt. RSSI value is usually from zero to negative one hundred and twenty decibels (0 to -120) dB. Thus, the closer the signal strength is to zero, the stronger it is and vice versa. RSSI was measured by using the signal strength indicator function of the wireless devices. Table 3.13 shows the geographical terrain of the locations under study and their respective RSSI values.

Table 3.13: RSSI measurements due to geographical terrain of location

Geographical Terrain	Received Signal Strength Indicator (RSSI) (dB)	
	Wi-Fi	TVWS
	Min/ Avg/ Max	Min/ Avg/ Max
Vegetation	-65 / -59 / -54	-57 / -53 / -51
Vegetation & Hills	-72 / -63 / -60	-65 / -56 / -54
Vegetation & High-Rise Structures	-68 / -61 / -59	-63 / -54 / -52

3.9.2.4 The effect of Temperature and Humidity on RSSI

Since the focus of this study is on long-range NLoS network backhaul for provision of Internet services in rural communities in the Central Region of Ghana, the effect of temperature and humidity on received signal strength has been tested at a network distance of 15 Km NLoS. RSSI measurements were taken for five (5) consecutive days (*morning, afternoon and evening at 6-10am, 12-4pm and 6-10pm respectively).* Temperature measurements were taken at the same period by using AccuWeather, an Android base online weather software. Average values of these measurements were used to determine the correlation between the two variables *(RSSI and Temperature).* This was done for both Wi-Fi and TVWS networks. Results obtained from the fiveday measurements is presented in Table 3.14.

Table 3.14: Effect of Temperature on RSSI

Day	Time	Temperature (O° C)	Received Signal Strength Indicator (RSSI) (dB) Wi-Fi	TVWS
1	6 – 10 am	26	-65	-58
	12 – 4 pm	29	-67	-62
	6 – 10 pm	27	-64	-56
2	6 – 10 am	25	-64	-61
	12 – 4 pm	28	-69	-64
	6 – 10 pm	26	-62	-55
3	6 – 10 am	25	-64	-52
	12 – 4 pm	30	-65	-57
	6 – 10 pm	27	-60	-61
4	6 – 10 am	26	-65	-59
	12 – 4 pm	29	-68	-62
	6 – 10 pm	25	-64	-58
5	6 – 10 am	24	-62	-54
	12 – 4 pm	27	-66	-58
	6 – 10 pm	25	-63	-57
			P = -0.5703	*P = -0.5217*

Again, the impact of absolute humidity on the RSSI was tested because humidity is another potential factor that affects RSSI. In order to test the impact of humidity on RSSI of the networks, received signal strength measurement were done on a rainy day. Table 3.15 shows results of thirty (30) minutes signal strength measurement taken for both Wi-Fi and TVWS networks. Six measurements were taken in all at five (5) minutes intervals.

Table 3.15: Effect of Absolute Humidity on RSSI

	RSSI (dB)	
Absolute Humidity (AH) %	**Wi-Fi**	**TVWS**
95	-69	-61
97	-72	-65
97	-74	-62
90	-60	-60
92	-63	-58
85	-59	-54
	P = -0.9356	***P = -0.8823***

CHAPTER FOUR

RESULTS AND DISCUSSION

4.0 Overview

In this chapter, we present analysis and discussion of the results obtained from the quantitative assessment of TVWS measurements done in sixteen (16) different locations in the Central Region of Ghana. This includes areas around the Cape Coast Teaching Hospital and fifteen other villages in and around the Cape Coast Metropolis. Signal propagation characteristics are analysed and TVWS network performance test results presented. The results obtain from measurements have been presented in the form of tables and graphs.

4.1 Quantitative Analysis of available TVWS

In this section, results obtained from the quantitative assessment of TVWS measurements done in sixteen (16) different locations in the Central Region of Ghana is presented. This includes areas around the Cape Coast Teaching Hospital and fifteen villages in and around the Cape Coast Metropolis. Quantitative analysis of available TVWS started with a critical assessment of secondary data from NCA. NCA data on the list of authorized TV stations in Ghana (Refer to Appendix A - list of authorized TVs) revealed that at the national level, out of the 117 authorized TV stations, only 51 representing 43.5% were online and 66 representing 56.6% were offline as at the time the study was conducted. But the situation was different at the sixteen (16) areas under studied. TV spectrum scan that was done recorded 39 as the maximum number of stations online and 25 as the minimum. The average number of stations online was 33.5 representing 28.6% of the authorized TV stations nationwide. With this data one can easily assume that about 71.4 % of this TV spectrum could be considered as white space; but further studies were needed to be able to ascertain this assumption able to ascertain this assumption. This is because with current digital TV broadcast, more than one TV stations could operate on a single channel. That is why the study adopted three different mode of spectrum assessment: protection view point, pollution view point and FCC rules in order to give an accurate estimation of the available TV spectrum that could be used as white spaces.

4.1.2 Comparison of Pollution Viewpoint, Protection Viewpoint and FCC Rule

Results obtained in Table 3.4a and Table 3.4b illustrate that at most of the locations studied, only a small portion of channels in the VHF and UHF band is utilized.TV Spectrum from the pollution viewpoint revealed that 13 of the locations representing 81.25% have 45 channels available as white space, while 100% of the locations have 41 channels available as white space. Results obtained from the protection viewpoint was not much different. It shows that 12 of the locations representing 75% had 45 channels, whiles 93% had 42 channels available for TVWS operations. The percentage of available white spaces increased marginally with the FCC regulations, with 12 of the locations representing 75% having 45 channels available and 100% having 42 channels available as TV white spaces.

4.1.3 Percentage of TVWS available in the Central Region of Ghana

Figure 4.0 shows that the Clinical Teaching Centre of the University of Cape coast, School of Medical sciences recorded the least amount of available TVWS in all the three (3) methods. Thus, recording 77.75% for Protection View Point, 82.24% for Pollution View Point and 82.35% for FCC Regulations method giving an average of 80.72%. By using the Protection View Point, Amosima, a village near Cape Coast recorded the highest amount of available TVWS, 91.04%. Asebu recorded the highest available TVWS for Pollution View Point, 91.39 with Jukwa recording 90.12%, being the highest for FCC Regulations method. On the average the Clinical Teaching Centre of the University of Cape coast, School of Medical sciences recorded the smallest amount of TVWS. This might have happened because it is the only urban area among the locations under study. This location has been added to the study because it is the centre of operation for the TVWS network. Asebu recorded the highest amount of available TVWS with about 90.19% of TV spectrum available to be used as white space. An average of 88.17% of TV spectrum in all the sixteen (16) locations was identified as TVWS. These amounts are far greater than TVWS values obtained from some rural parts of Japan, where only an average of 16 out of 40 channels representing 40 % were available (Shimomura, 2012). This is also larger than TVWS available in some rural communities of United State and some European countries (Nekovee, 2009).

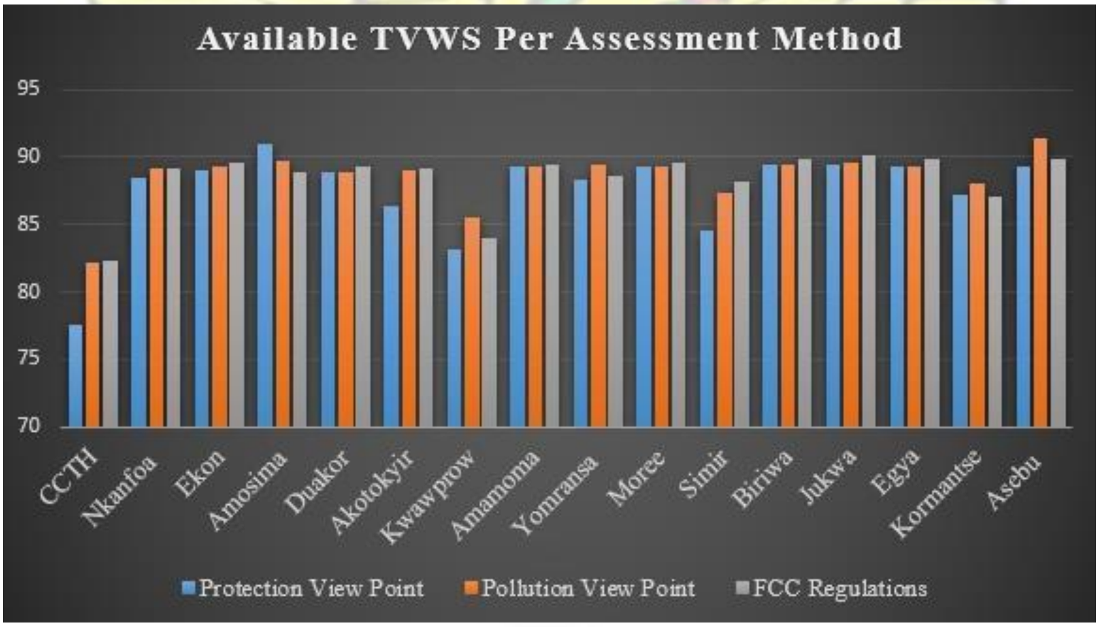

Figure 4. 0: Available TVWS per Assessment Method

4.2 Residual DTT Signal Interference

The results obtained from residual power of DTT in Figure 4.1 show that 15 of the locations representing 93.75% of the areas studied have a residual DTT field strength of less than 40 dBμV/m which means TVWS channels in these locations is of high quality and would be practically usable. This is because the quality of a TV white space signal is a function of the transmission power needed by the WSD to operate without causing any harmful interference to primary spectrum users and also dependent on the level of residual power from DTT transmitters at which no harmful interference would be caused to TVWS signals. This means the lower the transmission power of WSD and residual DTT power, the more isolated it will be from harmful signal interference.

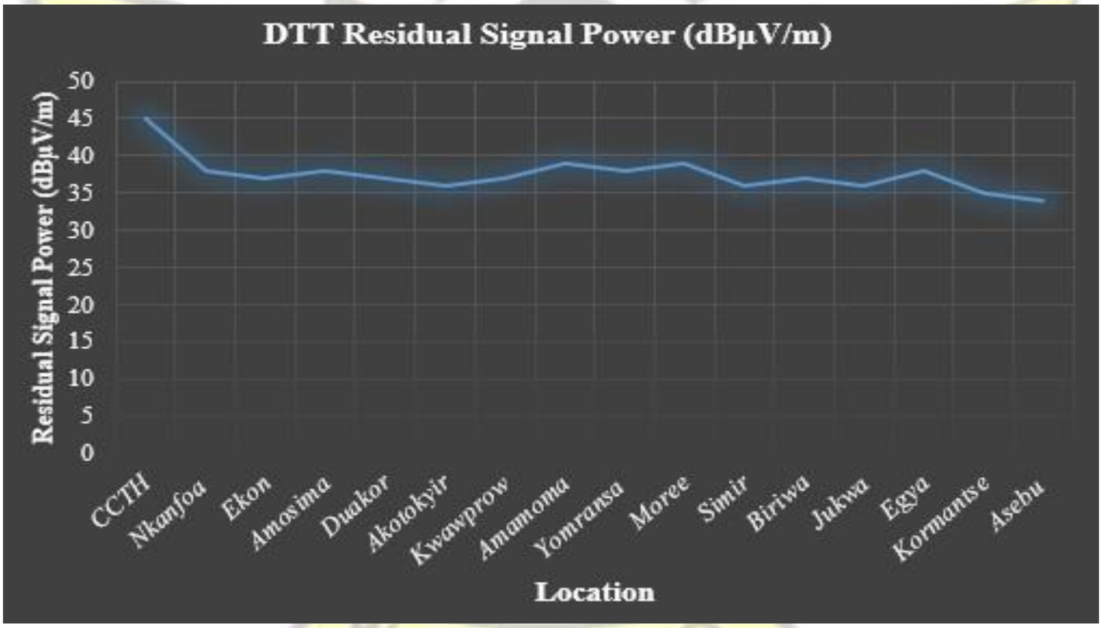

Figure 4. 1: Residual DTT field strength at the various locations

4.3 TVWS Geolocation Database

Figure 4.2a, 4.2b and 4.2c show the interfaces of the Home page, Regulators' tables and Add Channel of the TVWS Geolocation Database respectively.

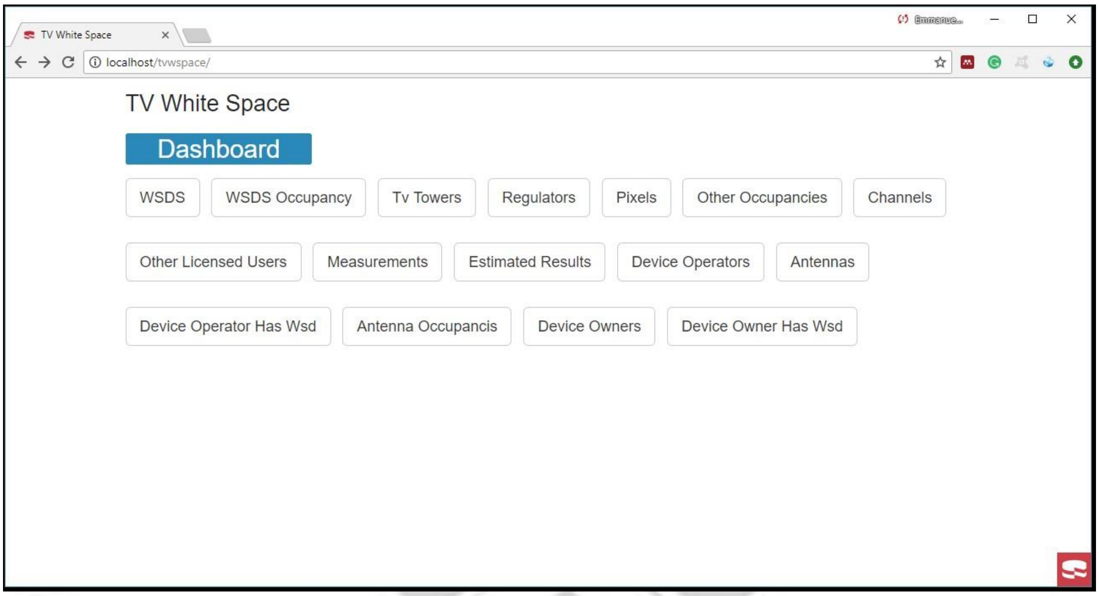

Figure 4.2a: Home Page of TVWS Geolocation Database

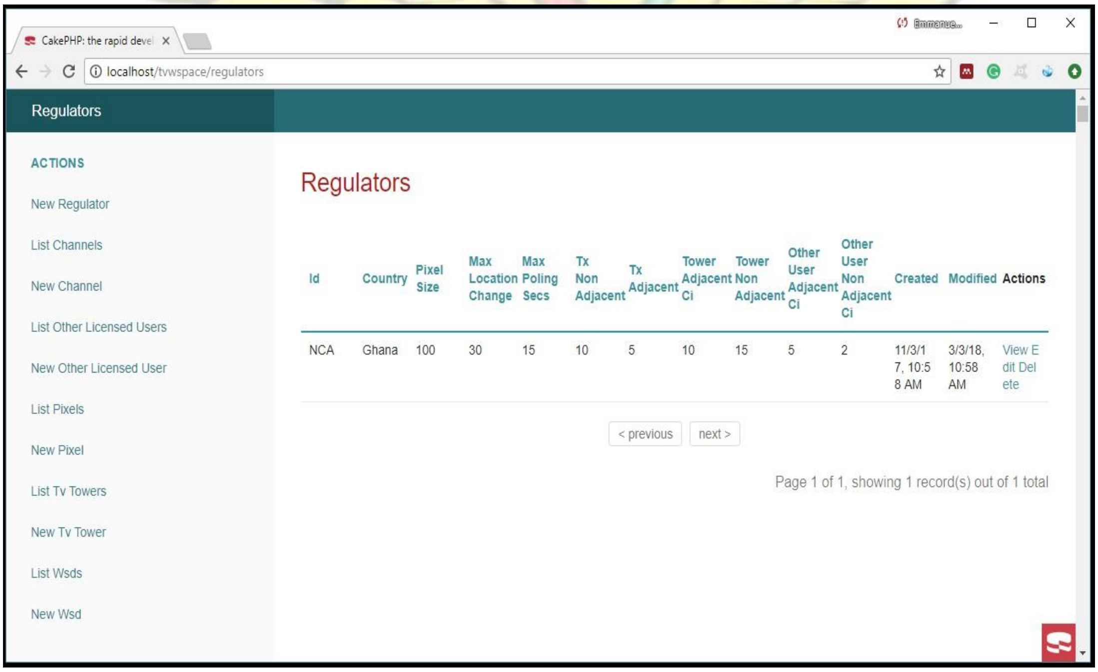

Figure 4.2b: Interface of Regulators' tables of TVWS Geolocation Database

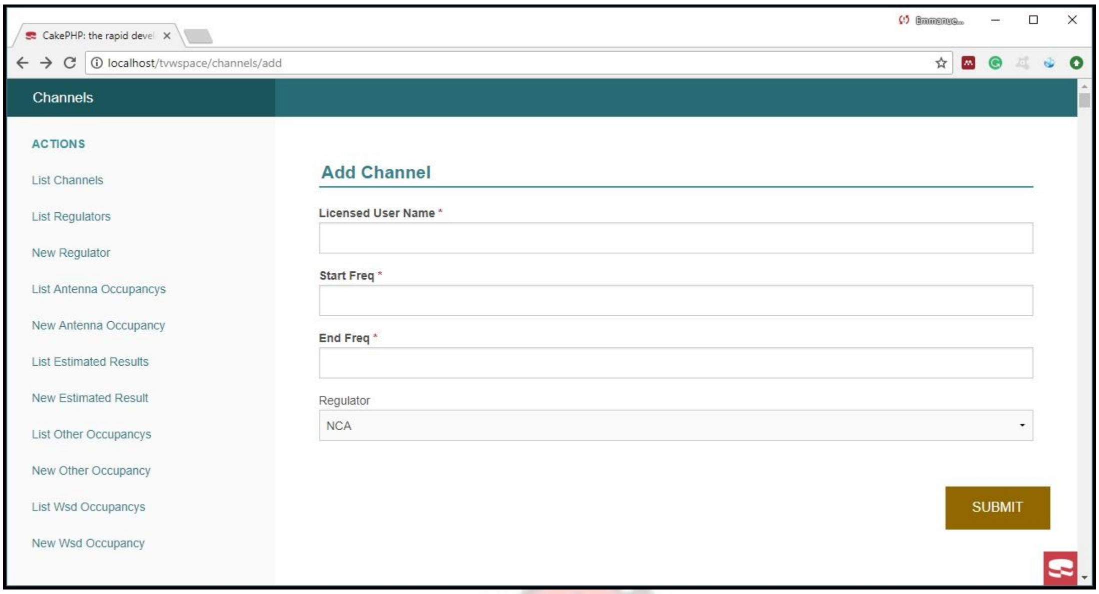

Figure 4.2c: Add Channel Interface of TVWS Geolocation Database

4.4 TVWS and Wi-Fi Network Performance Measurements

TVWS and Wi-Fi networks performance were test in both LoS and NLoS condition. The discussion of results on the performance measurements of the TVWS and Wi-Fi networks in terms of signal attenuation due to signal path loss data throughput, latency and RSSI are presented as follows:

4.4.1 Signal Path Loss

This section discusses results obtained from signal path loss measurements conducted for TVWS and Wi-Fi networks in both LoS and NLoS scenarios.

4.4.1.1 LoS Signal Path Loss

Line-of-Sight (LoS) signal path loss measurements were done up-to only a distance of 2km. This is because beyond that distance, line-of-sight could not be achieved. Results from LoS signal path loss (*Table 3.11*) shows Wi-Fi network recorded a high signal path loss than TVWS even in the LoS scenario. A signal path loss of 100.57 and 81.61 dBm were recorded for Wi-Fi and TVWS networks respectively at a network distance of 0.5Km. At a network distance of approximately 2Km a signal path loss of 112.95 dBm was recorded for Wi-Fi and 93.66 dBm for TVWS networks. The standard deviations for the signal loss computed for the two networks (*Wi-Fi = 6.19 & TVWS = 6.03*) suggest that the difference in the rate of signal path loss is negligible.

4.4.1.2 NLoS Signal Path Loss

Results obtained from signal path loss measurements for NLoS Wi-Fi and TVWS revealed that signal path loss is greater in the NLoS propagation as shown in Figure 4.3. It can be seen that the Wi-Fi network recorded a minimum signal path loss of 113.82 dBm whiles the TVWS network recorded 96.68 dBm. 203 dBm was recorded as the maximum signal path loss by the Wi-Fi network and 185.62 for TVWS network. The average NLoS signal path loss for the Wi-Fi network was 172.08 dBm with 155.76 dBm recorded for TVWS. Pearson Correlation computed to ascertain the relationship between distance and signal path loss showed a strong positive correlation between distance and signal path. A Pearson Correlation coefficient of 0.899 was recorded for the Wi-Fi and 0.894 for TVWS networks which confirms that signal path loss of a broadcast signal increase as propagation distance also increase. But it could be seen from Figure 4.2 that signal path loss of the Wi-Fi was higher than that of TVWS. The possible explanation could be because Wi-Fi operates in super high frequencies (SHF) and are susceptible to interference. Wi-Fi also operates with high power levels and because of that, has low penetrating capability thus, are not able to travel far. TVWS network recorded signal path loss lesser than that of Wi-Fi because it operates in VHF and UHF frequencies and at low power levels causing it to withstand interference and also travel far.

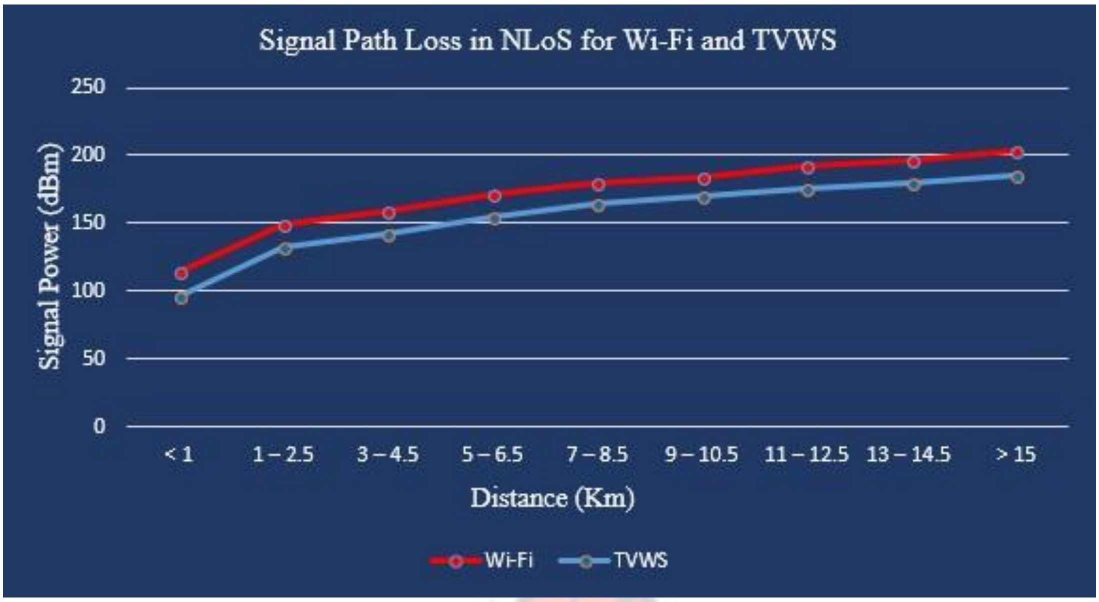

Figure 4. 3: Signal Path Loss for NLoS

4.5 The effect of Geographical Terrain on RSSI

The geographical terrain in which signal propagation is done, is likely to have some effect on the strength of the signal transmitted. For this reason, RSSI measurements were taken for three (3) different terrain settings. Results obtained as shown in Table 3.13, revealed that attenuation was minimal in the vegetation environment. In this environment Wi-Fi network recorded a minimum RSSI of -65 dB, maximum of -54 dB and average of -59 dB. This is slightly lower than that of TVWS, as -57 dB, -51 dB and -53 dB were recorded for minimum, maximum and average RSSI respectively. RSSI reduced further for both Wi-Fi and TVWS in the environment comprising vegetation and hills with the average rate of change in RSSI for Wi-Fi and TVWS being about 6 dB and 4 dB respectively. The situation was not much different for areas with vegetation and high-rise buildings, as these areas recorded a rate of change in RSSI of 4 dB and 2 dB for Wi-Fi and TVWS respectively.

4.6 The effect of Temperature and Humidity on RSSI

From Table 3.14, Pearson Correlation coefficient between RSSI and temperature for Wi-Fi and TVWS links are -0.5703 and -0.5217 respectively. This shows that there is a negative correlation between RSSI and temperature which means anytime temperature level increases there is a corresponding decrease in RSSI. This has been noted especially in the afternoon periods when sun shine level is high. This may have been because collision between light particles from the sun with radio signal as higher solar energy from the sun causes temperature to increase. This is possible because radio and sun waves are electromagnetic wave and hence share the same properties such as reflection, refraction and diffraction whenever they meet an obstacle.

Humidity is also another potential factor that affects RSSI. Figure 4.4, shows a clear relation between humidity and signal strength. Thus, when there is a rise in humidity, RSSI falls indicating a negative correlation and vice versa. The Pearson correlation coefficient computed for humidity and signal strength measurements shows the relationship between the two variables is statistically significant. Though correlation in signal strength and these weather elements (temperature and humidity) can be a good predictor of a potential causal relationship in signal strength variations, it does not strictly imply all variations in signal strength are caused by their impact rather they could be caused by other factors. It must be noted that the close relationship between the two variables (*temperature and humidity*) further complicated the attempt to distinguish between the actual impact of temperature and humidity on RSSI. For this reason, further studies would be needed to ascertain the impact of these weather elements (temperature and humidity) on RSSI independent of the other. Nonetheless, the results confirm findings reported in some previous literature (Banniser et al., 2008;

Wennerstrom et al., 2013), which states that temporal variation in signal strength are mostly due to changes in weather conditions.

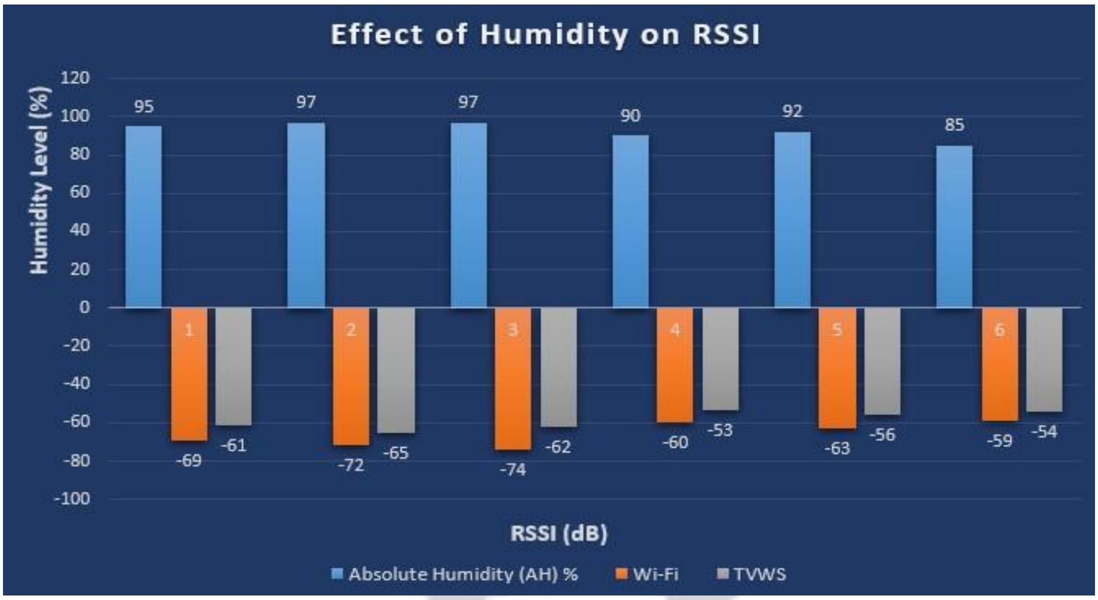

Figure 4.4: Effect of Absolute Humidity on RSSI

4.7 Network Throughput

Network data throughput refers to the amount of data that can be transmitted from one location (*source*) to another (*destination*) in a given amount of time. This is one of the parameters use to measure the performance of a network. Results obtained from throughput measurements by varying the channel width of the Wi-Fi and TVWS networks revealed that, a fairly linear relationship exist between the average data throughput and network channel width as shown in Table 3.9. From Table 3.9 it could be seen that data throughput increase with an increase in network channel width which is to be expected. Figures 4.5 shows that in the LoS network, the Wi-Fi network obtained 13.5 Mbps as maximum, 7.2 Mbps as minimum and 9.1 Mbps as average data throughput. These are slightly higher than data throughput measurements obtained from the TVWS network measurements as shown in Figure 4.6. The TVWS network recorded 11.1 Mbps, 6.8Mbps and 7.5 Mbps as Maximum, minimum, and average throughput respectively. This shows that Wi-Fi network can perform better than TVWS with a throughput difference of about 1.6 Mbps in LoS network in the absence of external effects from the environment.

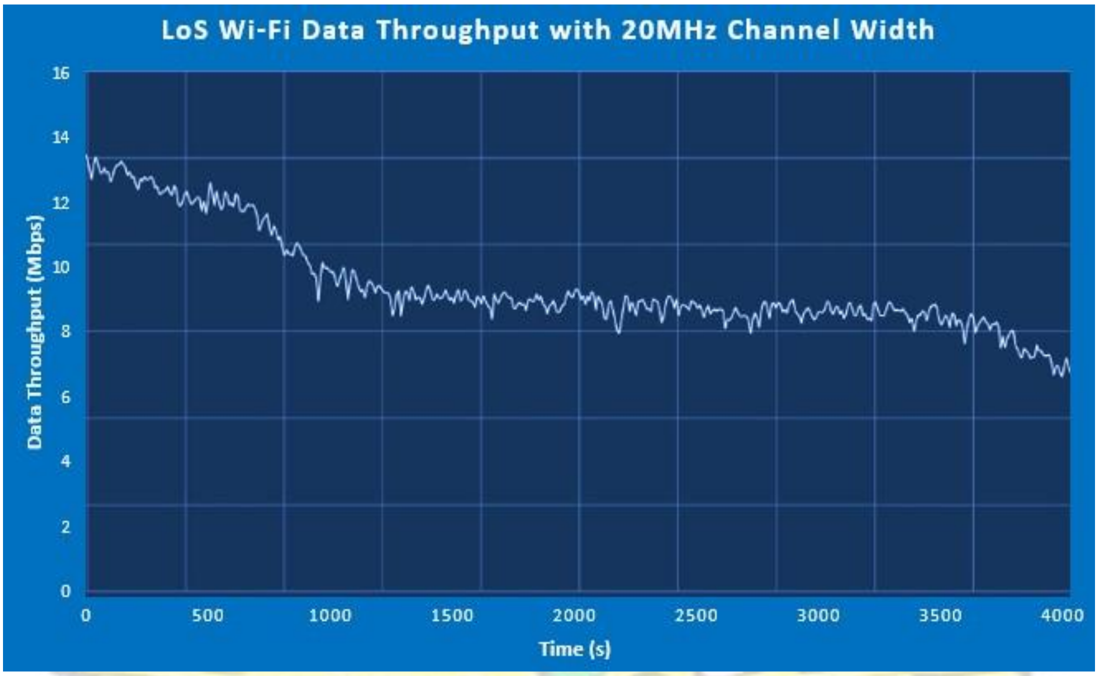

Figure 4. 5: LoS Wi-Fi Data Throughput

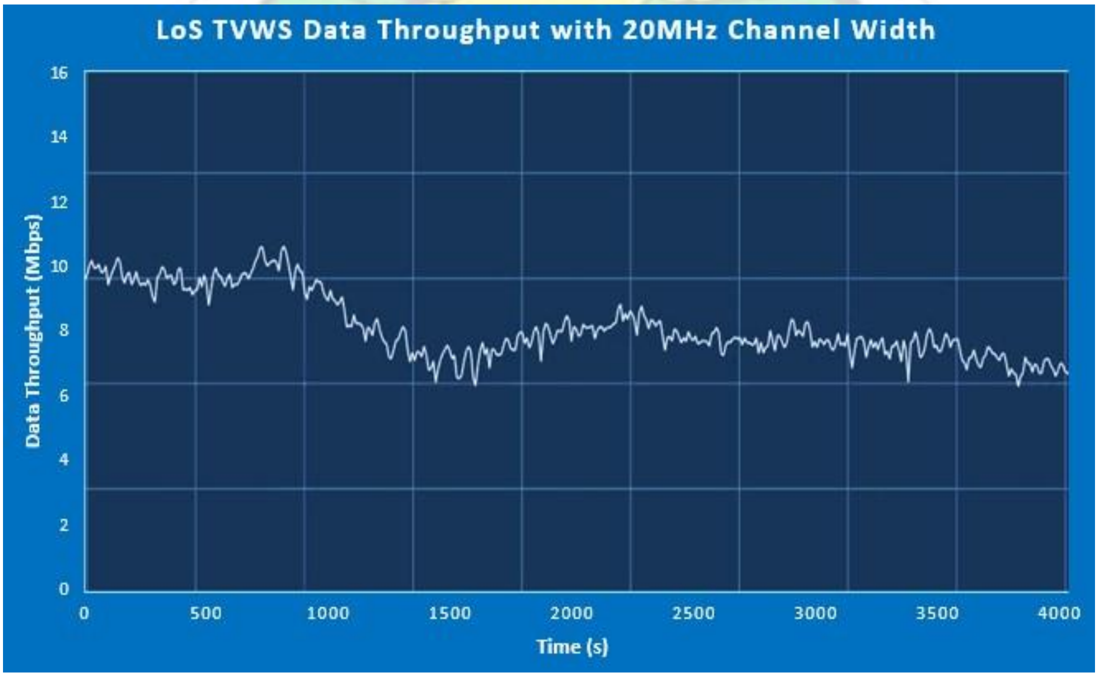

Figure 4. 6: LoS TVWS Data Throughput

In the NLoS mode the situation was slightly different. A higher throughput was recorded for the TVWS network compared to Wi-Fi as shown in Figures 4.7 and 4.8. The TVWS obtained a maximum throughput of 9.0 Mbps, a minimum of 5.1 Mbps, and an average of 5.8 Mbps while Wi-Fi recorded 8.9 Mbps, 3.8 Mbps and 4.2 Mbps as maximum, minimum and average respectively. These results prove that TVWS can perform better in the NLoS mode and the possible explanation for this result could be due to its high penetrative ability and resistance to environmental interference as compared to Wi-Fi.

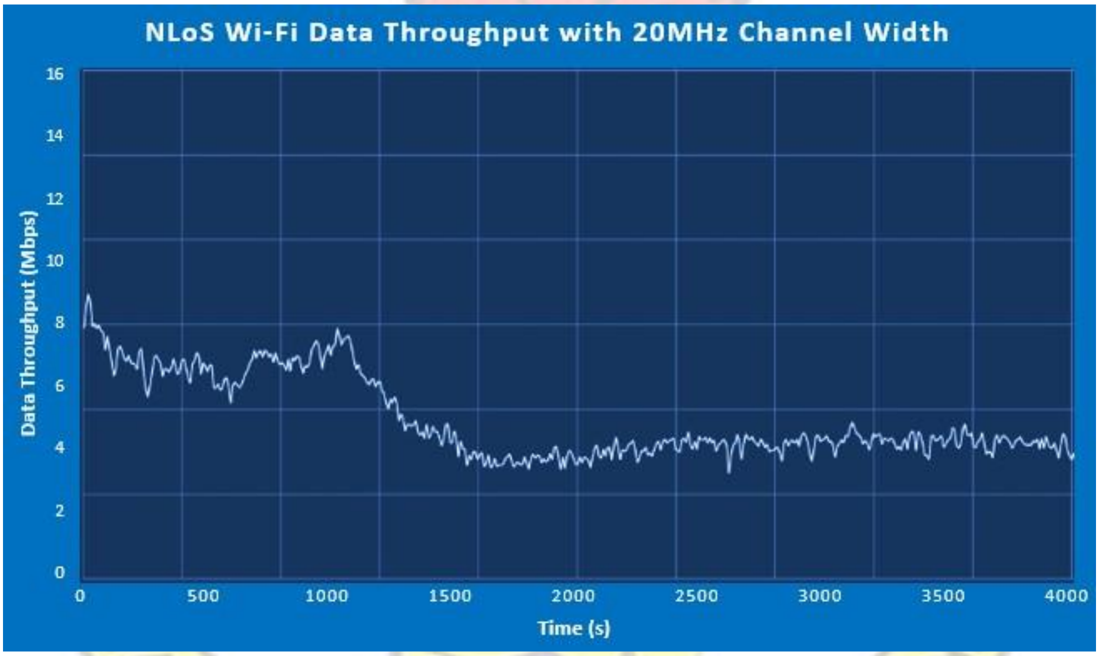

Figure 4. 7: NLoS Wi-Fi Data Throughput

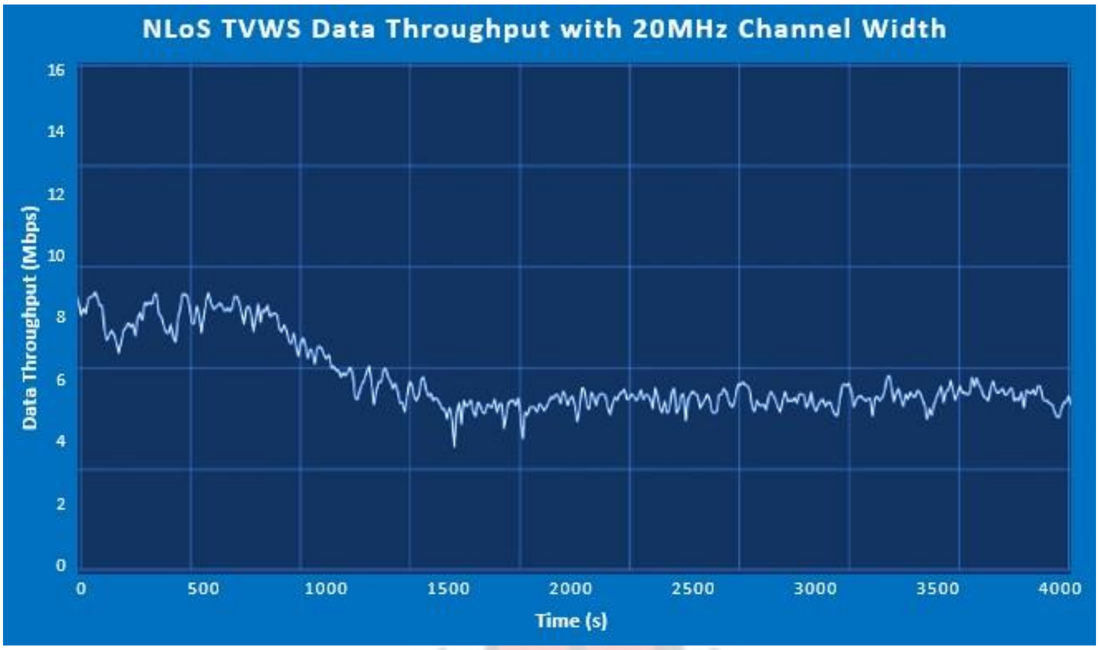

Figure 4. 8: NLoS TVWS Data Throughput

4.8 Network Latency

The latency of a network contributes to network speed and also helps to determine the time taken by data packet to travel to and from the destination and back to the source. The latency helps to determine delays typically experienced in the processing of network data (*the round-trip-time or RTT of the network*). Thus, the lower the latency of a network, the smaller the delay times while a higher network latency means network is likely to suffer from long delays in data transmission. Latency test is also used to measure the packets of data lost during data transmission. Data loss may cause break-up in voice communication, skipped video, extensive buffering and lag time which must not be tolerated in a communication network.

4.8.1 LoS Network Latency

Network latency test usually measures the time it takes for a network to transfer data packet from source to its destination and back, which is the round-trip time. The latency of both Wi-Fi and TVWS network at LoS distance of 2Km was tested by sending a ping request to the Server. Results from Figure 4.9 show that the Wi-Fi network recorded a minimum network latency of 1ms, an average of 2ms and maximum of 4ms. Four packets of data were sent and received within an average time of 2ms with 0% data lost which gives an excellent latency. For LoS TVWS network, a minimum time of 2ms, maximum of 10ms and an average time of 4ms were recorded as the latency. Also, four packets of data were sent and received within an average time of 4ms with 0% data lost also giving a very good latency as shown in Figure 4.10. This also gives an excellent network latency, but it could be seen that the LoS Wi-Fi network recorded a lower network latency than that of LoS TVWS network. This means network traffic congestion is lower in the LoS Wi-Fi network. Suggests that Wi-Fi performs better in LoS than TVWS.

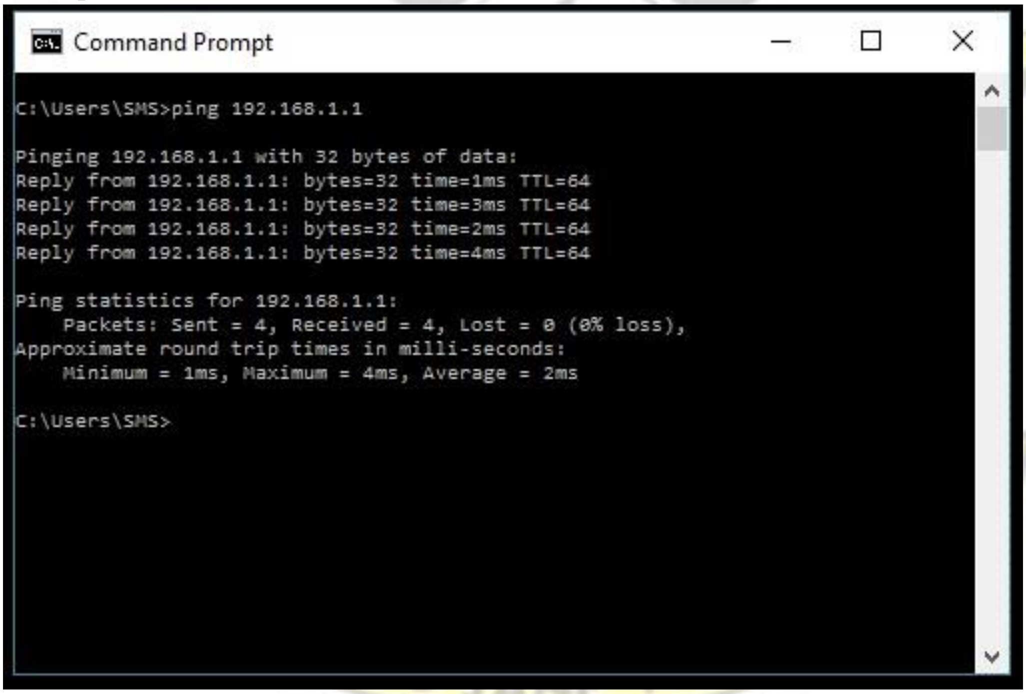

Figure 4. 9: LoS Wi-Fi network Latency measurement

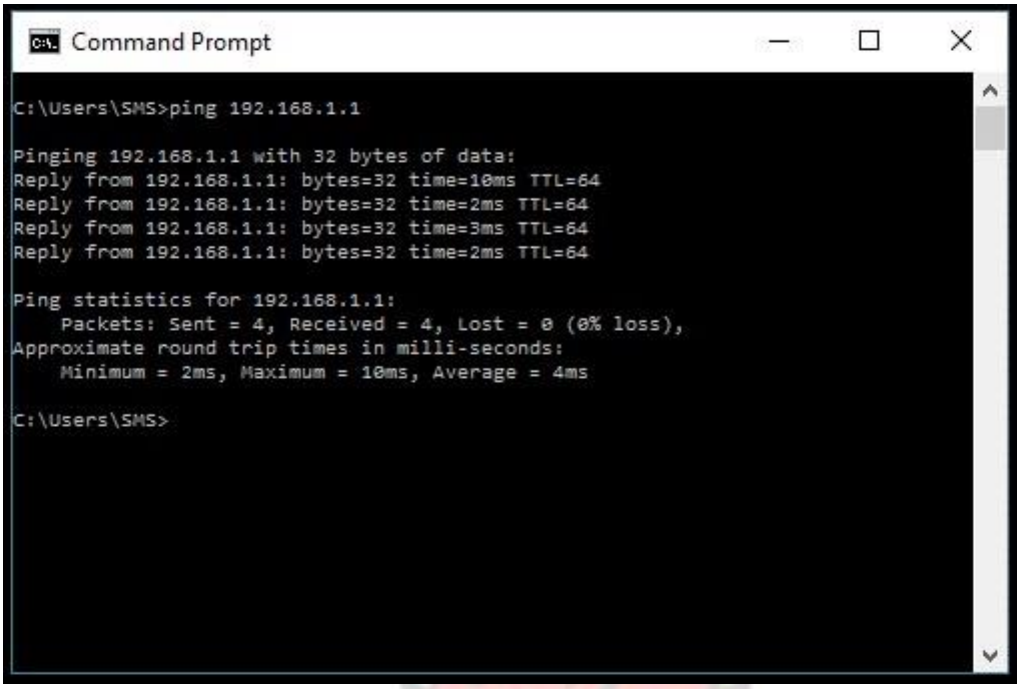

Figure 4.10: LoS TVWS network Latency measurement

4.8.2 NLoS Network Latency

It could be observed from Figures 4.11 and 4.12 that the network latency increased for both Wi-Fi and TVWS networks. It would be observed from Figure 4.11 that latency increase in NLoS Wi-Fi network was greater as compared to that of TVWS. A minimum latency of 4ms, maximum of 68ms and average time of 18ms were recorded with four packets of data sent and received within an average time of 18ms and 0% data lost. Still showing a very good latency hence very good network performance. But this latency is far bigger compared to that recorded in the LoS mode. In the NLoS TVWS, results from Figure 4.12 indicate a minimum latency of 4ms, maximum of 34ms and an average of 10ms with 0% data lost. This suggests that in the NLoS network, TVWS performed better than Wi-Fi. This might be accounted for, because the Wi-Fi network operates at SHF thus making it more prone to signal interference and less penetrative through foliage, mountains and high rise structures.

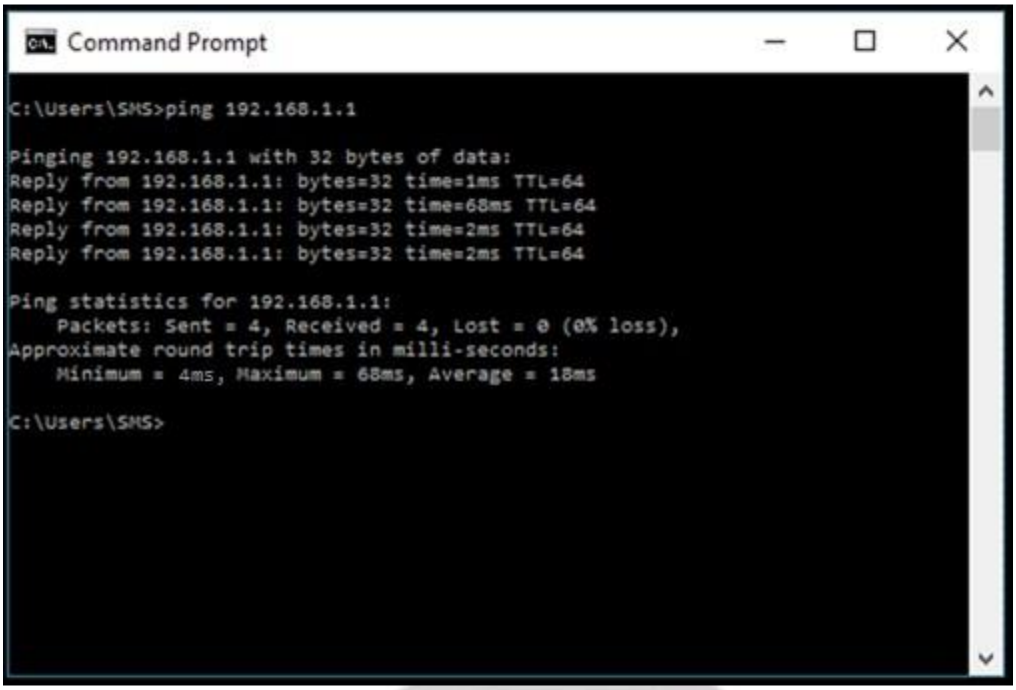

Figure 4. 11: NLoS Wi-Fi Network Latency measurement

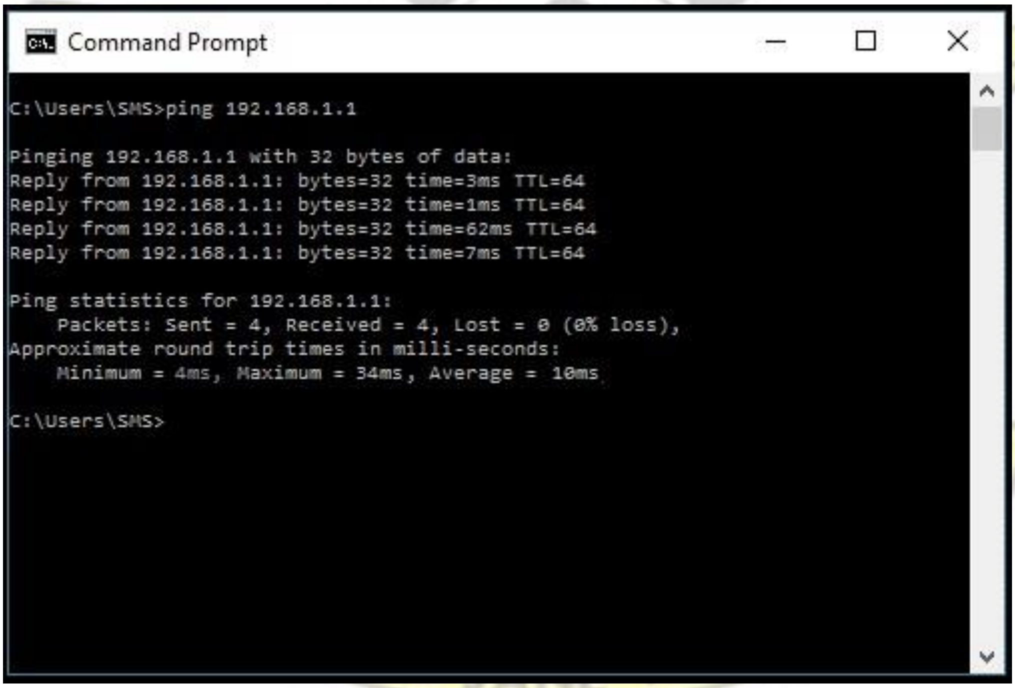

Figure 4.12: NLoS TVWS Network Latency measurement

4.9 Performance of Hybrid Method for TVWS Access

By FCC regulations, TVWS network operation is only permitted on the condition that, there would not be any harmful interference to incumbent spectrum users. It is for this reason why the hybrid method for accessing TVWS has been proposed in this work to help minimize WSD interference level to primary TV channels. Signal interference measurements were done to determine the level of interference by TV transmitters to WSDs in case the master WSD loses connection with the online GDB because Internet connection is down (*which is mostly likely to happen because of poor Internet connectivity in the locations under study*). Figure 4.13 shows the level of average signal interference to WSD is about -102dBm when internet connection between Master WSD and GDB is down. It could be seen from the graph that signal interference levels could be very harmful causing a reduction in signal strength and quality when internet connection breaks down.

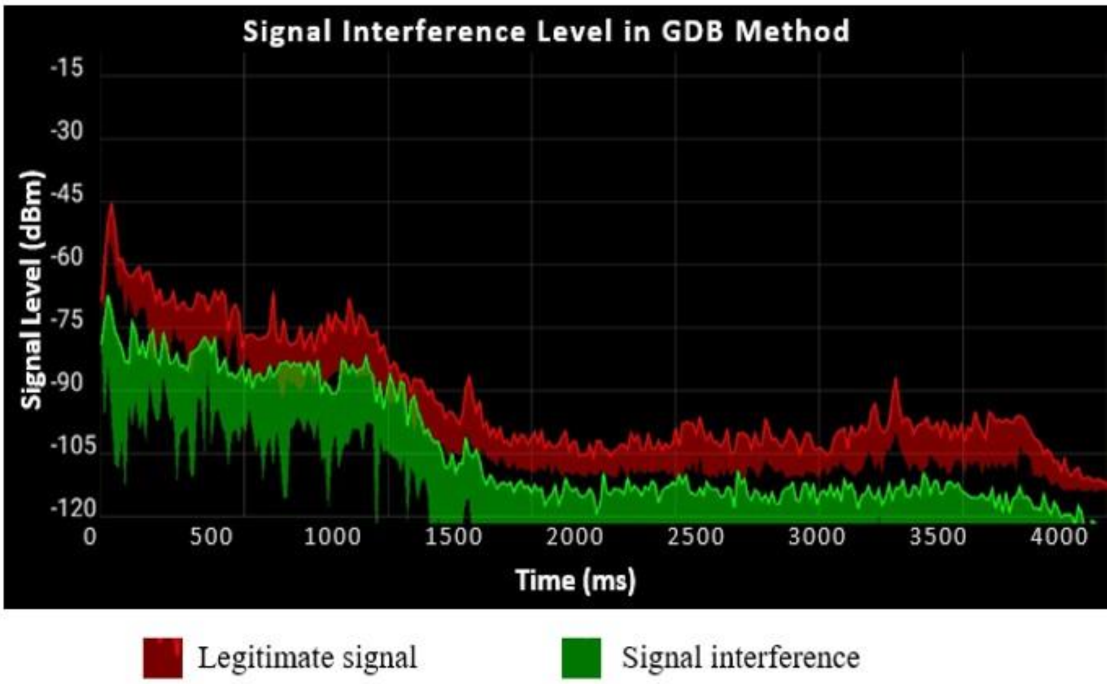

Figure 4. 13: Signal interference level when WSD loses connection with GDB

To mitigate this weakness the proposed hybrid method introduces two elements: Localised Geolocation Database and a dedicated spectrum sensing device that would help minimize interference in case WSD loses Internet connection. These elements act as intermediary between the master WSD and the online GDB. During operation the dedicated spectrum sensing device does a real-time scan of the spectra eco-system of the graphical area it is operating in and inform the master WSD through the LGD which channel to switch to when it senses any harmful interference from TV transmitters. This is done by updating the LGD with changes in spectrum utilisation in that particular geographic location. In this case the master WSD changes the frequency at which the network is operating. This enables signal strength and quality of the TVWS network to be preserved. Signal interference test conducted in the hybrid method reveal that harmful interference from TV transmitter could be minimized if not totally avoided. It could be seen from the graph in Figure 4.14 that though the average signal interference went up to about -90 dBm its' impact on signal strength and quality was near to zero. This may have been possible because of the quick swap in frequency of operation by the WSD network.

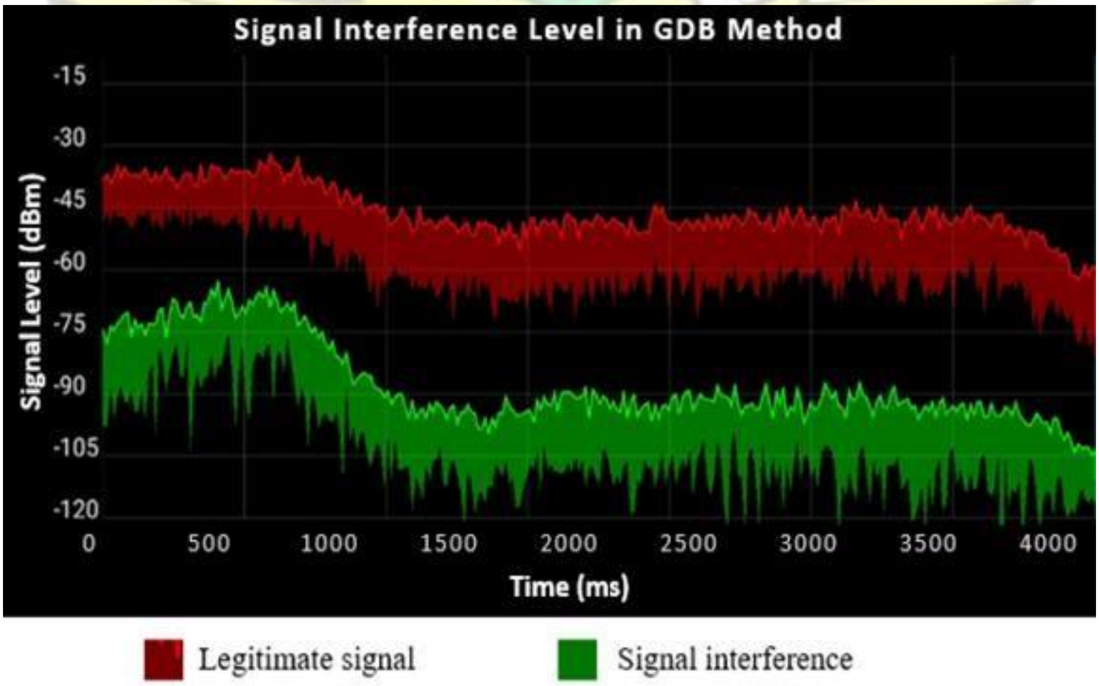

Figure 4. 14: Signal interference level in proposed Hybrid method

CHAPTER FIVE

SUMMARY, CONCLUSION, AND RECOMMENDATION

5.0 Conclusion

Despite the fact that the existing technologies that utilizes unlicensed spectrum bands have gone from strength to strength, a new opportunity for unlicensed spectrum use has emerged in the form of TV White Spaces spectrum (Zennaro et al., 2012). It is in this light that this thesis has investigated the existence of TVWS spectrum in the Central region of Ghana. In this work, TVWS spectrum measurement has been done in sixteen different locations in the Central Region of Ghana. The quantitative analysis of the available TV white space in the 57.5 – 226.5MHz VHF and 474 - 858MHz UHF TV band revealed that, unlike some rural communities studied in the developed world, a major portion of TV band spectrum in rural parts of Ghana is unutilized. Even when conservative parameters have been used the results show that, about 88.17% of the TV band spectrum are unused. This result is in line with literature, in that it unveils a significant amount of wireless access capacity which can be unleashed via the exploitation of TV White Spaces.

A user-friendly Television White Space (TVWS) localised geolocation database (LGDB) has been successfully developed. Network performance test for Wi-Fi and TVWS networks revealed that, Wi-Fi outperformed TVWS where a clear line-of-sight is available and with interference level being low. While TVWS performed better in NLoS network scenario and in an environment where interference levels are slightly high. Though geographical terrain conditions, temperature and humidity of the propagation environment had some effect on signal propagation for both Wi-Fi and TVWS networks, this effect was slightly high on Wi-Fi compared to TVWS. Higher network throughput was obtained from the NLoS TVWS compared to the Wi-Fi network.

The trial of the "Hybrid Method for TVWS Access" through the field work, has demonstrated that WSD can successfully coexist with the incumbent TV transmitters with minimal or no interference. This method ensured the deployment of TVWS with potentially higher transmission power without causing any harmful interference to incumbent users. Finally, this study has demonstrated spectrum efficiency by utilising licensed but unused and also unlicensed spectrum band for a high-speed communications network for the provision of Internet services in some surrounding villages of Cape Coast in the Central Region of Ghana.

5.1 Recommendations

From the results obtained in this thesis, it could be seen that TVWS networks can be deployed especially in rural and remote areas if there is enough information about unoccupied portions of the spectrum. This is because of the availability of large amounts of TV spectrum in these areas. TVWS is well suited for long distance and cost-effective NLoS network solutions. (Holland, et al., 2015). Real-time spectrum monitoring as seen in the proposed hybrid method for the protection of primary spectrum user and WSD, can help white space applications to optimize the selection and use of channels indicated as available by a geolocation database. NCA should expeditiously develop and implement its proposed regulatory framework. This will enable consumers to benefit from new TVWS applications whilst ensuring that coexistence with incumbent services is adequately catered for. Prompt and coordinated actions are therefore necessary from the side of standardization bodies and especially, national spectrum regulators in order to establish a sound technical and legal framework for such exploitation. Finally, instead of being threatened that spectrum allocated to them would be invaded, TV broadcasters should see the emergence of TV white space as a new era of technology for novel and unprecedented business opportunities.

5.2 Challenges

Due to time and financial constraints, this research work was conducted in only the central region of Ghana and was limited to Cape Coast and its surrounding villages. The researcher was again faced with challenges in getting data from TV spectrum users and the NCA.

5.3 Future Work

As part of our future work, we would like to use the hand-held RF Spectrum Analysers to investigate how cooperative spectrum sensing could be utilised as a protection framework for TV white space network implementation and also extend the measurements and analysis of available TVWS to the other regions of Ghana.

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APPENDICES

Table 6.0: Summary of TV Broadcasting Stations in Ghana

	Parameters		Area				
Type of TV Service	**Authorised Stations**	**Stations on Air**	**CCTH**	**Kwawprow**	**Akotokyir**	**Duakor**	**Amamoma**
Analogue Terrestrial TV	21	15	8	6	6	5	5
Digital Terrestrial Pay TV (Service only)	1	1	1	0	0	0	0
Satellite TV Broadcasting (PTVDTHB)	5	4	4	4	4	4	4
Digital Terrestrial FTATVPC (Nationwide Coverage)	23	4	3	3	3	3	3
Digital Terrestrial FTATVPC (Regional Coverage)	4	0	0	0	0	0	0
Satellite TV Broadcasting (PTV DTHB)	7	4	4	4	4	4	4
Satellite TV Broadcasting (FTADTHB)	8	2	2	2	2	2	2
Satellite TV Broadcasting (FTADTHSC)	47	20	17	16	17	15	16
Digital Cable TV	1	1	0	0	0	0	0
Total TV Stations	**117**	**51**	**39**	**35**	**36**	**33**	**34**

	Parameters		Area				
Type of TV Service	**Authorised Stations**	**Stations on Air**	**Nkanfoa**	**Biriwa**	**Moree**	**Ankaful**	**Kormantse**
Analogue Terrestrial TV	21	15	7	6	6	5	6
Digital Terrestrial Pay TV (Service only)	1	1	0	0	0	0	0
Satellite TV Broadcasting (PTVDTHB)	5	4	4	4	4	4	4
Digital Terrestrial FTATVPC (Nationwide Coverage)	23	4	3	2	3	2	2
Digital Terrestrial FTATVPC (Regional Coverage)	4	0	0	0	0	0	0
Satellite TV Broadcasting (PTV DTHB)	7	4	4	4	4	4	4
Satellite TV Broadcasting (FTADTHB)	8	2	2	2	2	2	2
Satellite TV Broadcasting (FTADTHSC)	47	20	17	16	15	14	13
Digital Cable TV	1	1	0	0	0	0	0
Total TV Stations	**117**	**51**	**37**	**34**	**34**	**31**	**31**

	Parameters		Area					
Type of TV Service	**Authorised Stations**	**Stations on Air**	**Amosima**	**Ekon**	**Yomransa**	**Egya**	**Asebu**	**Jukwa**
Analogue Terrestrial TV	21	15	5	4	6	6	4	4
Digital Terrestrial Pay TV (Service only)	1	1	0	0	0	0	0	0
Satellite TV Broadcasting (PTVDTHB)	5	4	4	4	4	4	4	4
Digital Terrestrial FTATVPC (Nationwide Coverage)	23	4	2	2	3	2	1	2
Digital Terrestrial FTATVPC (Regional Coverage)	4	0	0	0	0	0	0	0
Satellite TV Broadcasting (PTV DTHB)	7	4	4	3	4	3	2	2
Satellite TV Broadcasting (FTADTHB)	8	2	2	2	2	2	2	2
Satellite TV Broadcasting (FTADTHSC)	47	20	15	13	16	15	12	11
Digital Cable TV	1	1	0	0	0	0	0	0
Total TV Stations	**117**	**51**	**32**	**31**	**35**	**32**	**25**	**25**