THE UNIVERSITY OF HULL

The relationship between choice of spectrum sensing device and secondary-user intrusion in database-driven cognitive radio systems

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By

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Abstract

As radios in future wireless systems become more flexible and reconfigurable whilst available radio spectrum becomes scarce, the possibility of using TV White Space devices (WSD) as secondary users in the TV Broadcast Bands (without causing harmful interference to licensed incumbents) becomes ever more attractive. Cognitive Radio encompasses a number of technologies which enable adaptive self-programming of systems at different levels to provide more effective use of the increasingly congested radio spectrum. Cognitive Radio has the potential to use spectrum allocated to TV services, which is not actually being used by these services, without causing disruptive interference to licensed users by using channel selection aided by use of appropriate propagation modelling in TV White Spaces.

The main purpose of this thesis is to explore the potential of the Cognitive Radio concept to provide additional bandwidth and improved efficiency to help accelerate the development and acceptance of Cognitive Radio technology. Specifically, firstly: three main classes of spectrum sensing techniques (Energy Detection, Matched Filtering and Cyclostationary Feature Detection) have compare in terms of time and spectrum resources consumed, required prior knowledge and complexity, ranking the three classes according to accuracy and performance. Secondly, investigate spectrum occupancy of the UHF TV band in the frequency range from 470 to 862 MHz by undertaking spectrum occupancy measurements in different locations around the Hull area in the UK, using two different receiver devices; a low cost Software-Defined Radio device and a laboratory-quality spectrum analyser. Thirdly, investigate the best propagation model among three

propagation models (Extended-Hata, Davidson-Hata and Egli) for use in the TV band, whilst also finding the optimum terrain data resolution to use (1000, 100 or 30 m). it compares modelled results with the previously-mentioned practical measurements and then describe how such models can be integrated into a database-driven tool for Cognitive Radio channel selection within the TV White Space environment. Fourthly, create a flexible simulation system for creating a TV White Space database by using different propagation models. Finally, design a flexible system which uses a combination of Geolocation Database and Spectrum Sensing in the TV band, comparing the performance of two spectrum analysers (Agilent E4407B and Agilent EXA N9010A) with that of a low cost Software-Defined Radio in the real radio environment. The results shows that white space devices can be designed using SDRs based on the Realtek RTL2832U chip (RTL-SDR), combined with a geolocation database for identifying the primary user in the specific location in a cost-effective manner. Furthermore it is shown that improving the sensitivity of RTL-SDR will affect the accuracy and performance of the WSD.

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Dedication

I would like to dedicate this work
To my parents, lovely family wife and daughters

Also
To LIBYA as a country of unlimited support
Even in Difficult Time

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Abbreviations

CAN	Airborne Communication Node
ADC	Analogue to Digital Converter
AFH	Adaptive Frequency Hopping
AGC	Automatic Gain Control
AWGN	Additive White Gaussian Noise
CAN	Airborne Communication Node
CEPT	European Conference of Postal and Telecommunications Administration
CFD	Cyclostationary Feature Detection
CR	Cognitive Radio
DANL	Display Average Noise Level
DARPA	Defence Advanced Research Projects Agency
DC	Duty Cycle
DPC	Dirty Paper Coding
DMA	Defence Mapping Agency
DSA	Dynamic Spectrum Access
DSP	Digital Signal Processing
DTED	Digital Terrain Elevation Data
DVB	Digital Video Broadcasting
DVB-T	Digital Video Broadcasting Terrestrial
ECC	Electronic Communications Committee
ED	Energy Detection
FB	Filter bank
FCC	Federal Communications Commission
FFT	Fast Fourier Transform
FM	Frequency Modulation
GDMS	Geolocation Database Management System
GENI	Global Environment for Networking Innovations
GPIB	General Purpose Interface Bus
GPS	Global Positioning System

GSM	Global System for Mobile Communications
GTD	Geometric Theory of Diffraction
GUI	Graphical User Interface
IEEE	Institute of Electrical and Electronics Engineers
IMT	Intelligent Multimode Terminals
ITU	International Telecommunication Union
ITU-R	International Telecommunication Union – Radiocommunication
LOS	Line Of Sight
MFD	Matched Filter Detection
MTSE	Multi Taper Spectral Estimation
NGA	National Geospatial-Intelligence Agency
NIMA	National Imagery and Mapping Agency
NLOS	Non Line Of Sight
Ofcom	Office of Communications, Regulation Authority in United Kingdom
OSA	Opportunistic Spectrum Access
PD	Probability of Detection
Pf	Probability of False Alarm
PMD	Probability of Missed Detection
PSD	Power Spectrum Density
PU	Primary User
RBW	Resolution Bandwidth
RF	Radio Frequency
RMSE	Root Mean Square Error
RTL-SDR	Realtek-based Software Defined Radio
SDR	Software Defined Radio
SINR	Signal to Interference-plus-Noise Ratio
SNR	Signal to Noise Ratio
SRTM	Shuttle Radar Topography Mission
SU	Secondary User
TV	Television
TVWS-DB	TV White Space Database
TVWS	TV White Space
UHF	Ultra High Frequency
UK	United Kingdom
UMTS	Universal Mobile Telecommunications Services

USA	United States of America
USGS	United States Geological Survey
USRP	Universal Software Radio Peripheral
UWB	Ultra-Wide Band
VHF	Very High Frequency
Wifi	Wireless Fidelity
Wimax	Worldwide Interoperability for Microwave Access
WRAN	Wireless Regional Area Network
WRC	World Radio-communication Conference
WSD	White Space Device
WSDB	White Space Database

Chapter1: Introduction

1.1 Overview

Today, wireless communications systems are ever more constrained by availability of spectrum, due to an increasing demand for higher data transmission rates and channel capacity, while the wireless networks are regulated by government policy. Historically, the spectrum bands have been assigned to licence holders for the long term and over large geographic areas, which has led to spectrum scarcity for potential new spectrum users. Such issues can be addressed in wireless networks by using Cognitive Radio (CR) technology, even if all spectrum bands are allocated for licensed users. According to some measurements of Television (TV) band channel occupancy that have been conducted recently, the results show that many licensed services are transmitting sporadically, that giving approximately 35% spectrum occupancy. It can be argued that this represents inefficient use of the frequency resources, which has given a strong impetus to researchers in the field of CR technology to suggest a solution to this issue. This depends basically on use of the spectrum at a given time and in a particular place, with the ability to switch from one area of the spectrum to another to perform opportunistic communication and also being able to adapt smartly to the primary user as presence or absence in a precise frequency at a specific time and location.

This goal has generated interest in CR, which according to the report of Federal Communications Commission (FCC), "is a radio that can change its transmitter parameters based on interaction with the environment in which it operates. This interaction may involve active negotiation or communications with other spectrum users and/or passive sensing and decision making within the radio. The majority of cognitive radios will probably be Software Defined Radio (SDR), but neither having software nor being field reprogrammable are requirements of a cognitive radio”. The FCC report has shown that according to most measurement studies, it is clear that the vast majority of licensed spectrum is unutilized across many time and frequency slots. The main idea of cognitive radio technology is to reuse or share the spectrum, which is licensed to the Primary User (PU) and then allow Secondary Users (SU) to exploit and communicate over unused spectrum at a particular time and in a specific location. It is also seeking to maintain efficiency and reliability in spectrum use. Cognitive radio is considered an intelligent wireless communication system which can be aware of and learn from the environment and then adopt new states to deal with incoming Radio Frequency (RF) stimuli, making corresponding changes in operating parameters including transmit-power, carrier frequency, and modulation strategy (Ghasemi & Sousa, 2005; Bodepudi Mounika, Kolli Ravi Chandra, Rayala Ravi Kumar, 2013).

The main aims of most CR studies are focused on protecting PUs from spectrum interference, by using appropriate spectrum sensing techniques before SU transmission. But there are still many technical challenges. These relate to understanding the current behaviour of the spectrum, the accuracy and reliability of the sensing in order to give real opportunity to the SU, sharing the current spectrum of interferences, and effectively coordinating SUs for the licensed and unused spectrum. Therefore, there are many technical problems that need to be resolved before CR is implemented. More precisely, this thesis focusses on a variety of problems involved in characterising and experimentally evaluating detection methods by comparing the three main classes of spectrum sensing techniques on different criteria, offering a new development of realtek-based software defined radio (RTL-SDR) suitable for conducting measurement for whole band 320 MHz instead of just 3.2 MHz by creating a specific algorithm and evaluation of the inexpensive RTL-SDR and demonstration of its effectiveness for detection of the percentage of spectrum utilisation compared with results from the conventional high cost Agilent spectrum analyser. Combined geolocation database and sensing techniques in a real environment by using different spectrum devices for evaluation of the sensing time and to increase the accuracy of the sensing methods. For promotion of the understanding of the current spectrum usage of the different wireless services, many empirical measurements have been conducted in the context of cognitive radio worldwide (Chiang et al., 2007; Wellens et al., 2007). However, the results of these measurement campaigns showed no exploitation of the spectrum licensed temporally and spatially.

As radios in future wireless systems become more flexible and reconfigurable and available radio spectrum becomes scarce, there is the possibility of using TV white space devices (WSDs) as secondary users in the TV Broadcast Bands without causing harmful interference to licensed incumbents, and to contribute to avoid spectrum sensing problems such as shadowing or fading between the users, which might occur in CR when using a sensing method only. The important requirements for spectrum sensing are fast, robust and reliable signal detection in a low signal-to-noise ratio (SNR) environment. Currently, one candidate method could be to utilise a geolocation database approach. The white space device should be able to determine available channel opportunities for a given location by accessing a database of TV White Space (TVWS) channels including data on each transmitter and each site, variable channels, transmitter power, and time of validation (Gurney et al., 2008). Therefore, the TV channel can be protected from harmful interference by accurate prediction of TVWS using an appropriate propagation model. Design of any wireless network depends on accurate prediction of radio propagation, which impacts deployment and management strategies.

The main purpose of this thesis can be summarised as follows: firstly, to improve spectral utilization by allowing users from crowded bands to bleed off into nearby empty bands and identify how the transition can be made from conventional radio to CR by design of a TVWS Database using Terrain Maps and Validated Propagation Models; secondly, using a simulation system to investigate the best among several spectrum sensing techniques, specifically Energy Detection (ED), Matched Filter Detection (MFD) and Cyclostationary Feature Detection (CFD). Other purposes of the thesis are to conduct measurements in many locations by using different spectrum devices to understand the current spectrum usage in the context of cognitive radio and also to study the efficiency and accuracy versus cost in both spectrum analysers.

1.2 Motivation and Objectives

In the present day, the use of the TV band by CR systems on a SU basis has become a realistic option and has attracted much attention due to the potential to exploit underutilized TVWS for other communications, based on time and location. The main motivation for focusing on spectrum availability in the current worldwide digital transition of the TV broadcasting band is that some studies have shown the existence of significant vacant spectrum (white space)(Pietrosemoli & Zennaro, 2013; Dzulkifli et al., 2011a). The term white space originally referred to the underutilized frequency in the Very-High Frequency (VHF) and Ultra-High Frequency (UHF) bands that are traditionally allocated to terrestrial TV broadcast services, which is deliberately left blank among analogue TV channels to avoid interference between them. In most areas of the world, the white space is in the range of 470-790 MHz and varies widely in extent and frequency from area to area and also from one country to another. In most countries, when the transition from analogue to digital TV broadcasting commenced, the term white space became more reflective of the nature of the TV spectrum. This resulted in wide ranges of the bands being unused in most countries. The main advantages of unused TVWS include the superior propagation properties of the VHF and UHF bands resulting in a modest transmitter power requirement for secondary devices. Also, when compared to higher frequencies, for instance the 2.5 GHz used for WiMax, TVWS signals can travel longer distances without additional infrastructure, particularly over rough terrain.

In addition, the superior propagation properties at VHF and UHF result in good indoor and outdoor reception and do not require line-of-sight. These advantages can make TVWS technologies a good candidate for addressing broadband wireless information services with the possibility to provide a service in rural areas with minimum infrastructure investments. In theory, by depending on spectrum sensing, CR has the capability to detect PU activity without interference. On the other hand, in practice, much work is still required to test the CR's capability with more accuracy. For that reason, regulatory authorities around the world (such as the office of communications (Ofcom) in the United Kingdom, the FCC in the USA and the Electronic Communications Committee (ECC) in Europe) are not yet allowing secondary use of the spectrum based on CR technology alone. As a result, they have started to advocate a TVWS geolocation database approach for more accurate spectrum use identification and to prevent harmful interference to PUs.

The research objectives of this PhD thesis address three main aspects:

1- The main goal of the practical research work is to conduct spectrum occupancy measurements in the Humber region, UK in different locations and to compare them with results derived using various propagation models by using a digital terrain database in different resolutions for creating a TVWS database in the mentioned region;
2- The goal of the second aspect of the research is to evaluate the performance of the low cost device RTL-SDR compared with high cost spectrum Analyser by conducting the spectrum occupancy measurements in different locations and then

provide evidence of the utility and effectiveness of using the inexpensive RTL-SDR;

3- In this part, investigate the potential for implementation of inexpensive RTL-SDR solutions and their ability for sensing geolocation database channels in a real environment, as compared with high cost spectrum analysers, by creating a flexible system model for the implementation.

1.3 Thesis Outline

This thesis is divided into seven chapters, as illustrated in Figure 1.1. **Chapter 1** explains the main motivation and objectives behind this research. **Chapter 2** reviews the previous history and background of wireless communication technologies that led to the development of CR. **Chapter 3** is the beginning of the central part of this thesis, which by using simulation techniques makes clear comparisons among spectrum sensing techniques, using six criteria: time and spectrum resource consumed, required prior knowledge, complexity, accuracy and performance and then gives the advantages and disadvantages of each, and suggests alternative solutions. In **chapter 4**, a spectrum measurement system scheme has proposed, which has the ability to investigate the spectrum occupancy of the UHF TV band in the frequency range from 470 to 790MHz using a low cost software defined radio (RTL-SDR) and compare the results with those derived using a Spectrum Analyser (SA, Agilent E4407B) which is considerably more expensive. **Chapter 5** applies comparison to investigate which propagation model has better performance, and could be selected for creating a TVWS geolocation database as a primary source of detecting TVWS in the developing world. Candidate models are compared with real measurements and assessment made of their accuracy in predicting signal attenuation versus propagation range in different types of terrain environment. In **Chapter 6,** propose a scheme for implementation of combined geolocation database and infrastructre sensing in the TV band to investigate the potential usefulness of an inexpensive RTL-SDR in sensing geolocation database channels, when compared with high cost spectrum analysers. **Chapter 7** provides a summary of the results and makes suggestions for appropriate further work.

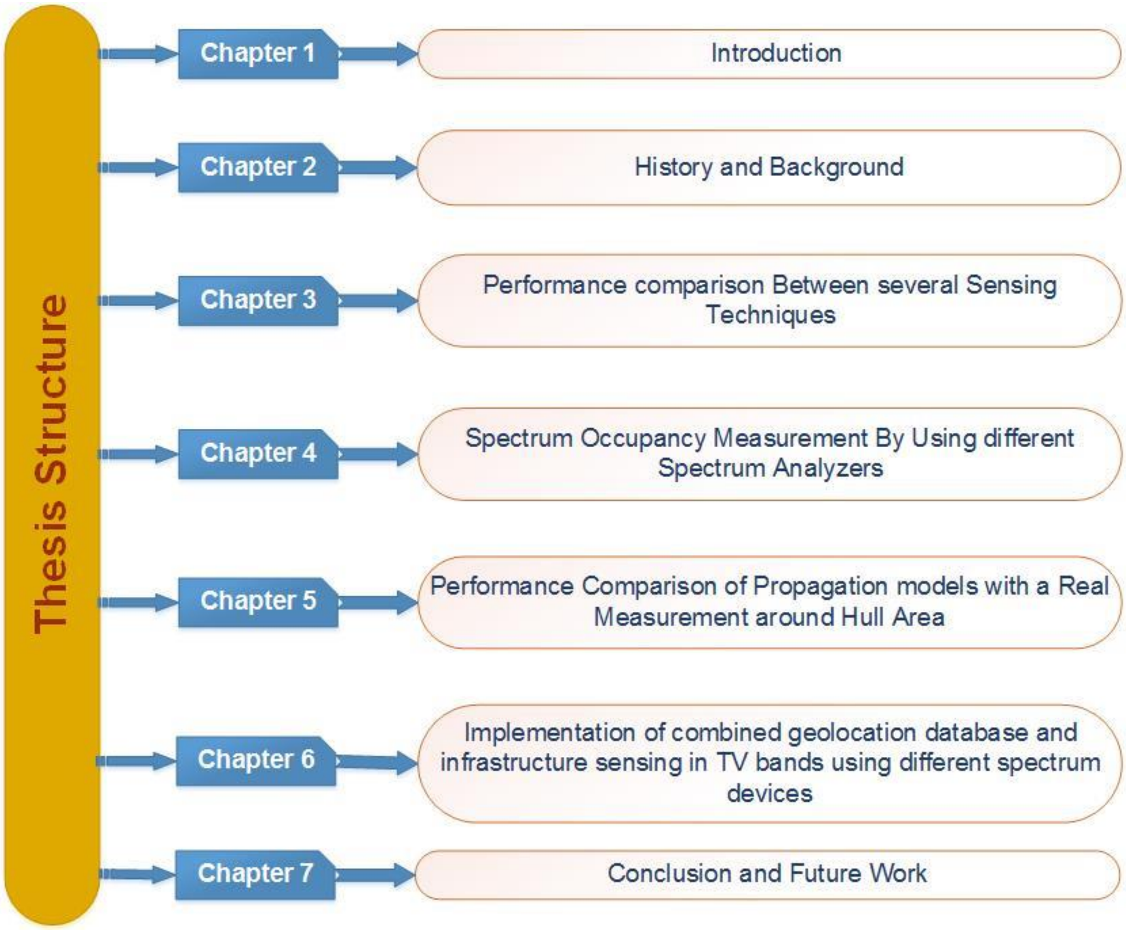

Figure 1-1: Thesis Structure

1.4 Thesis Contributions

The main thesis contributions can be summarised as follows:

- Investigate and compare three main classes of spectrum sensing techniques (ED, MFD and CFD) and analysis in terms of time and spectrum resource consumed, required prior knowledge and complexity. Ranking the three classes according to accuracy and performance.
- Improve spectral utilization by allowing users from crowded bands to bleed off into nearby empty bands by using TVWS databases.
- Design new technique for undertaking full TV band measurement by using RTL-SDR instead of using 3.2 MHz resolution.
- Introduce and compare spectrum occupancy of the UHF TV band in the frequency range from 470 to 790 MHz by using two different devices, the low cost device RTL-SDR and high cost spectrum analyser. The spectrum occupancy measurements provide evidence of the utility of using the inexpensive RTL-SDR and illustrate its effectiveness for detection of the percentage of spectrum utilisation compared with results from the conventional high cost Agilent spectrum analyser.
- Investigate the best empirical propagation model for predicting TVWS by examining the performance of three propagation models (Extended-Hata, Davidson-Hata and Egli) in the TV band 470 to 790MHz and compare with a comprehensive set of propagation measurements taken in randomly-selected locations around Hull, UK.
- Design of Cognitive Radio Database using Terrain Maps and Validated Propagation Models, and then describe how such models can be integrated into a

database-driven tool for CR channel selection within the TVWS environment by creating a flexible simulation system for creating a TVWS database.

- Propose a flexible system model for implementation of combination of the geolocation database with infrastructure sensing in TV bands by using different spectrum devices and then investigate the use of inexpensive RTL-SDR and its ability for sensing geolocation database channels in the real environment, comparing with that of a high cost spectrum analyser.

1.5 Publications

The period of research has produced a number of papers in international journals and conferences. Firstly, it will be list the papers that are already published:

1.5.1 Journal Publications

[1] Fanan, A., Riley, N., Mehdawi, M., , Alfahad, O. (2017). Performance of a TV white space database with different terrain resolutions and propagation models, Telfor Journal, Vol. 9, No. 2, 2017.

[2] Mehdawi, M., Riley, N. G., Paulson, K., Fanan, A., & Ammar, M. 2013. Spectrum occupancy survey in Hull-UK for cognitive radio applications: measurement & analysis. International Journal of Scientific & Technology Research, 2(4), 231-236.

1.5.2 Conference Publications

[1] **Fanan, A.M**., Riley, N.G., Mehdawi, M., Ammar, M. and Zolfaghari, M., 2014, January. Survey: A Comparison of Spectrum Sensing Techniques in Cognitive Radio. Kuala Lumpur In *Int'l Conference Image Processing, Computers and Industrial Engineering (ICICIE'2014) Jan* (pp. 15-16).

[2] **Fanan, A**., Riley, N., Mehdawi, M., Ammar, M. and Zolfaghari, M. Comparison of spectrum occupancy measurements using software defined radio RTL-SDR with a conventional spectrum Analyser approach. In *Telecommunications Forum Telfor (TELFOR),* November *23rd, 2015* (pp. 200-203). IEEE.

[3] **Fanan, A.M**., Riley, N., Mehdawi, M. and Ammar, M. Comparison of propagation models with real measurement around Hull, UK. In *Telecommunications Forum (TELFOR),* November *24th*, 2016, (pp. 1-4). IEEE.

[4] **Fanan, A.M**., Riley, N., Mehdawi, M. and Alfahad, O. Implementation of combined geolocation database and infrastructure sensing in TV bands using different spectrum devices. *In 25th Telecommunications forum TELFOR (TELFOR), in Serbia, Belgrade, November 21-22, 2017 (pp. 1-4). IEEE.*

[5] Mehdawi, M., Riley, N. G., Ammar, M., **Fanan, A**., & Zolfaghari, M. (2013, November). Cooperative wideband spectrum sensing with multi-bit hard decision in cognitive radio. In *Telecommunications Forum (TELFOR), November 21st , 2013* (pp. 220-223). IEEE.

[6] Mehdawi, M., Riley, N. G., Ammar, M., **Fanan, A**., & Zolfaghari, M. (2014, November). Experimental detection using cyclostationary feature detectors for Cognitive Radios. In *Telecommunications Forum Telfor (TELFOR),* November *22nd ,2014* (pp. 272-275). IEEE.

[7] Ammar, M., Mehdawi, M., Riley, N. G., **Fanan, A**., Paulson, K., & Zolfaghari, M. "A Spectrum Sensing Test Bed based on Matlab and USRP2".(2013). *Int'l Conference Image Processing, Computers and Industrial Engineering (ICICIE'2014)* Jan. 15-16, 2014 Kuala Lumpur (Malaysia).

[8] Ammar, M., Riley, N. G., Mehdawi, M, **Fanan, A**., & Zolfaghari, M. Physical Layer Security in Cognitive Radio Networks. *International Conference on Artificial Intelligence, Energy and Manufacturing Engineering (ICAEME'2015*) Jan. 7-8, 2015 Dubai (UAE)

[9] Mehdawi, M., Riley, N.G., Ammar, M., **Fanan, A**. and Zolfaghari, M., 2015, November. Spectrum occupancy measurements and lessons learned in the context of cognitive radio. In *Telecommunications Forum Telfor (TELFOR), November 23rd, 2015* (pp. 196-199). IEEE.

[10] Ammar, M., Riley, N., Mehdawi, M., **Fanan, A**. and Zolfaghari, M., Detection threats and mitigation techniques in cognitive radio based on localization of signal source and trust worthiness. *Proceedings of 4th ICAESAM*, Dec, 2015 pp.77-83.

Chapter2: History and Background

2.1 Introduction

The focus of this chapter is on explaining some concepts that assist in finding suitable solutions to the radio spectrum scarcity problem. First, Dynamic Spectrum Access (DSA) models, which help in increasing the spectrum efficiency. Then consider the general definition, and motivation of CR and discuss the main radio functions of CR. Also, this chapter seeks to provide an understanding of SDR in terms of its background and history, definition, advantages and prototypes. This chapter then goes on to give a brief discussion of TVWS in terms of definition and extent of use including the unutilised portions of radio spectrum in VHF and UHF bands. In addition, the Chapter highlights the importance of using Geolocation database technology in TVWS and describes its impact in contributing to improved spectrum efficiency. Finally, based on recently studies that have been conducted by the International Telecommunication Union (ITU), the chapter clarifies the importance of spectrum management systems in regulating the radio spectrum as a national and international resource, and explains the main elements of such systems.

2.2 Dynamic Spectrum Access models

Dynamic spectrum access can be categorized under three main models, the dynamic exclusive use model, the open sharing model, and the hierarchical access model, as shown in Figure 2.1.

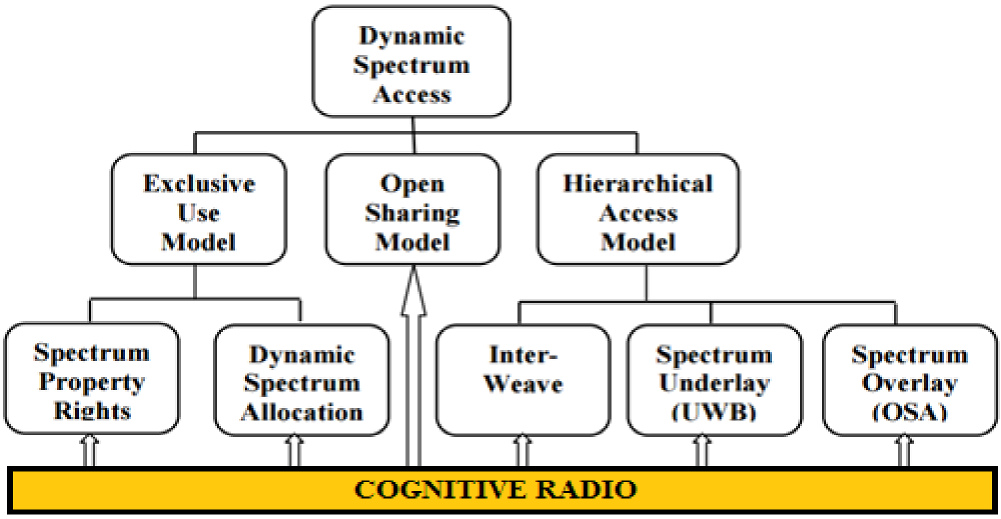

Figure 2-1: Dynamic Spectrum Access models

2.2.1 Dynamic Exclusive Use model

This model is used to preserve the basic structure of the current spectrum regulation policy; the government has licensed some parts of the spectrum to services for exclusive use. The primary concern is how to improve spectrum efficiency by flexibility of use. This model is classified into two approaches: dynamic spectrum allocation and spectrum property rights. The latter approach permits licensees to offer spectrum for sale and to select technology freely. Hence, the economy and business sectors will play a more significant part in driving towards the improved gainful utilisation of this restricted asset. Note that despite the fact that licensees can share the rights to a lease of the spectrum for more profit, the regulation policy does not mandate such sharing. The other approach, dynamic spectrum allocation, can improve spectrum efficiency by dynamically allocating spectrum to different services based on traffic statistics, whether on a temporal or spatial basis (Ghosh et al., 2014).

2.2.2 Open Sharing Model

According to spectrum commons described by (Lehr & Crowcroft, 2005), this model can be used for open sharing among users, who might use different services. Centralised spectrum sharing (Raman et al., 2005) or Distributed sharing, which is considered as the basis of managing the spectral area, has had enormous success in the wireless communication especialy when working within the license-exempt bands and advocates of this model derive their support for the model from this success (Zhao & Swami, 2007).

2.2.3 Hierarchical Access Model

The Hierarchical Access Model is divided into three DSA models as illustrated in Figure2.1: Interweave, Underlay and Overlay. The Interweave model can be described as a set of realistic criteria for DSA. The SU is not allowed to access a licensed spectrum band while a PU is still active anywhere in the same band, which is different from the Overlay and Underlay DSA models. Absolute priority should be given to the PU in a particular spectrum band such that when the SU is utilising the spectrum, it must leave whenever the PU starts to use the same spectrum.

Interweave

In the interweave paradigm also referred to as opportunistic spectrum access, the SUs is temporally constrained into using the spectrum band that is not used at a specific time and in a particular location. The main ideas underpinning this model relate to opportunistic communication and actual motivation of the CR. Many studies and measurements have been conducted by several universities (Mehdawi et al., 2013), which indicate that the majority of the spectrum, most of the time is underutilised.

In other words, there exist significant voids in space, time, and frequency, which are referred to as spectrum holes or white spaces. These holes are not in constant use in the spectrum bands, whether licensed or unlicensed. It might be that a single or subset of spatial holes is not occupied by the primary users. A SU could exploit spectral holes (defined relative to the PU signals) for operating in the orthogonal dimensions of time, space or frequency, by opportunistic use of the spectrum white space, thereby contributing to improved spectrum utilisation efficiency. The PU (licensed or unlicensed) should be detected in the interweave technique for one or more of the space-time-frequency dimensions. This detection can be challenging, especially when the activity of the PU changes over time or geographical location.

Spectrum Overlay or Opportunistic Spectrum Access (OSA)

Spectrum Overlay is a model which has contributed to improve DSA recently. The overlay can allow SUs to transmit on the same licensed spectrum band while the PU is still accessing that band. The transmission power of the secondary user can be limited, which leads to having a different constraint, instead of constraining the interference from the secondary to the primary user. The main target of the overlay DSA model is maintaining the PUs' performance; as long as PUs suffer no degradation then SUs are permitted to transmit simultaneously with PUs. Channel coding is considered the first method for the overlay DSA model (Goldsmith et al., 2009). Specifically, when a SU transmitter recognises a signal packet that has been transited by the PU transmitter, the spectrum controller can define two transmission power levels, one for transmitting the SU's own packet and another one for transmitting the PU's packet, which can contribute to enhancing the total power received at the PU receiver. At the primary receiver, the signal to interference and noise ratio (SINR) is not degraded. Interference to the SU receiver can be avoided by using a technique called dirty paper coding (DPC) or Costa precoding (Jindal & Goldsmith, 2004) for efficient transmission of digital data through a channel subjected to some interference known to the transmitter, which contrives to cancel the interference caused by the PU packet. Another approach is using network coding to model the overlay DSA (Xin et al., 2010). Within this method, the secondary user can serve as a dependable node among the nodes, whether it was disconnected or weakly connected. Through coding of the network, it can encode a package of SU in the PU package. The package transportation interface should not access separate spectrum, without impacting the PU performance.

In the channel coding approach, for transmitting a PU packet, the secondary user might split enough power, and the SINR will be increased at the PU receiver. Hence, the performance of the PU is improved effectively, while the network coding approach can increase the rate of data transmission, which offers the possibility of increasing the PU throughput.

Spectrum Underlay or Ultra-Wide Band (UWB)

In the Underlay DSA model, the secondary user is permited to transmit over the licensed spectrum band even if the PU still has access to the band. There are two methods that operate below the threshold related to the accumulated interference from all SUs. In the first approach, the SU can transmit power below the threshold over a wide spectral range along with the narrowband PU on each licensed band. This approach is mainly used for short range SU communication employing ultra-wide band technology. The second approach is based on Interference Temperature, which allows SUs to use higher power to transmit on a licensed spectrum band whilst remaining below a threshold. The measurement of the total interference to the PU, and also how to apply this constraint on SUs are considered as the main challenges, according to the FCC (Petracca et al., 2012).

2.3 Cognitive Radio (CR)

The compilation of many measurements taken in different regions over a long time period demonstrates low utilisation of the radio spectrum in most of these measurements (Harrold et al., 2011). CR technology can enable the flexible, efficient and reliable use of the radio spectrum by relying on the characteristics of radio operating according to the environment conditions in actual time. CRs have potential to use whole frequency bands intelligently, when they are not used by the primary user, without harmful interference to licensed users. CR has become an encompassing term across many varied technologies enabling differing levels of self-programming to be used with a focus on different functionalities which the radio spectrum can support, including the availability of wireless access and optimisation of the radio resource. Also, dynamic spectrum access can be realised by future devices, realising the full future potential of CR and its ability to manage interference effectively. Also, Haykin defined CR as a radio that has a sense of its surroundings, and also has the capability to learn and adapt to changes in radio parameters at anytime, anywhere, with the objective of efficient and reliable spectral communication (Haykin, 2005; Singh & Saxena, 2012; Akyildiz et al., 2009).

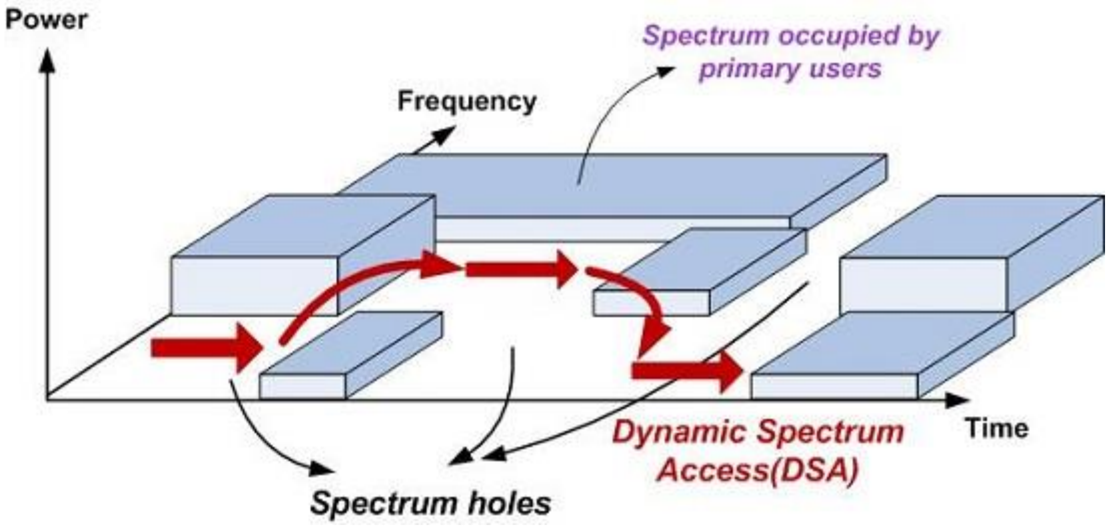

Figure 2-2: Radio Spectrum

2.3.1 Cognitive radio functions

Four main functions characterise CR, providing the capability to use or share the spectrum and to achieve the primary objectives of efficient utilisation of spectrum and providing highly reliable communications when and where needed. Figure 2.3 shows the lifecycle of CR as a secondary radio system which involves spectrum sensing, spectrum sharing, spectrum mobility and spectrum decision (Tabaković, 2011).

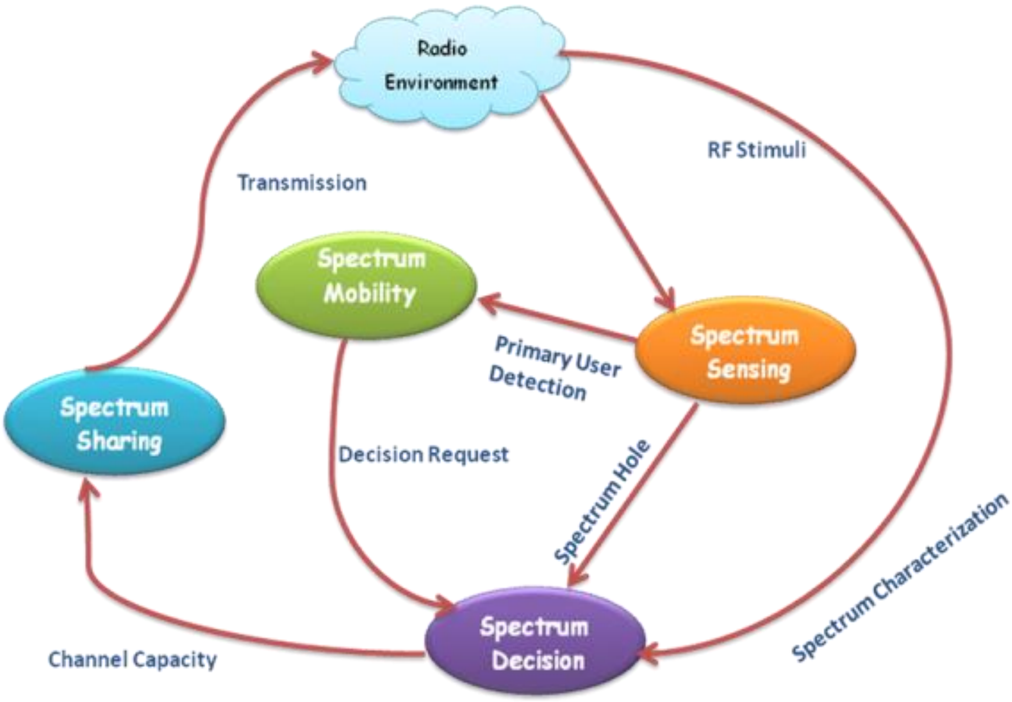

Figure 2-3: Cognitive Radio lifecycle

Spectrum Sensing is the main core of CR, which senses the radio environment continuously to explore unutilised frequency bands which can be exploited by CR (Ziafat et al., 2011). Spectrum sensing is defined by (Haykin et al., 2009) as "assignment of finding spectrum gaps by sensing technique, the radio spectrum in the local neighborhood of the cognitive radio receiver in an unsupervised manner". Consequently, the main goal of spectrum sensing is to give more opportunities to CR users to temporarily access the unoccupied spectrum for transmission without interference to the licensed (primary) users.

Spectrum Decision is an operation based on the spectrum sensing which provides sensing information to cognitive radio, operating frequency, and its corresponding technical parameters. To enhance quality of service without causing excessive interference based on this information, CR can use data from the policy database. CR networks need to decide which secondary user can use suitable spectrum bands. This process will be implemented by spectrum decision (Saxena & Basha, 2013; Tabaković, ; Lee & Akyldiz, 2011).

Spectrum Mobility in this thesis is defined as suggested by (Lee & Akyldiz, 2011) as: "maintaining seamless communication requirement during the transition to better spectrum.". To implement this process, the spectrum mobility aspect of CR networks is divided into two parts; Spectrum Handoff and Connection Management. The Spectrum Handoff means transfer of continuous data transmission from the current spectrum to unused spectrum. In the event of the arrival of a PU in the spectrum in use, the SU should leave the licensed spectrum immediately. Thus, the handoff process yields a transmutation delay. Consequently, the Connection Management will manage and adjust protocol stack parameters to compensate for the handoff delay (Christian et al., 2012).

Spectrum Sharing ideally results in spectrum holes being used by some SUs. A key challenge of CR is how to "achieve a balance between its self-goal of transferring information in an efficient way and altruistic goal to share the available resources with other cognitive and non-cognitive users" (Tabaković,). Hence, it can be said that scheduling of use of spectrum holes among CR users will contribute to preventing excessive interference to PUs and between SUs.

A cognitive radio network is created intelligently to be able to monitor and be aware of changes in its radio environment in a sensitive manner, which makes spectrum sensing a priority among other CR tasks. Spectrum sensing presents challenges which are represented as some factors that have negative impacts on spectrum detection (Lee & Akyldiz, 2011). Firstly, signal-to-noise ratio (SNR) detection might need to operate at very low thresholds. Secondly, there are two issues relating to wireless channels that make spectrum sensing complicated: time dispersion and multipath. Finally, detection of noise power might not allow accurate detection of holes in the spectrum band, as the noise level might change over location and time. Spectrum sensing has been widely investigated by many researchers (Yadav & Rathi, 2011; Gardner & Chen, 1992). Spectrum sensing is considered as the main challenge of CR, which needs to detect spectrum holes reliably for SUs in the radio environment. According to (Jiang et al., 2008; Stabellini & Javed, 2010; Shobana et al., 2013) spectrum sensing is divided into three different schemes in terms of system performance: Firstly, a full sensing scheme, which needs to sense the target spectrum during each activation. Thus all of the available spectrum allocations are sensed by CR users to exploit suitable and available spectrum. Secondly, a restricted sensing scheme, whereby users only sense the spectrum in their ideal resource set (Jiang et al., 2008). Finally, a minimum sensing scheme, in which users can communicate over the suitable spectrum holes directly, without sensing.

There are some spectrum techniques already involved in current wireless standards, which have some features of cognitive radio such as IEEE 802.11K, Bluetooth and IEEE 802.22. For instance, Bluetooth uses Adaptive Frequency Hopping (AFH) to reduce the interference between wireless systems. AFH contains a sensing algorithm to decide if there is a device present in a channel or not in order to avoid already occupied channels (Yucek & Arslan, 2009).

2.4 Software Defined Radio (SDR)

SDR has been under research for more than 40 years, although since it was first introduced the concepts of utilisation and associated implications have changed. The basic idea of SDR is to provide certain functionality in communication devices operating like personal computers which can be moved from one place to another, with the possibility of changing the characteristics of these functions according to the location and time. Such SDR devices can be programmed to allow working on one device with different communication modes.

Therefore, the hardware requirements of a communication platform can be reduced by adoption of SDR techniques (Gultchev et al., 2005).

The general definition of SDR is an adaptive radio communication systems. Some radio components such as , mixers, modulators/demodulators, filters, and detectors have developed from hardware implementation to software implementation. This means the radio components can be combined with software by reconfiguring radio system characteristics such as frequency and transmitter power. This allows flexiblility to change radio parameters and analyse the radio environment during the operational time. Such a combination will contribute to improving spectrum efficiency and resolving frequency congestion problems. However, due to the cost consideration in most current technology and some restriction of the wireless technology, some features of SDR are not attainable to apply in commercial systems. Restrictions include limitations on the maximum transmitter power, which must not cause interference with the PU (Akhi, 2003).

2.4.1 Background and History of SDR

Historically, SDR is not a recently discovered technology, it was first introduced in 1970 in the USA by the US Defence Advanced Research Projects Agency (DARPA) as the Speakeasy system, which was created for military use. This application was multi-purpose, enabling communication over a wide range of frequencies, cryptographic types, some modulation techniques and data encoding methods. Also, the US Air Force has the potential to support approximately ten different radio protocols to operate military radio devices anywhere over a frequency range between 2 MHz and 2 GHz (Gultchev et al., 2005). The work on Speakeasy led the USA Department of Defence to improve the technology and create other projects such as the Speakeasy II joint tactical radio system and airborne communication node (ACN) Here the main goal was to reduce reconfiguration time while the radio was in service. These efforts were not limited to the USA only and there have been similar efforts in both Japan and Europe. In Japan in December 1998, a software radio research group was formed to encourage research and development in software radio. Multimode transceivers have been developed by several companies using SDR components. The main focus of research in Europe was on the ability to deliver voice, video and data to mobile users by the Flexible Integrated Radio Systems Technology (FIRST) project. Multi-media services need a wide range of mobile services and also development and deployment of flexible Intelligent Multimode Terminals (IMT), which were developed by Universal Mobile Telecommunications Services (UMTS) (Ju, 2010).

In 1992, the first key paper on the subject of software radio was published by Joe Mitola for the IEEE National Telesystems Conference, it was entitled “Software Radio: Survey, Critical Analysis and Future Directions”, and contributed to opening up the concepts of SDR to the broad community of researchers, although the software radio prototype was used as a receiver only at this stage. Later on, in 1998, Mitola referred to "cognitive radio", which enabled the radio to be aware of its spectral environment and use the necessary information to adapt to the environment as needed (Zhang, 2013).

The emergence of SDR opened many possibilities for improving the future of wireless communication and making it more flexible, reliable, upgradable and reusable, by using software to reconfigure some of the traditionally hardware-based components, thereby contributing to reduce platform cost.

Many SDRs have been developed using the Realtek RTL2832U (RTL-SDR). These have different characteristics such as sensitivity or frequency range and most of them are not constructed as high performance SDRs, with the resolution of typical USB devices being only 8 bits. To achieve a wide dynamic range some SDRs use 12, 14, 16 bits or more.

However, the most serious problem seems to be that the RTL-SDR is not RF-shielded and has a high noise floor which is different from one sample to another. The main reasons for this problem might be leakage of RF into the antenna port of the silicon tuner, USB noise, lack of selective front-end filters and local TV/FM/GSM transmitter noise. Also connection of the RTL-SDR directly to a personal computer (PC) increases the noise and it is recommend to use a USB extension cable to connect the RTL-SDR at least 1 m away from the PC to reduce the noise. As specified in the data sheet, the maximum bandwidth of the RTL-SDR is 3.2 MHz and depends on the processor speed and memory capacity of the PC, which means if the frequency range is wider than 3 MHz multiple hops must be made in order to cover the entire spectrum. The largest stable bandwidth that can be achieved is 2.4 MHz or 2.8 MHz and setting the bandwidth too large with a slow PC leads to loss of some samples (Nika et al., 2014).

Furthermore, the operation of scanning a portion of the spectrum becomes relatively slow since due to switching the RTL-SDR frequency band, the scanning of a span of 40 MHz might take a significant amount of time, particularly when the FFT size is large. In the case of changing of the signal rapidly in the frequency domain, the RTL-SDR response will be too slow and then will lose the capability to capture the signal. Therefore, RTL-SDR used as a spectrum analyser is suitable for analysing quasi-stationary signals and also in cases when the absolute power measurement is not critical. Analysing small signals below -10 dBm is the best area for the RTL-SDR to avoid the problem of LNA overload, otherwise, external attenuators should be used.

2.4.2 SDR advantages

SDR has advantages relative to traditional radio which include more flexibility in terms of communication system. A further benefit is that, as long as the tuner input frequency, Analogue to Digital Converter (ADC) sampling rate and computing power are sufficient, any receiver within reason can be implemented in pure software, without hardware changes. In addition, it allows bug fixing by remote reprogramming, which can be undertaken during operating time, offering significant reduction of maintenance time and cost. The existing infrastructure can be updated with new capabilities and features without high expenditure which can help the service providers to deal with their networks easily in the future. In contrast, the only restriction on the SDR is that, the input frequency tuner must match the signal that it is desired to receive. The sampling rate must be high enough to catch the signal according the Nyquist sampling theorem. For instance, if the signal has 1 MHz bandwidth, it needs at least that bandwidth in the receiver front end, a corresponding sample rate of at least 2 Mega samples per second and sufficient computing power (Tuttlebee, 2003).

2.4.3 Research Prototypes for SDR

A number of prototypes of SDR have been developed by researchers in recent years for accelerating the development of current and future communications. Different models of Universal Software Radio Peripheral (USRP) platforms have been created by Ettus. USRP is the leading commercially-available SDR platform. It can support a range of applications and was built to transmit and receive radio signals across a wide range of frequencies and modulation schemes. Communication engineers and researchers from leading institutions around the world are now using USRP for a wide range of RF applications, including cognitive radio, spectrum monitoring and as next generation wireless systems. A USRP transceiver provides a powerful platform as a solution for prototyping RF and future communications systems (Zhang, 2013). As network experimentation has attracted the attention of many researchers in line with the rapid development of communications, a new term has emerged called “network programmability”. This was one of the important requirements, used by the Global

Environment for Networking Innovations (GENI) to simplify network management and provide more flexibility (Elliott, 2008). Another recent device that can transform a wide portion of radio spectrum to intelligible information and which can be used to advantage in CR systems is the RTL-SDR USB-connected dongle. This was intended to be used for decoding digital TV signals, but some researchers discovered that it can detect a very broad portion of radio spectrum. It can be combined with a PC and appropriate software, such as SDR#, to perform various spectrum scanning operations. Various RTL-SDR models have been created to operate in different wide frequency ranges. The pace of innovation of the SDR has increased significantly through proliferation of applications in various fields, such as reception of weather satellite images in VHF by using RTL-SDR (Laufer, 2014).

2.5 White Space Definition

Recently, communications demands have increased rapidly. Currently, in most developed countries, where terrestrial radio frequencies are used for delivery of TV broadcasting services, a switchover from analogue to digital broadcasting is already completed or still underway, whereas some other countries are still using analogue systems. However, in both kinds of systems, unused frequencies are still available in most locations around the world. Hence, a licensed spectrum became available to SUs sanctioned by the regulatory authorities in the UK, USA and other countries; where TV white space refers to the degree of use or the underutilised portions of radio frequency in the VHF and UHF TV bands. Both FCC and Ofcom have considered the potential of CR devices in TV bands and how to avoid harmful interference to licensed users of these bands. FCC has approved rules in the USA that allow unlicensed devices to operate in TV bands, while in the UK Ofcom has published statements allowing the unlicensed spectrum to coexist with the licensed spectrum as long as it does not cause harmful interference to spectrum incumbents.

Furthermore, wireless microphones are incumbent in the UHF TV bands in many countries. In white spaces, many unlicensed devices can operate on a TV channel, but their transmissions should not interfere with a TV transmission nor with wireless microphones. Three methods have been considered for preventing harmful interference to incumbents (Nekovee, 2009), including the use of databases as discussed in the following section.

2.6 Geolocation Database Management System(GDMS)

Use of a Geolocation Database is seen as one of the main detection methods using the TV white space concept in practice, which can avoid signal detection problems such as fading effects and shadowing. A Geolocation Database requires some information of the PU such as frequency of operation, transmission power, size, location, transmission time and type of antenna. This information will protect spectrum incumbents from SUs, who will access the database by sending a query to obtain the available channels in a given area at a certain time. Furthermore, a Geolocation Database might have a proxy for making queries and identification of available channels for white space device (WSDs) (Paulo Marques, 2010)(CEPT).There are two options for using such a database. The first is to use a single database, which can be accessed by all WSDs, although this might cause some delay in the query response. The second option is to use multiple identical databases, where the master WSD could select closed databases corresponding to different types of devices and there would be no real difference. The main advantage is that a standard protocol is not required. However, a disadvantage is that databases can be established and maintained by different manufacturers in multiple countries. Multiple database providers should provide the same sets of available channels to the master WSD, regardless of which database. Also it is necessary to consider cost, speed of response to database queries and efficient and effective management and ensure that these parameters are comparable among the databases. Therefore, databases should be updated regularly and there should be a trade-off with synchronizing between databases, which can solve location problems such as fading effects and detection errors of sensing techniques. The master WSD could be the wireless router in a house, whereas the slave devices could be mobile, laptop or other devices. The connection between master and slave is called Super WiFi (Mwangoka et al., 2011), which can operate over a long distance to send a signal from a fixed device master to a fixed device client or personal/portable client, as illustrated in Figure 2.4 (Nekovee, 2010; Feng et al., 2011).

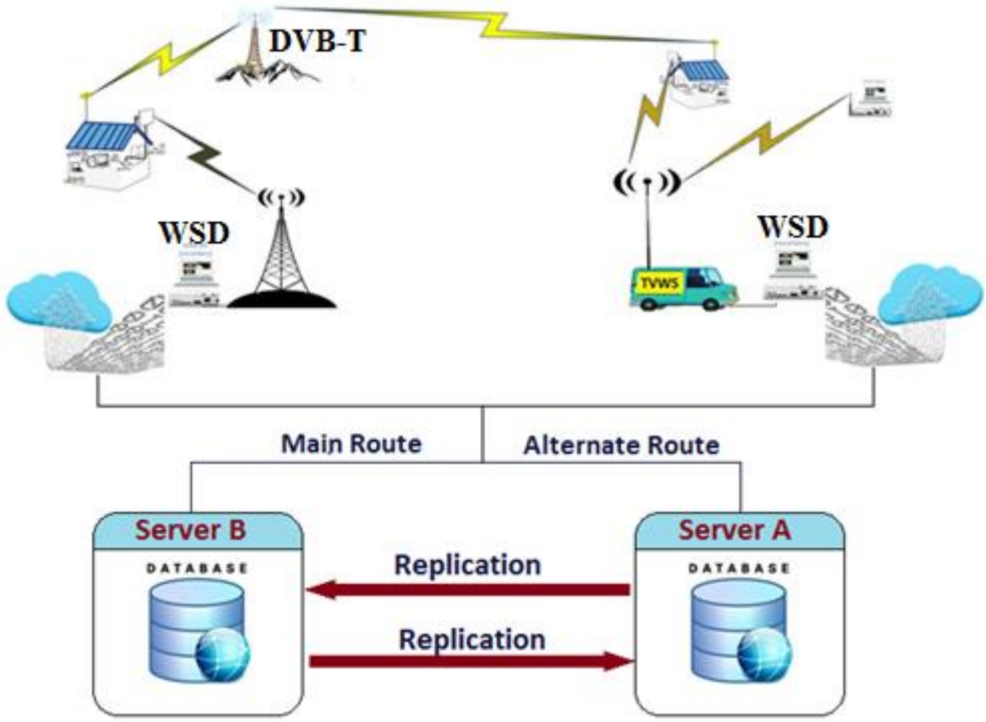

Figure 2-4: TVWS and Geolocation database mechanism

2.7 Spectrum Management Concepts

There are several important fundamental concepts about the radio spectrum including the reasons why it is important to regulate the spectrum resource and how benefit can be derived from its use in future communications. This section begins by explaining the view that the radio frequency spectrum may be regarded as a natural resource, with descriptions of trends in spectrum management systems, definitions, spectrum managment elements and the spectrum management processes (McLean Foster, Martin Cave,Robert W. Jones, 2007).

2.7.1 RF spectrum as national resource

Nowadays, RF spectrum is considered to be a national resource like gas, petrol and minerals. The spectrum of radio waves can be a valuable resource around the world, from which everyone could profit. Use of radio spectrum has increased significantly in all fields of life, whether for scientific, social, cultural or developmental purposes, with the number of service end users increasing enormously. Various kinds of services can be provided by different kinds of spectrum bands, such as emergency services, military purposes, air traffic control, radio astronomy and marine communications, while secure communications have been used by defence forces to ensure protection for users.

2.7.2 Spectrum management system

Due to the enormous increase in demand for radio systems worldwide, many applications using radio waves following the normal competitive laws of nature, might be used incorrectly and cause interference with each other. Such interference could prevent the benefits that could be offered to more users. An appropriate spectrum management system could avoid such interference problems, to ensure equitable access to the radio spectrum range that is allocated to a specific application in a particular time and location. The regulation of the spectrum should include several procedures: planning, engineering, monitoring and enforcement. Even though there is still a possibility of conflicts among users who have access to the spectrum, which might increase or not, for this reason spectrum management systems are not satisfactory to all users. The mitigation of radio spectrum interference is one of the important tasks of the spectrum management system and to attain maximum advantage from efficient and effective use of radio spectrum. The most significant of the numerous organizations that contribute to solving spectrum problems is the International Telecommunication Union (ITU) as illustrated in Figure 2.5.

As already mentioned, a spectrum management system is divided into four elements to manage the spectrum effectively and efficiently; **s**pectrum planning, spectrum authorization, spectrum engineering and spectrum monitoring, each of which is described as follows.

Spectrum planning is a high level technical document, which defines the allocation of bands to different types of spectrum services. In terms of the spectrum arrangements in most countries, the planning document is the first plan that should be consulted. The allocation of parts of the spectrum for particular uses depends on several procedures: international agreements, technical characteristics including radio propagation, identifying national policy priorities and also the practicalities of using of various portions of the spectrum.

Spectrum authorisation is the process of granting users access to the spectrum resource by using different types of communication equipment and allocating specified frequencies or sub-bands to a particular user, who might or might not have potential to grant or transfer spectrum rights to other users, or authorize use of certain equipment for using a certain spectrum. The main activities of authorization are licensing, whether through individual, system or class licences, and also assessment, equipment authorization, certification of radio operators and the acceptance of registration and international notification.

Spectrum engineering has a key role in examining electromagnetic compatibility standards of the equipment, and ensuring that it is not susceptible to other radiation hazards. Also, depending on the equipment proposed for use in a certain radio system, spectrum engineering contributes to identifying the suitable frequency band for that equipment according to applicable standards.

Spectrum monitoring is an important method to contribute to protection of national security from external threat, which might result from interference in security communication. Such threats can be discovered easily and promptly by radio surveillance. It also contributes to ensuring that users follow the international radio traffic regulations and prevents them from causing any mutual interference. One of the main benefits is contribution in combating and reducing organised crime (McLean Foster, Martin Cave,Robert W. Jones, 2007).

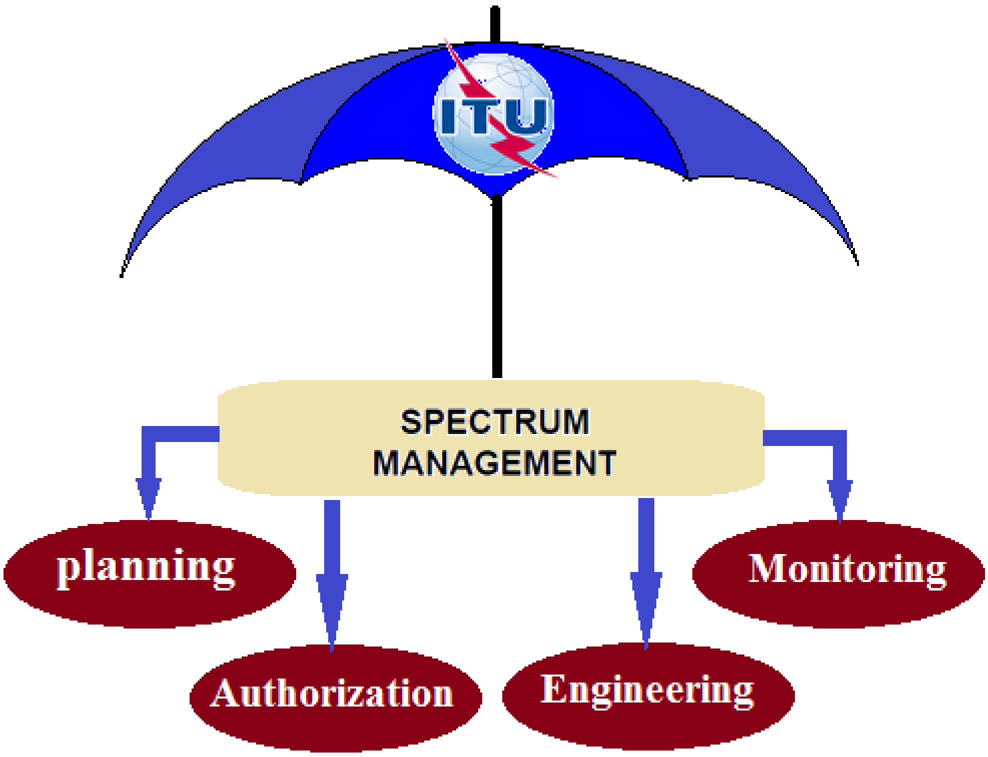

Figure 2-5: Spectrum Management Elements

2.8 Conclusion

Based on the study of various concepts relating to the improvement of spectrum efficiency, in order to meet stakeholders' requirements, this chapter gives a clear idea about the importance of, and the interdependence among, those concepts in contributing to use of unutilised spectrum for economic growth, particularly in developing countries. Therefore, it can be concluded that the WSD is an important device that has several features: capability to sense the radio environment and the ability to connect with a geolocation database. Two detection techniques used by SDR along with a spectrum management system can be used to detect the available channels from White Space according to international radio traffic regulations. This raises the question of what is a suitable technique to be used by a WSD for sensing the environment. Consequently, this chapter has set the scene for a comparison study between several spectrum sensing techniques, which will be discussed in detail in the next chapter.

Chapter3: Spectrum Sensing Techniques

3.1 Introduction

In the present, one of the most challenging issues in CR systems is spectrum sensing concepts, which is considered an extremely well researched topic. In this chapter compares three main classes of spectrum sensing techniques (Energy Detection (ED), Matched Filter Detection (MFD) and Cyclostationary Feature Detection (CFD)) in terms of time and spectrum resource consumed, required prior knowledge and complexity, and then rank the three classes according to accuracy and performance.

This chapter is organized as follows. Firstly, spectrum sensing techniques are classified and then the advantages and disadvantages of each are extracted. Finally the comparisons among spectrum sensing techniques are discussed by using six criteria: time and spectrum resource consumed, required prior knowledge, complexity, accuracy and performance.

3.2 Spectrum Sensing Techniques

Various spectrum sensing techniques were proposed to identify the presence of PU signals and the extent to which exploitation of that spectrum by a SU may take place when the PU is absent. The most popular spectrum sensing techniques are classified under three major categories; Non-Cooperative detection, Cooperative detection and Interference based detection, as shown in Figure 3.1 (Mounika et al., 2013).

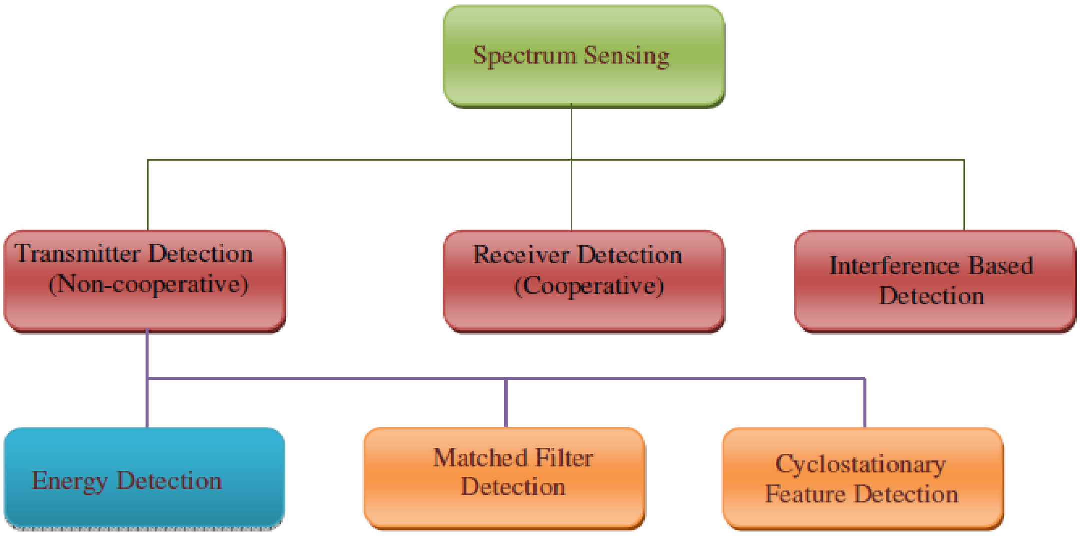

Figure 3-1: Spectrum Sensing Techniques

3.2.1 Non-cooperative spectrum sensing

This form of spectrum sensing is also known as single-user sensing (or local detection), and occurs when a cognitive radio acts on its own. A transmitter detection approach is based on the ability of the CR to receive weak signals and identify whether the PU is presence or absence in a certain spectrum. This approach can be defined as a basic hypothesized model for transmitter detection in the following (Ghasemi & Sousa, 2005; Abdulsattar & Hussein, 2012):

$$x(t) = \begin{cases} n(t) & H_0, \\ hs(t) + n(t) & H_1, \end{cases} \tag{3.1}$$

Where $s(t)$ represents the transmitted signal, $x(t)$ denotes the signal received by the SU, $n(t)$ is an Additive White Gaussian Noise (AWGN) and h is the amplitude of the channel gain. The hypothesis corresponding to the absence of a PU signal is represented by H_0, (white space) and H_1, is the hypothesis that the signal is present (occupied).

Several methods of the non-cooperative spectrum sensing techniques have been proposed including ED, MFD and CDF.

3.2.1.1 Energy Detection (ED)

Energy detection is a non-coherent detection technique, producing the primary user detection and its statistics. The advantages of using ED include low computational cost, easy implementation, less complexity and no need of any prior knowledge of the PU, depending only on the power of PU signal to determine whether the signal is present or absent. These advantages make ED the simplest method for detection of PU signals (Tabaković, ; Singh & Saxena, 2012; Saxena & Basha, 2013; Ziafat et al., 2011; Aulakh, 2009; Subhedar & Birajdar, 2011).

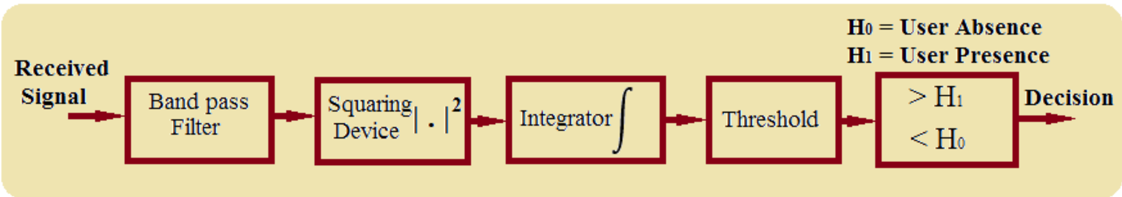

Figure 3-2: Energy detector block diagram

Figure 3.2 depicts the block diagram of the ED technique, showing that the signal will go through the band pass filter with bandwidth W, and is then integrated by the integrator block. The output will be compared with the threshold value, which may be adaptive, based on the channel conditions, or be a fixed value. Since ED is based on energy received that is compared with a predefined threshold for estimating the presence of a signal, ED is called a blind signal detector.

In contrast, the weakness of this technique for signal detection is that it depends on comparing the power of the received signal to the threshold level, whereas this threshold level is affected by the noise floor. The latter can be estimated but the signal power is difficult to estimate as it relies on two factors; distance between the PU transmitter and CR and ongoing transmission characteristics. As a consequence, the selection of threshold level might lead to some drawbacks of the ED technique. If the threshold is too low some noise spikes may be detected as PUs causing false alarms. On the other hand, when the threshold is too high, missed detection will occur, because the weak PU signals will be ignored as shown in Figures 3.3 and 3.4 below (Aulakh, 2009; Ikuma & Naraghi-Pour, 2008).

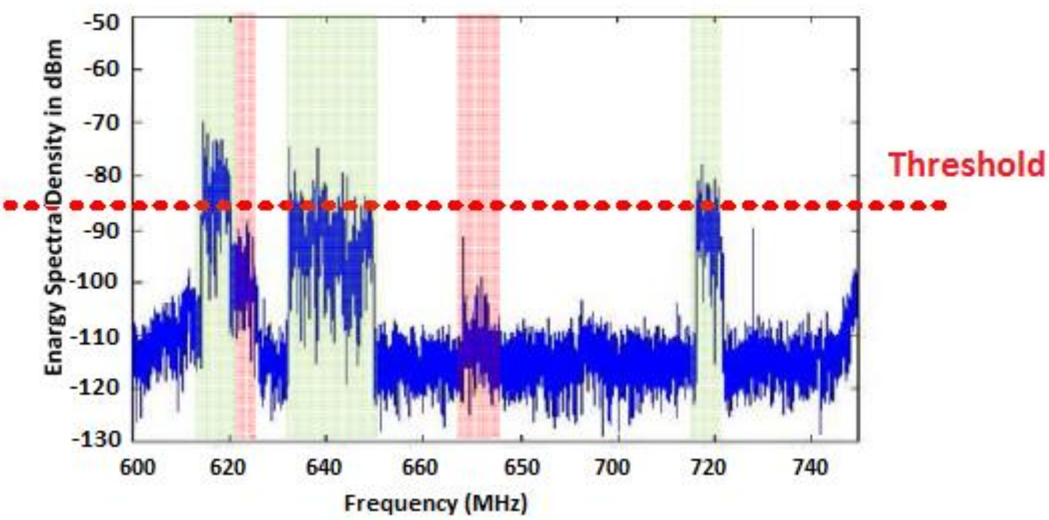

Figure 3-3: Illustration of Missed Detection

Therefore, the performance of ED is dependent on the suitable selection of the threshold in the frequency domain, which depend on the knowledge of noise variance. Another disadvantage is that the accuracy of signal detection is low compared with other techniques. Hence, it can be assumed that the received signal has the simple form as shown in the following equation (Aulakh, 2009; Yucek & Arslan, 2009; Worcester polytechnic institute, 2011).

$$x(t) = s(\mathrm{t}) + \mathrm{n}(t) \tag{3.2}$$

where $s(t)$ denotes the detected signal, while $n(t)$ is the AWGN sample, and t is a time sequence sample number. It can be noted that $x(t) = n(t)$ when the primary user is absent and $s(t) = 0$. Thus, the decision metric can be taken as having the following form:

$$M = \sum_{n=0}^{N} |x(t)|^2 \tag{3.3}$$

where N denotes a period of the observation. The output of the metric M can be compared with a fixed threshold λ for obtaining the occupancy decision of the band, occupied or not. It can distinguish four probability states for the signal and three probability results of the signal detection for the decision making process. Two hypotheses are required to match the statistical properties of metric output M:

$$H_o \ : \ y(n) = w(n)$$
$$H_1 : \ y(n) = s(n) + w(n) \tag{3.4}$$

It can be clearly seen in the Table 3.1, that both statuses of PU signal, detector have the same value (1) for present or (0) for absent, which means that $H_o$or $H_1$are well performed, whether prevent or accept the SU for using the spectrum. This kind of good decision is called the probability of detection (P_d) which may be presented as:

$$P_d = P_r(M > \lambda | H_1) \quad \text{or}$$
$$P_d = P_r(M < \lambda | H_0) \tag{3.5}$$

On the other hand, there are two wrong decisions of the signal detection algorithm, Missed Detection (P_m) and False Alarm (P_f). P_m only occurs when the detector has not detected the signal despite it being present in reality, which causes increased interference to the PU. It can be written as:

$$P_m = P_r(M < \lambda | H_1) \tag{3.6}$$

Whereas, P_f can be illustrated when the signal detection of detector is present but in the real world there is no signal, which is formulated as following:

$$P_f = P_r(M > \lambda | H_0) \tag{3.7}$$

Table 3.1: The decision making probabilities of the signal detection

Primary signal Status	Detector status	Result	Decision
Present (1)	Present (1)	Prevent SU (P_d)	Correct Decisions
Absence (0)	Absence(0)	Accept SU (P_d)	Correct Decisions
Present (1)	Absence (0)	Miss detection	Wrong Decision
Absence (0)	Present (1)	False alarm	Wrong Decision

The optimum estimation of decision threshold λ can be selected based on the variation of the noise power and detected signal power, but in most cases, the detected signal is changed by changing the transmission characteristics and the distance among PU and SU. In the ITU spectrum monitoring handbook it is recommended that the threshold is set at 10 dB above the noise floor average (ITU, 2010), while some studies selected the threshold between 3 and 6dB above the noise floor (Chiang et al., 2007; Mehdawi et al., 2013).

3.2.1.2 Matched Filter Detection (MFD)

Another technique used for spectrum sensing is MFD, which is recognised as the optimum method to detect PU transmissions when the form of the transmitted signal is known. It is a technique commonly used in radar systems. In addition, MFD also is considered as a linear filter designed in digital signal processing (DSP) which is used to maximize the output signal to noise ratio for given input signal (Ziafat et al., 2011; Yadav & Rathi, 2011; Bodepudi Mounika, Kolli Ravi Chandra, Rayala Ravi Kumar, 2013). However, a MFD effectively requires demodulation of the PU signal, and as a consequence this technique requires perfect prior knowledge of the PU, represented as signal features such as modulation type, bandwidth, operating frequency, pulse shaping and frame format. It can be seen from Figure 3.5 that the selected threshold will receive the output of MFD for comparison to decide whether the spectrum is occupied or not (Subhedar & Birajdar, 2011; Yucek & Arslan, 2009).

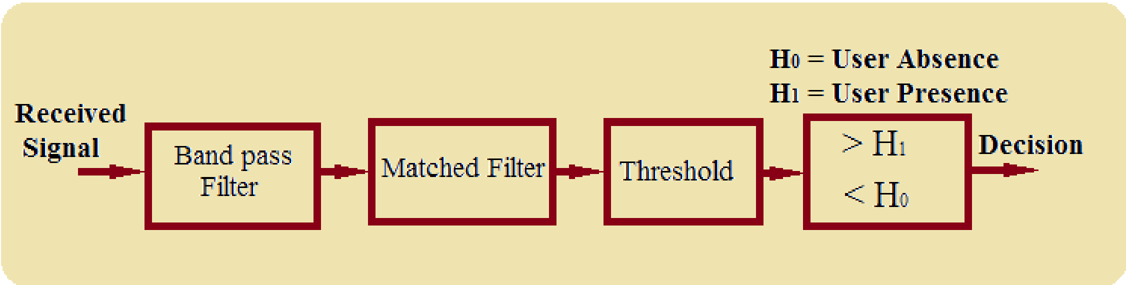

Figure 3-4: Matched Filter Detection block diagram

The matched filter will receive the signal as given:

$$x(t) = hs(t) + n(t) \tag{3.8}$$

According to the basic hypothesis model as presented in the previous part, the PU will be absent when $the\ s(t) = 0$.

Matched filtering can be described as convolution of the input with the time-reversal of the known signal (template) and is identical to cross-correlation in the input signal r(t) if correctly identified, illustrated as;

$$r(t) * s(T - t + \tau) \tag{3.9}$$

Where T denotes the duration of the template, τ denotes the shift in the template, t is event time, which is unknown and needs to be estimated. The following equations illustrate the calculation of the probability of detection, P_d, and false alarm, P_f .

$$P_d = Q(\frac{\lambda - E}{\sigma_w \sqrt{E}}) \quad (3.10)$$

$$P_f = Q(\frac{\lambda}{\sigma_w \sqrt{E}}) \quad (3.11)$$

where E denotes the energy of the deterministic signal, Q represents a distribution function of Gaussian complexity, and σ_w^2 denotes the noise variance.

The advantages of this method are represented in the following points. Firstly, the detection process requires only short sensing time and a low number of samples to meet the required level of false alarm or missed detection. Secondly, it has high processing gain and high accuracy compared with other techniques. Also it provides the optimal detection performance. Even though the method has its advantages, it also has some disadvantages; the power consumption of MFD is large in different receiver algorithms which need to be implemented to detect PUs. MFD requires a dedicated receiver for every PU signal type. Also MFD needs a perfect knowledge of the PU signal format. Some workers have suggested that the implementation complexity of a MFD-based sensing unit is impractically large (Aulakh, 2009; Ziafat et al., 2011; Tandra et al., 2004).

As already seen, the performance of the matched filter relies on the extent of the availability of prior knowledge of PUs which leads to increasing cost and more complexity. Consequently, the good performance and high accuracy which is potentially available by using MFD is at the expense of increased cost and complexity.

3.2.1.3 Cyclostationary Feature Detection (CFD)

Cyclostationary Feature Detection (CFD) is a method for detecting transmitted signals of PUs by analysing known periodic features in the received signals. The CFD method can distinguish between noise and a PU signal at very low signal-to-noise ratio (SNR) values. In addition, the detection basis of this method relies on the inherent redundancy in the PU transmissions. One of the greatest advantages is that the CFD method has the ability to identify the modulation scheme, given appropriate template data. Hence, CFD needs partially knowledge of the PU, but can detect the PU signal at very low SNR values (Aulakh, 2009; Yadav & Rathi, 2011; Aparna & Jayasheela, 2012).

On the other hand, the CFD takes a long time during computation which is considered slightly complex. And also it is worse than energy detection when the noise is stationary (Taboković, ; Ziafat et al., 2011; Yadav & Rathi, 2011). In addition, the cost of this technique is slightly high caused by the partial knowledge which is required for this method to detect the PU.

Consequently, it can be said, the performance of this technique relies on several factors including noise uncertainty, modulation scheme identification and redundancy in the transmissions of the PU. So in summary, the performance improvement of CFD is at the expense of increasing cost and time.

3.2.1.4 Other Non-Cooperative Spectrum Sensing Techniques

There several other proposed spectrum sensing methods, such as filter bank-based spectrum sensing, wavelet transforms-based detection and waveform-based sensing, which will be briefly overviewed.

Filter bank-based spectrum sensing (FB) is considered as a simplified version of multi-taper spectral estimation (MTSE), which can detect multicarrier transmission where each band has only one prototype. Behrouz Farhang (2008) has proposed this method for spectrum estimation which potentially has application to spectrum sensing in CR, and also is considered a very conventional technique. The main drawback that makes this method rarely utilised, is that it needs too many additional requirements to be conveniently utilised in spectrum sensing. With consideration of the structures of the filter bank used for multicarrier communications, it also requires many band pass filters in its receivers (Farhang-Boroujeny, 2008; Chiang et al., 2009).

The wavelet transform-based detection is proposed by Tian and Giannakis in 2006. They used this approach for detecting signal edges over a wideband channel in the power spectrum density (PSD), which may be regarded as the boundary between spectrum holes and occupied channels. Hence, based on the CR information, it contributes to finding spectrum opportunities. However, this kind of technique is commonly used in image processing for most applications that are used for detecting edges (Subhedar & Birajdar, 2011; Tian & Giannakis, 2006).

Waveform-based sensing is considered as coherent sensing which is mainly used to detect whether or not the PU signal is transmitted. In wireless systems, there are known signal patterns which are used to assist synchronisation or for other purposes. Such patterns include spreading sequences, preambles and regularly transmitted pilot patterns. Such known patterns can be used in waveform-based sensing whose performance is based on the correlation between a known copy of the pattern itself and the received signal. Thus, this method can be performed on the systems where the signal patterns are known. Furthermore, it may be shown that in this method, increasing the length of the known signal pattern will impact directly on the performance of the sensing algorithm and its effectiveness in detecting PU transmissions (Yucek & Arslan, 2009; Thomson, 1982).

3.2.2 Cooperative Sensing technique

Cooperation is proposed as a solution to problems that arise in spectrum sensing due to noise uncertainty, fading, and shadowing. Cooperative sensing decreases the probabilities of missed-detection and false alarm considerably. In addition, cooperation can solve the hidden PU problem and it can decrease sensing time. In cooperative sensing, several SUs combine their findings to arrive at a more reliable decision. This can be essential in severe fading environments since if the SUs are sufficiently far apart, it is much less likely that they are all in the same fading dip. Hence, PMD (and/or Pf) decreases significantly. The final decision of cooperative sensing can be based on hard decisions (e.g. a majority vote), or on soft decisions (including additional information). There will be some trade-off between the final decision quality, the required processing, and the required communication overhead (Akyildiz et al., 2011).

3.2.3 Interference based detection

Interference management is important in cognitive radio networks since secondary usage is allowed only if the SU interference does not degrade the PU quality of service below a tolerable limit. In this interference model, each primary receiver has an interference temperature limit that defines how much noise and interference it can tolerate to guarantee certain quality of service. This creates spectrum opportunities for the SUs. Using this model, cognitive radios can measure and model the interference environment and adjust their transmission characteristics such that the interference to the PU is not above the regulatory limits. However, the major drawback of the model is that the interference temperature should be measured at the PU receivers, which is not feasible in practice. The FCC has abandoned the concept of interference temperature as unworkable. At the same time, the FCC has also encouraged researchers to solve the problems related to the interference temperature and make it feasible (Prathmesh Ghanekar,Pallavi Dhole and Nilesh Patil, 2014).

3.3 A Performance Comparison of Different Spectrum Sensing Techniques

In this section compares the performance of three well-known classes of algorithms-ED, MFD, and CFD. During the comprehensive study of spectrum sensing techniques in Section 3.2, criteria which directly affect the performance and accuracy of each technique were discussed. In particular, these aspects for ED, MFD and CFD are presented in Figures 3.6 and 3.7. A comparison has been made of time, cost, prior knowledge, complexity for each technique (illustrated in Figure 3.6) and how these aspects impact on the accuracy and performance (as shown in Figure 3.7). The comparison of performance has been represented in three different relative categories; low, medium and high (Fanan et al., 2014).

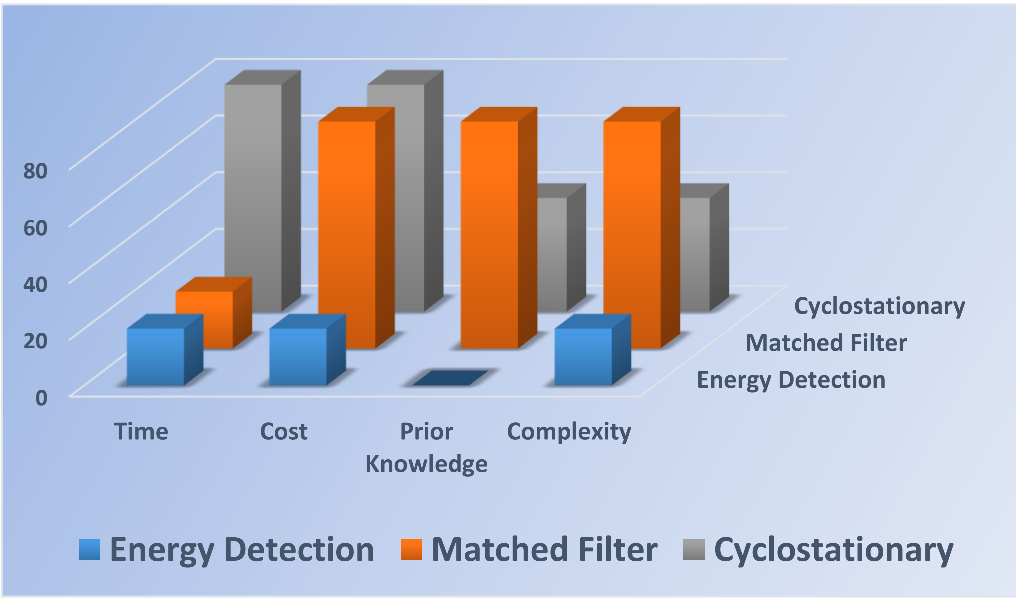

Figure 3-5: Comparison of spectrum sensing techniques

It can be clearly seen that ED has short time, low cost, no prior knowledge and less complexity but correspondingly the accuracy and performance are low because these criteria rely on some factors such as suitable threshold selection and noise stability. It is unrealistic to expect to find these stationary factors in all the times and various places. Whereas the MFD technique as illustrated in Figure 3.6 has good performance and high accuracy, it is at the expense of increasing the cost, more complexity and requiring perfect knowledge to operate this technique. In contrast CFD analysis has slightly better performance and possesses higher accuracy than ED, but it needs long time, high cost and partial prior knowledge which make it less complex than MFD. Therefore, each of these techniques has advantages and disadvantage where some advantages are at the expense of significant problems which might impact directly on the technique working properly and effectively in reality. Hence, in practice it is necessary to search for an optimum technique which might contain less complexity and high efficiency and which is able to adapt its operation to suit prevailing conditions. The overall goal of efficient spectrum sensing is to use the minimum spectrum for the actual sensing task, possibly at the expense of increased processing cost at each terminal.

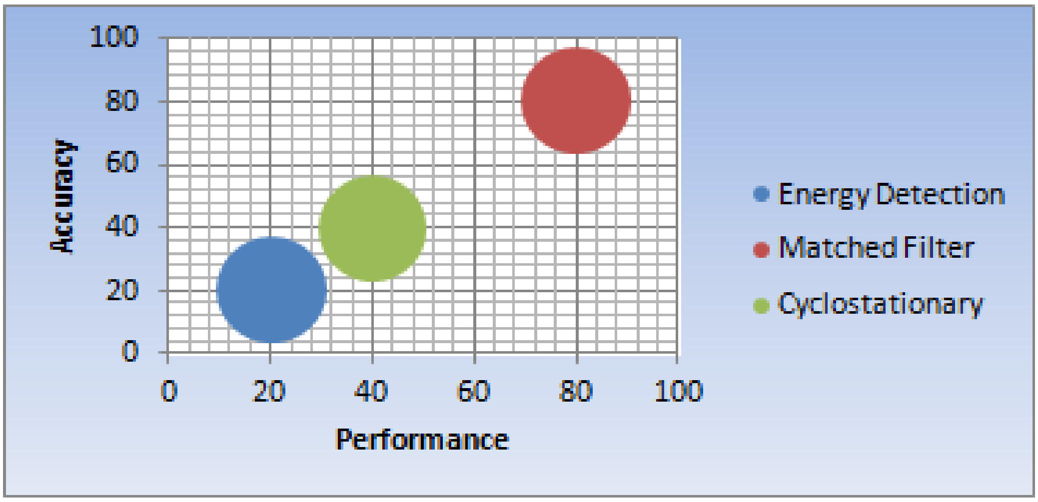

Figure 3-6: Comparison of spectrum sensing techniques (Singh, 2012a)

3.4 Simulation platform for Spectrum Sensing Techniques ED, MF and, CFD

In this section, proposes an algorithm for the discussed spectrum sensing techniques in the preceding sections. The algorithm computes and compares spectrum sensing techniques based on the probability of detection (Pd) and probability false alarm (Pf). This performance of detection methods is analysed in terms of Receiver Operating Characteristics (ROC) curves for the three different scenarios; ED, MFD and CFD, using a Monte-Carlo method for producing simulation parameters.

Figure 3.8 show the probability of detection versus probability of missed detection for three different methods.

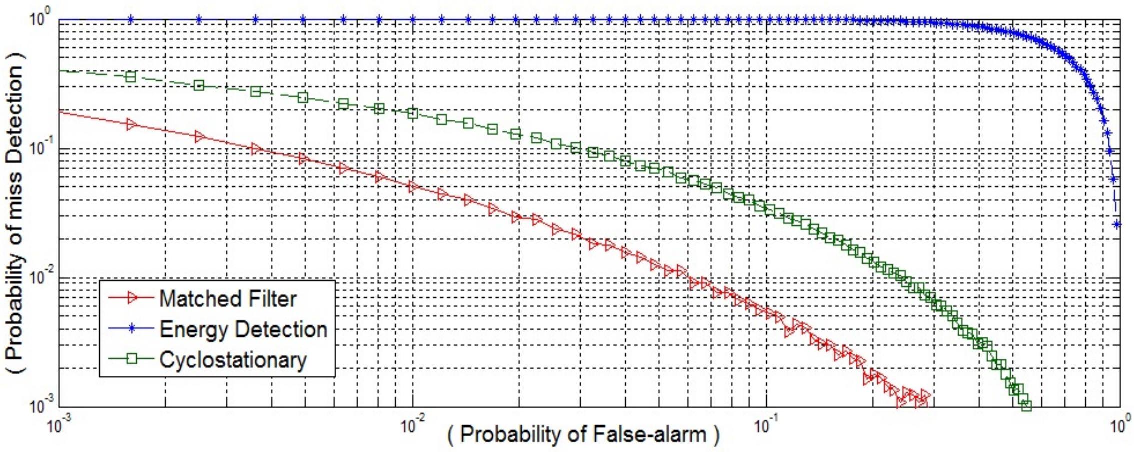

Figure 3-7: Complementary ROC curves for various spectrum sensing techniques (ED, MFD, CFD) with SNR=0 dB

The simulation results of spectrum sensing techniques shown in Figure 3.8 indicate that the matched filter is the best among the three techniques. The CFD technique is closest to the MFD and the ED is worst among them. In terms of the required processing, the ED is the easiest and it does not require any prior information. However, both the MFD and CFD, on the other hand, require prior information. For instance the matched filter requires full signal information and CFD requires partial information. This is clearly difficult to implement, and as well will be very expensive and very complicated to build in (Fanan et al., 2014).

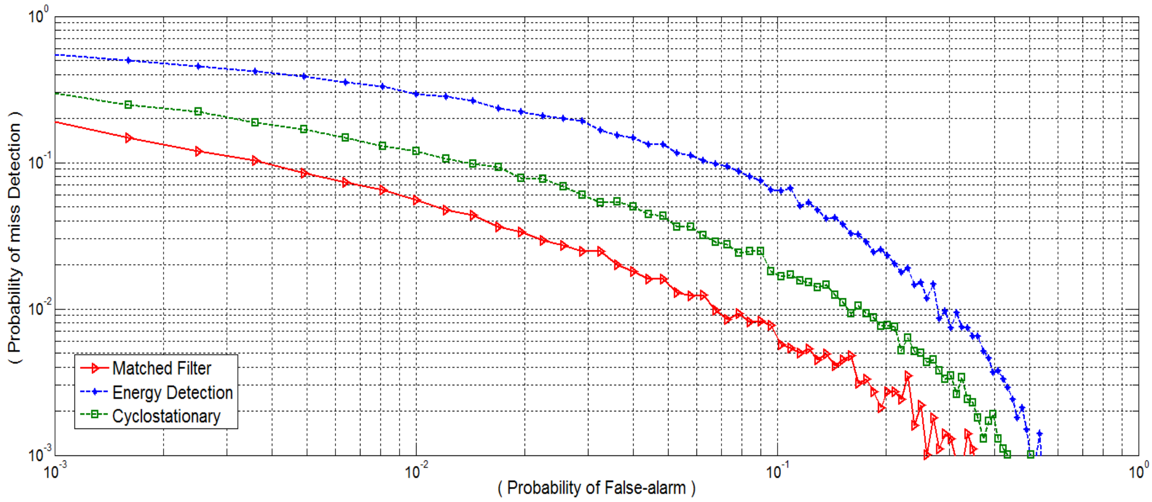

Figure 3-8: Complementary ROC curves for various spectrum sensing techniques (ED, MFD, CFD) with SNR=6 dB

Figure 3.9 indicates that when SNR is increased to 6 dB, all the proposed methods have a high probability of detection and low probability of missed detection compared with the SNR=0 dB case in Figure 3.8. This not a good example, however, since it will increase the complexity of the system. An alternative solution is to use cooperative sensing which reduces the false alarm rate and increases agility and has accurate signal detection and this will therefore be our research direction for future work (Wang, 2009). In this thesis results show that there is significant improvement in terms of reduced required average SNR for detection when using cooperative sensing. In particularly, for Pd equal to 0.9, local spectrum sensing requires SNR=16 dB while in cooperative sensing with n=10 its only need average SNR of 5 dB for each individual receiver.

3.5 Conclusion

In this chapter, compares the accuracy and the performance of three signal detection techniques; energy detection (ED), matched filter detection (MFD) and cyclostationary feature detection (CFD) by using several criteria such as time, cost, prior knowledge and complexity. It has been found that the performance and accuracy of each relies on the extent to which prior knowledge of the PU signal format is available. Furthermore, the complexity also increased when spectrum sensing techniques require more prior knowledge to detect a PU transmission. In contrast, increasing knowledge causes increasing cost and takes more time to compute. Therefore, it needs another technique, which might be done in future work, by combining the best features of two techniques, resulting in minimum requirement for prior knowledge of the PU signal, low cost, short computation time and minimum complexity.

Chapter4: Comparison of Software Defined Radio and Spectrum Analyser to assess TV band Spectrum Occupancy in the Hull area

4.1 Introduction

The TV band has attracted the majority of attention from researchers due to the considerable potential for exploitation of available white space that is not utilized based on time and location. The Federal communication commission (FCC) in the US has started to allow use of unutilized spectrum in TV band on a secondary-user basis (Federal Communications Commission, 2010). One of the main motivations for focusing on spectrum availability in the current worldwide digital TV broadcasting band, is that recent studies have shown the existence of significant amounts of vacant spectrum (white space) (Pietrosemoli & Zennaro, 2013; Dzulkifli et al., 2011b). Software defined radio (SDR) is one of the main enablers of the concept of CR, utilizing a radio architecture with high flexibility and re-configurability through use of software as much as possible instead of relying entirely on hardware. The spectrum available can be sensed and the radio system can adapt to the prevailing radio environment by use of cognitive radio. The goal of this chapter is to investigate the spectrum occupancy of the UHF TV band in the frequency range from 470 to 862 MHz using a commercially-available low cost SDR, called RTL-SDR, which is in the form of a USB ‘‘dongle’’, and to compare the results with those derived using a Spectrum Analyser (Agilent E4407B) which is considerably more expensive. Both systems will be used with various antennas.

4.2 Software Defined Radio (RTL-SDR)

Historically, hardware-based radio devices have limited functionality and the only method available to modify them is physical intervention, which has implications for production costs and flexibility. In today's world, several devices have been developed recently using SDR which have contributed to the growth of research in CR. Such devices include the Realtek-based Software Defined Radio (RTL SDR). This device contains two main chips, Raphael Micro R820T radio tuner and the Realtek RTL2832U which has USB data pump and an 8-bit ADC as shown in Figure 4.1 (J.-M Friedt, 2012).

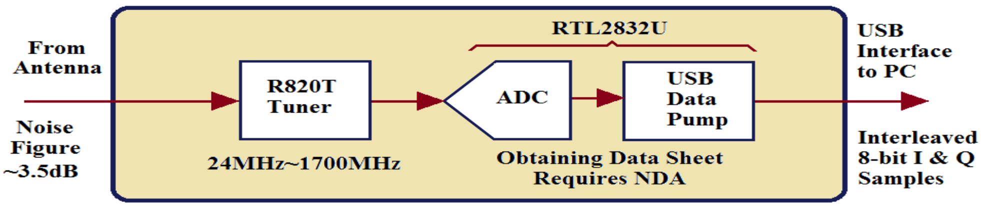

Figure 4-1: The RTL-SDR high level block diagram

The main purpose of this design was to receive DVB channels and most versions of the RTL-SDR contain DVB software which can be used to watch TV channels and use TV remote control (J.-M Friedt, 2012; Stewart et al., 2015). Although the RTL radio has limited sensing bandwidth i.e 3.2 MHz compared to other expensive devices, they can still scan the 390 MHz frequency range in less than 2.7s. However, the accuracy of spectrum scan and spectrum measurements using the RTL-SDR is affected by various factors as follows: firstly, the RTL-SDR dongle sensitivity (or "deafness") which dictates its ability to detect weak signals; secondly another factor affecting the measurements is that the measurement location is not very high up, the dongle may be blocked from receiving signals from some transmitters.

4.2.1 USB Dongle Testing

The Realtek RTL2832U R820T Tuner Receiver Dongle is used for testing the capability of scanning different TV channels by conducting the measurement of Channel 53 by using a TV antenna as shown in Figure 4.2. In this measurement the antenna was placed on the top of a house with height approximately 11 meter at location (latitude 53.76511, longitude -0.34722). Using MATLAB software for analysis, each frequency was monitored individually to study the capability of using the RTL-SDR to measure a frequency domain of more than 3.2 MHz extent automatically.

Figure 4-2: USB DVB-T RTL-SDR TV DAB FM Realtek RTL2832U R820T Tuner.

Various centre frequencies have been tested to monitor the characteristics of an RF signal when detected in the RTL-SDR used as a spectrum analyser. From the figure below, it can be seen that the noise floor is at approximately -45 dBm on a sunny day, with a centre frequency of 726 MHz and frequency bandwidth 3.2 MHz. It was noticed that each measurement frequency has same behaviour with different power, the noise floor is gradually decreased from the centre frequency up to 1 MHz in both sides and then decreases steeply down to approximately -90 dBm as illustrated in the Figure 4.3. Also the SDR-RTL does not have an input attenuator, which caused the high noise floor. The RTL-SDR receiver block was modelled in Simulink Matlab 14b. Its input is a radio signal source and it outputs a column vector signal of fixed length specified by the samples per frame parameter in the model.

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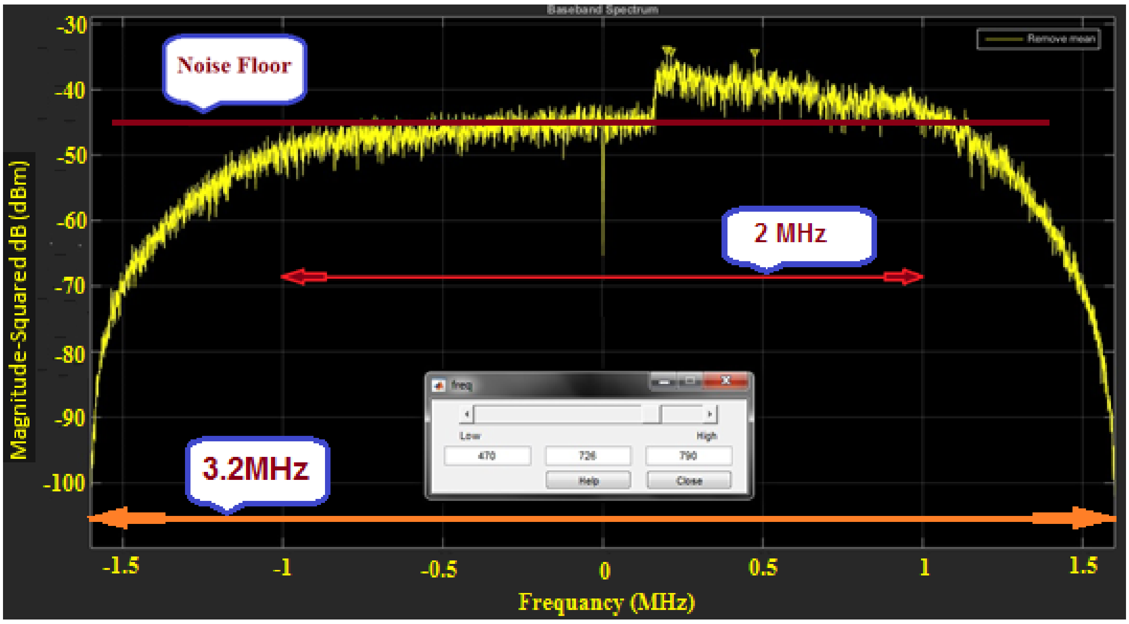

Figure 4-3: Measurement of Centre frequency 726MHz in sunny day bandwidth 3.2 MHz

Whereas, when the measurement was repeated on a day with light rain, at the same frequency, same location and using the same equipment, it was seen that the noise floor was increased by about 17 dB as shown in Figure 4.4. The signal power is approximately -19 dB and noise floor is ranging between -28 dB and -30 dB, the percentage of regression in both figures are slightly similar despite the difference in noise floor.

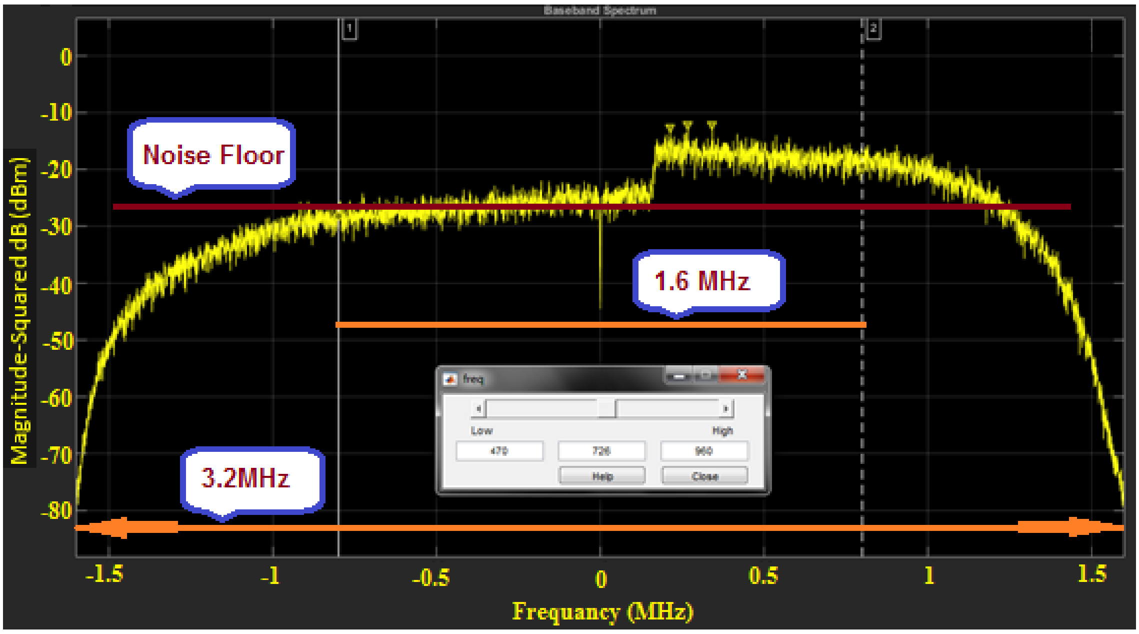

Figure 4-4: Measurement of centre frequency 726MHz in light raining day bandwidth 3.2 MHz

On the other hand, when changing the bandwidth of the measurement from 3.2 MHz to 2 MHz for testing, the percentage of the sloped signal and compared with Figure 4.4 , it was observed that the percentage of regression is increased, which caused distortion to the signal in both sides as illustrated in the Figure 4.5.

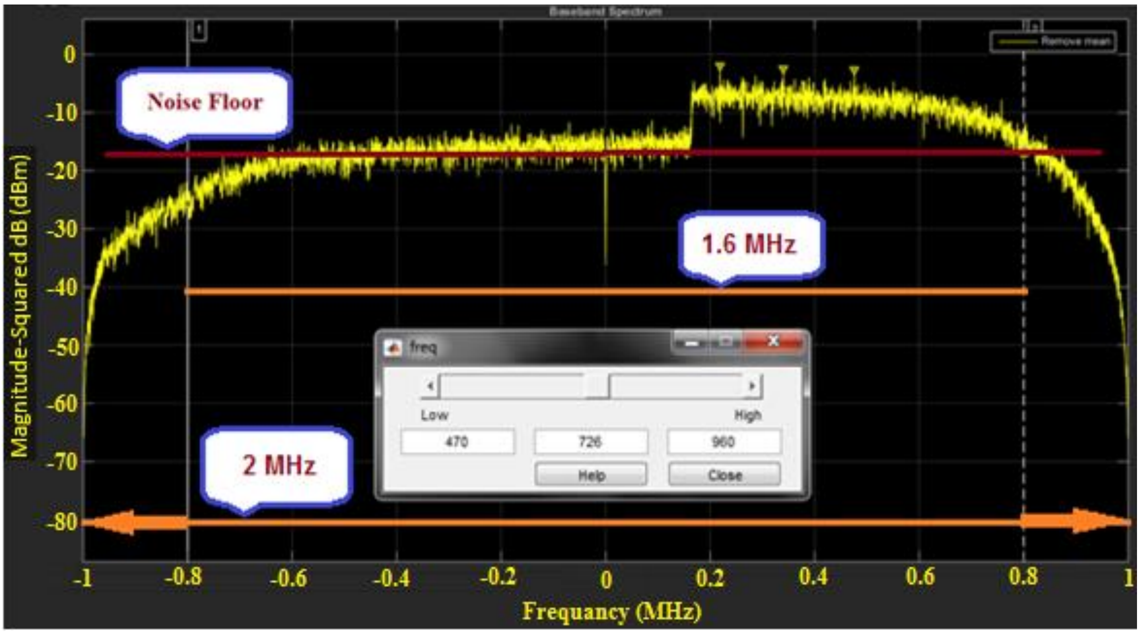

Figure 4-5: Measurement of centre frequency 726MHz in heavy raining day bandwidth 2 MHz

Therefore, it is preferred to measure the full bandwidth 3.2 MHz instead of just 2 MHz, which can then be used to select the appropriate bandwidth without any distortion of the signal and reduce the measurement time. In the event, it was decided to choose 2 MHz as the frequency step between each measurement, rather than the maximum of 3.2 MHz for reasons explained in the following section.

4.2.2 RTL-SDR Spectrum Analyser and using multiple Hops Techniques

The technique that has been created to measure and calculate TV received signal is illustrated in Figure 4.6 where each measurement bandwidth is 3.2 MHz, which the maximum bandwidth of the dongle RTL-SDR. However, it only selected 1 MHz from centre frequency in each side, and neglect 1.6 MHz from both sides in every hop.

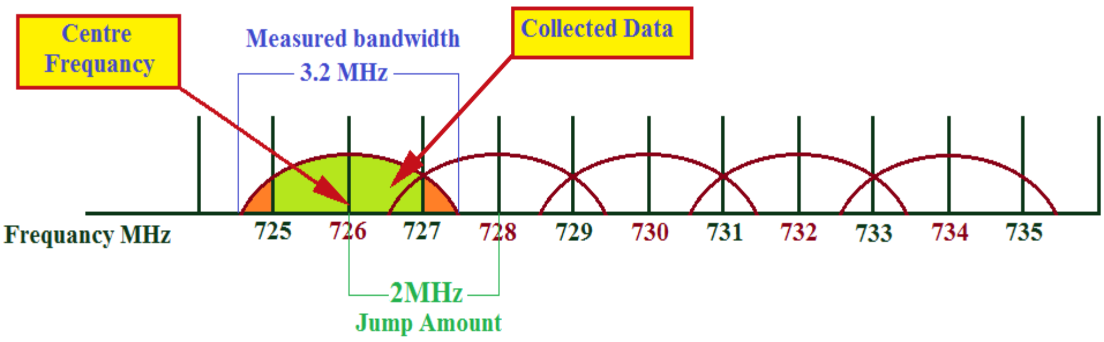

Figure 4-6: RTL-SDR Measurement Technique

A Simulink diagram for spectrum analysis with RTL-SDR is shown in figure 4.7. This has been used to analyse received TV signals and investigate measurement of the whole channel using the multiple hops technique.

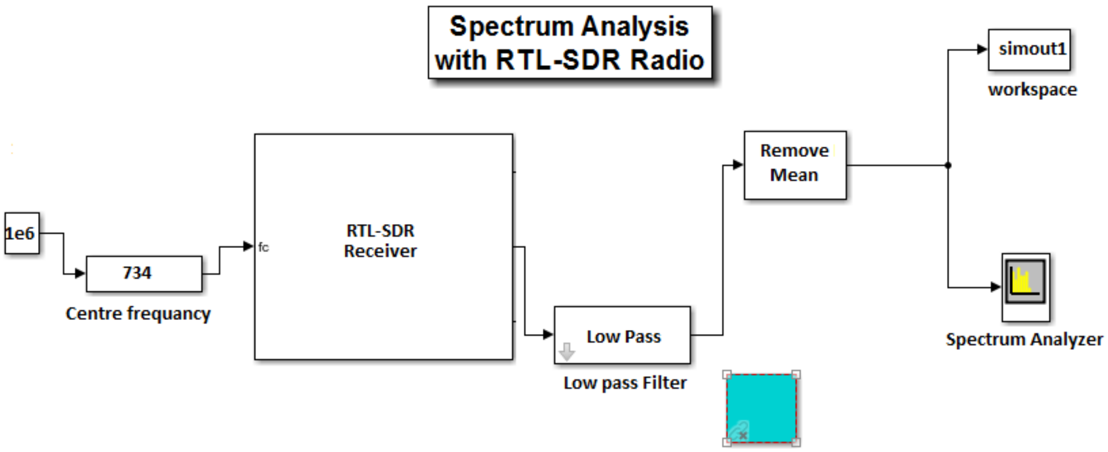

Figure 4-7: spectrum analysis with RTL-SDR radio Simulink diagram

It can be clearly seen from Figure 4.8, that to measure the whole of channel 53 requires four hops and combination of the data segments to contain the whole channel as shown in Figure 4.9.

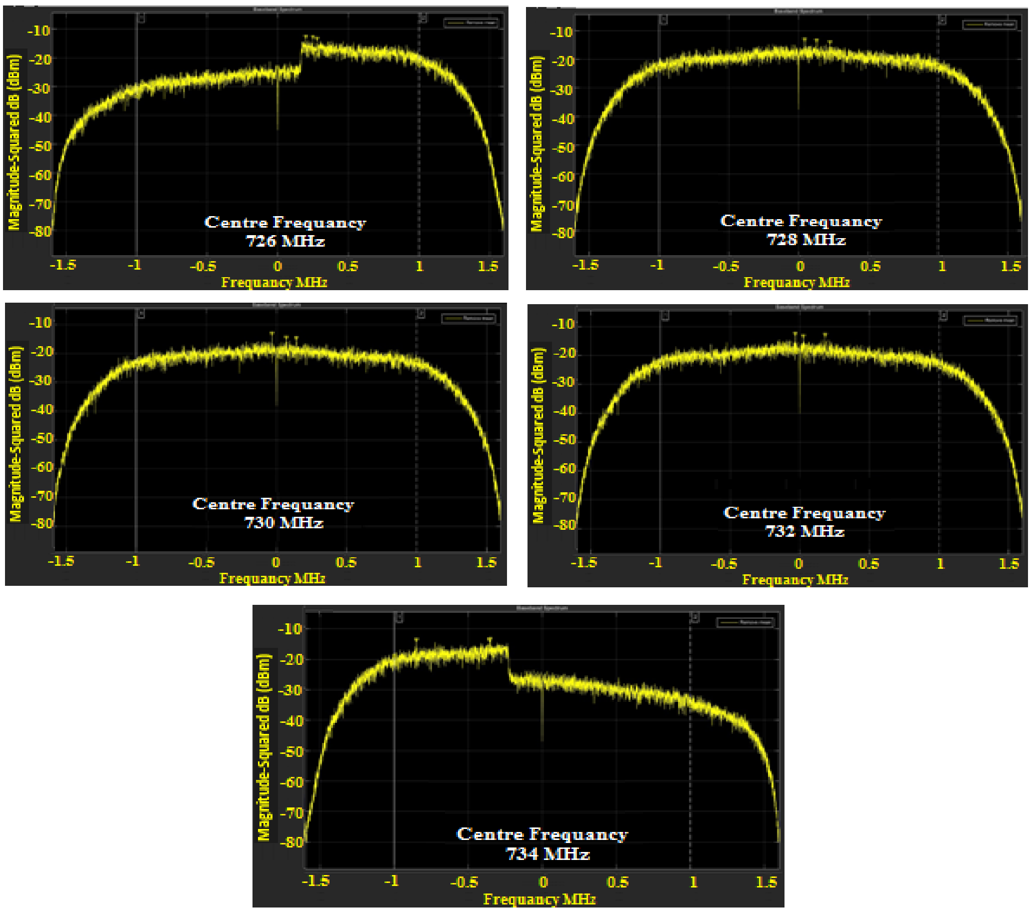

Figure 4-8: Channel 53 Measurement by using multiple hobs technique

The main reason to take only 2 MHz instead of 3.2 MHz the signal from both sides has sloped when measured every 3.2 MHz as illustrated in Figure 4.8, which causes in correct measurement data of the RTL-SDR device if taking into account whole measurement band (3.2MHz).

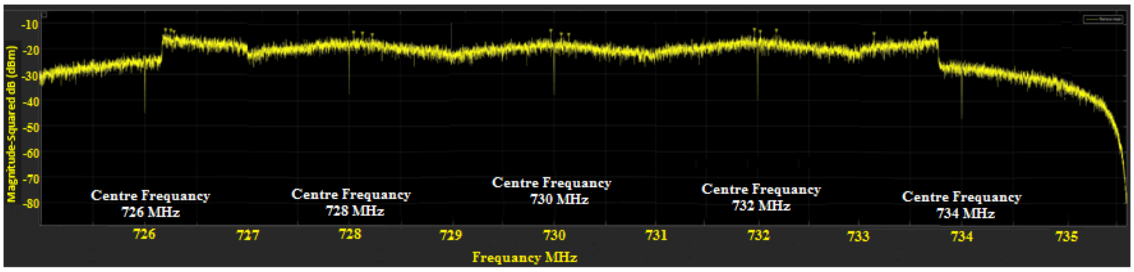

Figure 4-9: Channel 53 after combined the Measurement segments frequency range 726 MHz to 734 MHz

4.3 Geographical Location and Measurement Equipment

The measurements were taken at the top of the Applied Science building at the University of Hull, using various types of antennas as shown in Figure 4.9 which were positioned in direct LOS of all transmitter signals. Most of the channels received in the City of Hull emanate from Belmont and Emley Moor transmitters. The measurement location is roughly 50 Km away from the Belmont transmitter and Emley Moor is approximately 87 km away (Fanan et al., 2015).

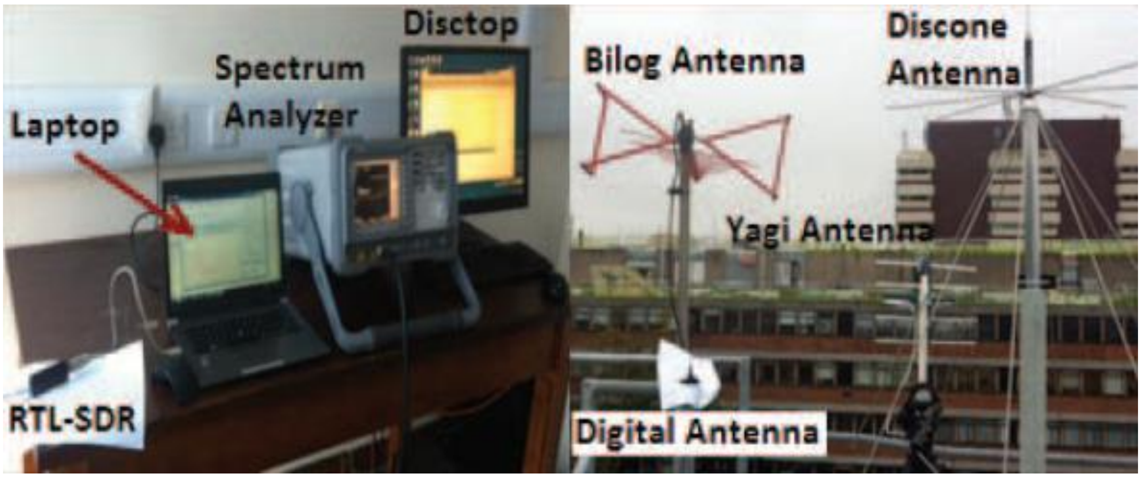

Figure 4-10: Measurement equipment in this paper: Antennas, spectrum analyser,

Also, the equipment employed in this study consisted of four separate antennas which were placed on the top of building: digital antenna, TV antenna, Discone Antenna and Bilog antenna, with characteristic which are listed in the Table 4.1. Each antenna can be fed to either of the two measurement systems: spectrum analyser or low cost software defined radio. The low cost software defined radio (full designation RTL-SDR DVB-T Tuner Receiver) has a frequency range 24MHz~1700MHz. Further information on the specification of the RTL SDR can be obtained from (Laufer, 2014). The validation of correct working of RTL-SDR was done by comparing the result of RTL with that from the spectrum analyser (Agilent E4407B). The received signals are loaded from the spectrum analyser via a general purpose interface bus (GPIB) connected to a laptop PC where the raw data were stored into Bin files. Data analysis was undertaken offline using Matlab 2014b to produce the occupancy results and then compared with RTL SDR occupancy results based on several criteria.

Table 4.1: Antennas Characteristic

Antenna Name	Frequency range	Antenna gain	Polarisation
Yagi	470-860 MHz	12 dBi	H
Digital	VHF 174-230MHz HUF 470-862MHz	3.5 dBi	V
Bilog	30MHz - 3GHz	6 dB	H
Discone	25MHz- 2GHz	2.2DBi	V

4.3.1 Measurement Setup

The main configuration parameters for the RTL-SDR and spectrum analyser are shown in Table 4.2. The measurements were switched between the two systems to receive the signal from various antennas. Because the RTL-SDR has bandwidth limited to a maximum of 3.2 MHz, the work illustrated in this chapter, intended to fulfil the need for measurements in the TV band range 470-862 MHz, has led to development of a measurement methodology and design of a measurement system model for the RTL-SDR to measure the whole TV bandwidth of 390 MHz. A graphical user interface (GUI) has been designed in Matlab 2014b software as shown in Figure 4.10. This system was designed to be more flexible with less complexity to measure a specific channel or any bandwidth within frequency range of the RTL-SDR.

The band is scanned sequentially in segments of 2.4 MHz, instead of using 3.2 MHz, to avoid lost samples by using a jumping technique. The number of segments used will impact on the overall scan delay.

Table 4.2: RTL-SDR and Spectrum Analyser Configurations

Parameters	Spectrum Analyser	RTL-SDR
Frequency range	470-862 MHz	470-862 MHz
RBW	10KHz	851.77Hz
Sweep points	401	512
Sweep time	Auto selected	Auto selected
Automatic gain control (AGC)	Off	Off

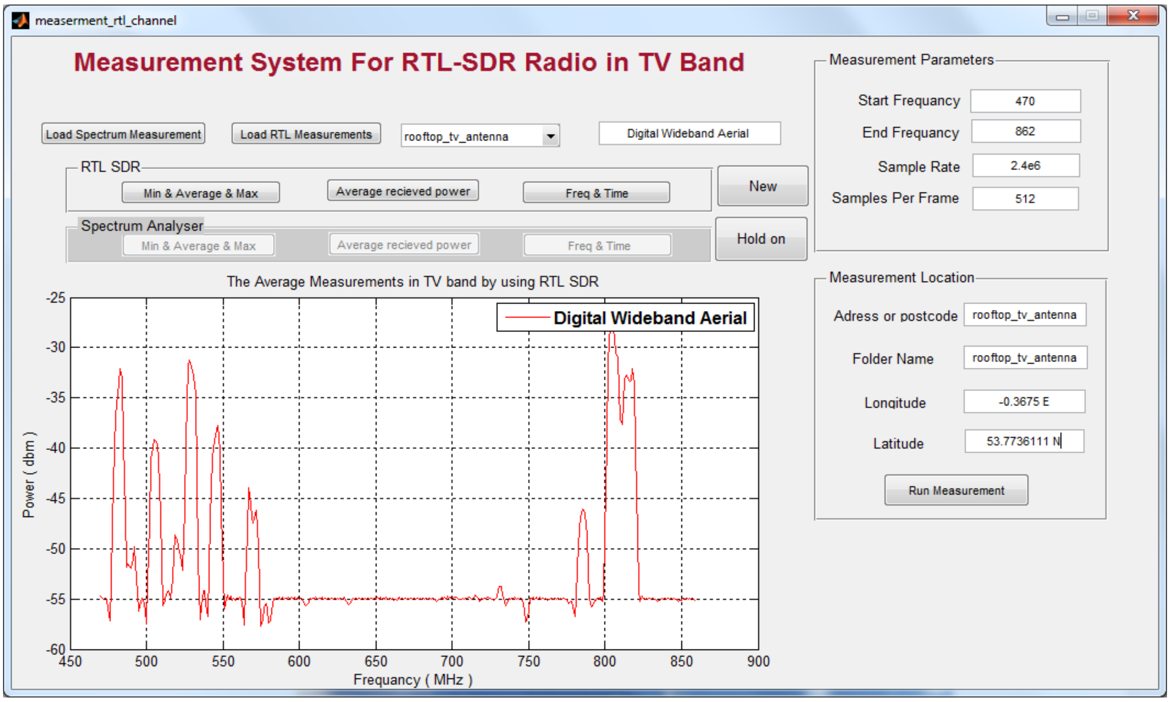

Figure 4-11: The GUI for the RTL-SDR System

RTL-SDR measurement methodology

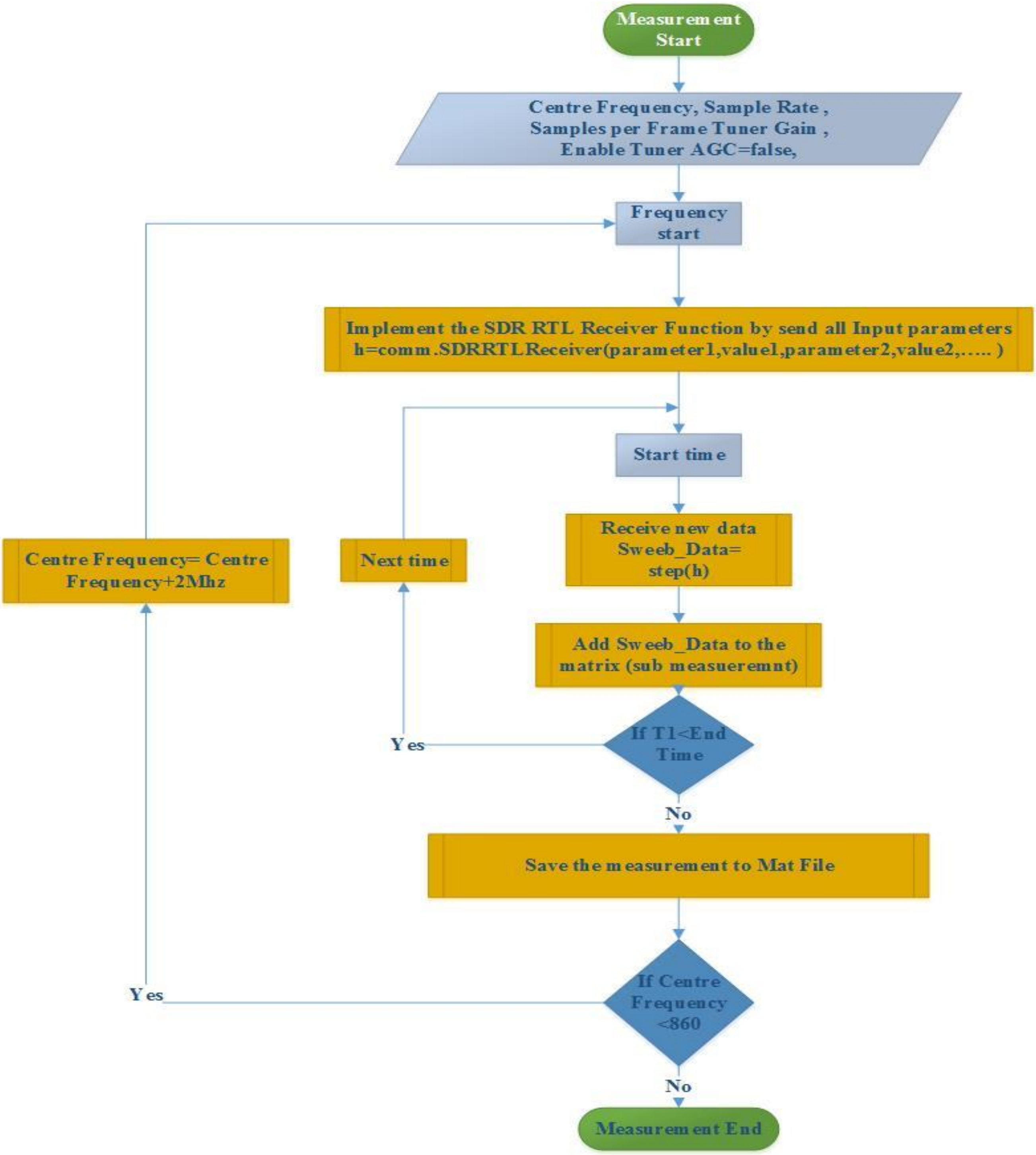

Figure 4-12: Signal calculation and Measurement methodology

4.3.2 Data Processing

The steps that have been taken to detect the spectrum occupancy include processing by using the computational package MATLAB 2014b, and may be divided into several areas: Data preparation, Adaptive Threshold Setting and Duty Cycle (DC) Averaging of TV band spectrum using different antennas.

- **Data Preparation:**

The data can be collected as received power from the two devices in the same structure of an [I x J] matrix in mat and bin files.

- **Adaptive Threshold Setting:**

The high cost spectrum analysis and inexpensive RTL-SDR have noise floors of -97 and -55 dBm respectively, which led to selection of different thresholds by selecting a fixed margin above the noise floor for each system. The ED technique is employed to detect the received signal whether below or above the threshold. The decision threshold as

Figure 4-13: Signal calculation and Measurement methodology

recommended by ITU is 10 dB above the average noise floor (Monitoring, 2011). On the other hand, some of studies used 3 to 6 dB above the noise floor as mentioned in (Chiang et al., 2007). It can be observed that, in the TV frequency range, the external noise floor varies around a common level. Therefore, a threshold 4db above the noise floor was selected for both systems.

- **Duty Cycle Averaging:**

Measurements that have been collected for the frequency range f_i over a period of time t_j can be represented by $P(f_{i,}t_j)$. The duty cycle can be expressed as a ratio or a percentage of time that a channel is occupied or as a measure of how often a signal is present during a period of time (Mehdawi et al., 2013). The duty cycle average is denoted by Df_i, whilst Nf_i denotes the overall number of samples at a frequency channel as shown in equation 4.1.

$$Df_i = \frac{\sum_{n=1}^{Nf_i} p(f_i, t_j)}{Nf_i} \tag{4.1}$$

The spectrum occupancy can be calculated for the overall spectrum band or for particular observed frequencies and can be determined by calculating the overall number of samples at time period t_j which is denoted Nt_j. Average duty cycle $D(f_i, t_j)$ can be calculated by using the following equation (Dzulkifli et al., 2011b):

$$D(f_i, t_j) = \frac{\sum_{n=1}^{Nf_i} p(f_i, t_j)}{Nf_i \ x \ Nt_j} \tag{4.2}$$

4.4 Analysis of Spectrum Occupancy Using RTL-SDR and Spectrum Analyser

Before moving to analysis of spectrum occupancy for each antenna, the first part of the measurement results are shown in Figure 4.13 and Figure 4.14. Each figure is composed of four different average received power versus frequency plots measured with the four antennas for the frequency range of the measurement study (470-862MHz). Based on the first impression and following the average spectrum allocations, the low portion of the band between 470 to 600 MHz has the nature of the high power broadcast channels in both figures. These channels are considered mostly allocated for broadcast communication and were easily detected by both devices whereas there appears to be less utilisation above 730 MHz. Comparing the two figures, the results using the spectrum analyser indicate that the average received power of broadcast channels by using TV antenna is similar compared with the Bilog antenna in both figures.

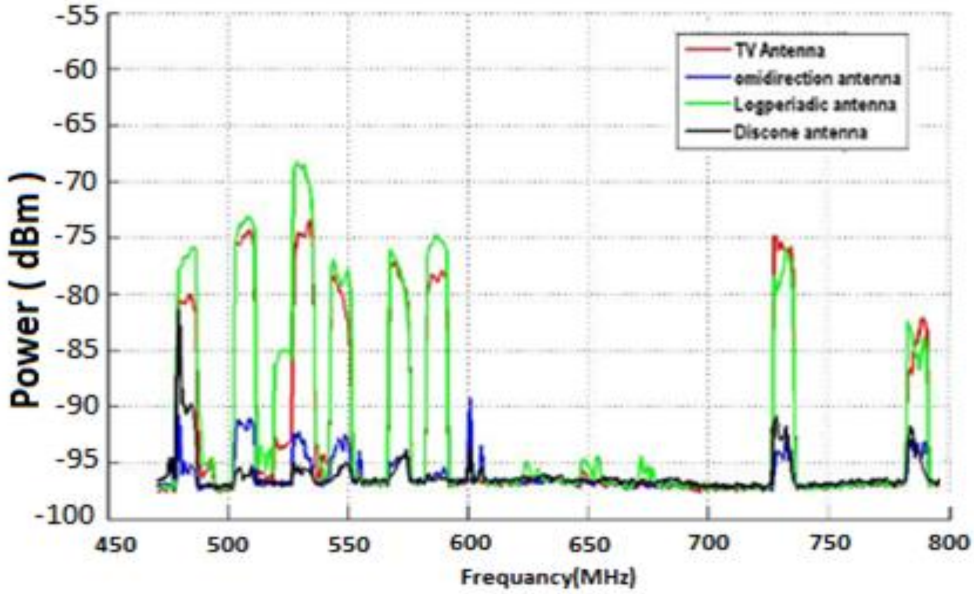

Figure 4-14: Average received power versus the frequency band 470-862 MHz by using RTL-SDR.

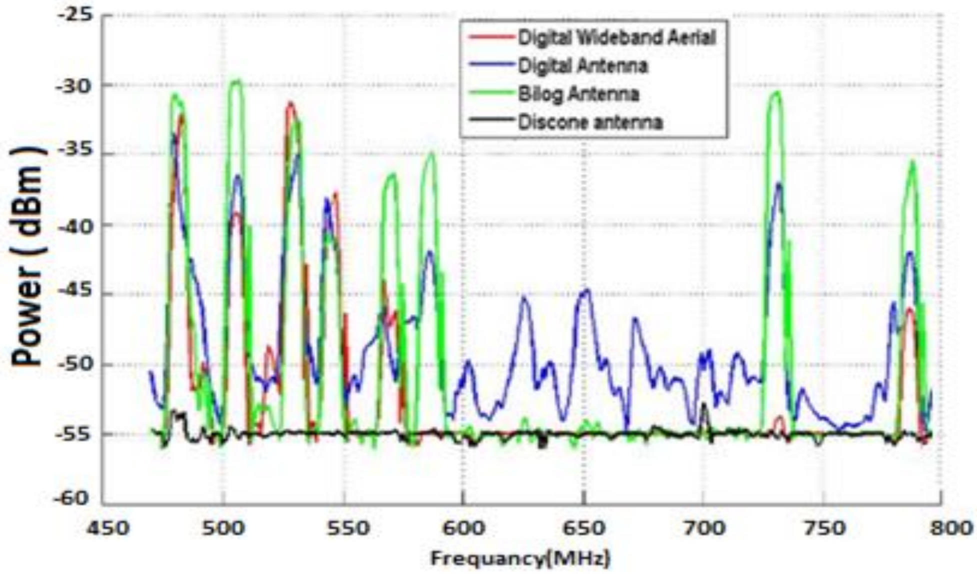

Figure 4-15: Average received power versus the frequency Band 470-862 MHz by using spectrum analyser.

However, the digital antenna exhibits weak signals and low utilisation in the 600-700 MHz region. On the other hand, use of the digital antenna along with the RTL-SDR indicated heavy utilisation in the UHF TV broadcasting band, which is mainly due to the location of the measurement site, which is mostly served by two broadcast transmitters, Belmont and Emley Moor. In contrast, the Discone antenna is considered the worst antenna among them and has very low utilisation and very weak signals. Although the overall measured data indicate that the spectrum occupancy derived by individual antennas in both receiver devices might exhibit large variations, they do not provide a clear picture of how spectrum utilisation is perceived by the low cost and high cost devices. Therefore, for a better view of the occupancy pattern, will consider selected antennas in further detail.

The measured duty cycle, calculated 4 dB above the noise floor in both devices. The threshold values of the spectrum analyser and the RTL-SDR are -96 and -51 respectively, as a function of frequency, which is indicative of the utilisation level perceived by each antenna will be discussed. The average duty cycles for the Bilog antenna when using the RTL-SDR and spectrum analyser is 25.89% and 26.18% respectively, as illustrated in Table 4.3.

Table 4.3: The Percentage of Duty Cycle Average in Different Antennas in RTL-SDR and Spectrum Analyser

Type of antenna	RTL-SDR Duty Cycle Average	Spectrum Analyser Duty Cycle Average	Difference
Digital Wideband Aerial	20.76%	24.43%	3.67%
Digital Antenna (DTA218)	60.25%	11.47%	48.78%
Bilog Antenna CBL 6143	25.89%	26.18%	0.29%
Discone antenna	5.64%	9.47%	3.83%

These results indicate that the percentage of the spectrum occupancy is fairly similar for the two systems, except when using the Digital Antenna. The difference between the RTL-SDR and spectrum analyser systems when using the Digital Wideband antenna is

3.67%, which is not much different from the value of the difference between devices when using the Discone antenna (3.83%). On the other hand, the percentage of Duty cycle average when was using the Digital antenna is very high in the RTL-SDR case and lower using the spectrum analyser. Measurements were conducted to investigate the impact of the tuner gain value on the receiver power. Here the CH53 has been selected which is situated within the bandwidth 720-740MHz. The effect of changing the tuner gain value from 0-50 dB on received power is shown in Figure 4.14.

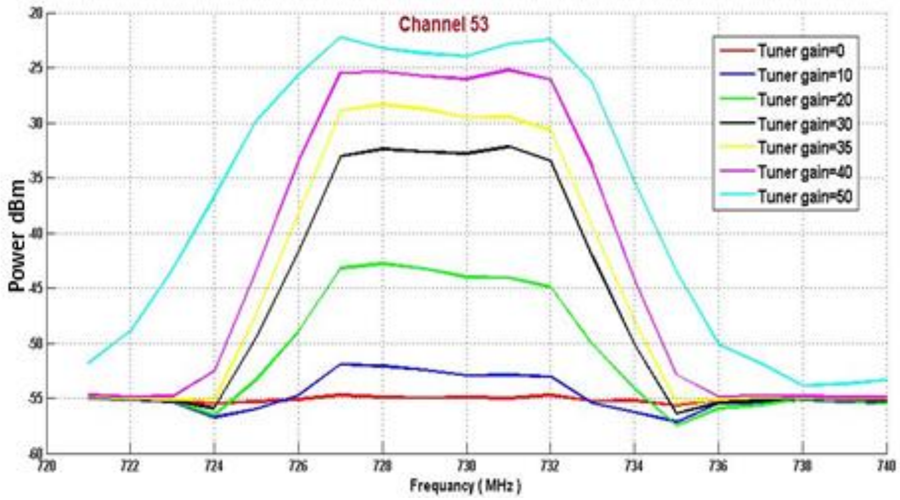

Figure 4-16: Average received power of channel 53 by different value of tuner gain

4.5 Conclusion

In conclusion, it has shown that is possible to use the RTL-SDR software defined radio dongle with minimum external hardware as an inexpensive spectrum monitoring device instead of a high cost spectrum analyser.(Sierra & Arroyave, 2015) This opens the door for the development of efficient collaborative cognitive radio systems, where many geographically-dispersed terminals need to sense the radio environment in a cost-effective manner.

Chapter5: Comparison of Propagation Models with a measurement campaign around Hull

5.1 Introduction

Propagation models are used widely in any network planning, which is beneficial for applying interference studies, specifically for conducting feasibility studies and network management before initial deployment proceeds. Although the TV signal strength propagates across space, it is decreasing due to many factors, such as receiver location, signal path loss that might be increased significantly between the transmitter and receiver due to the receiver position and also that there is often not a direct line of sight between Rx and Tx. Therefore, there are many reasons which might increase signal path loss, such as height and location of the receiver, base station height, diffraction, refraction, free-space loss, terrain contours, absorption and scattering of signal power by the earth's atmosphere and distances between Rx and Tx (Saptarshi Gupta, 2013). In ground communications, the direct path loss will be increased by the rough terrain which presents a multiple of propagation obstacles. For the simulations presented here, real terrain data for the appropriate area of Yorkshire have been obtained. Also, the deterministic model will use the geometric theory of diffraction (GTD) based on knife-edge diffractions for calculation of the path loss of diffracted fields based on a particular predetermined terrain profile that will contribute to improving propagation models for good prediction of TVWS (Jang, 1997). The main key to determining the protection area of TV transmitters relies on the accuracy of propagation models to predict the TVWS in different reception sites and under realistic terrain conditions, which vary widely from one region to another. The main aim is to investigate which of the propagation models has better performance, which could be selected for creating TVWS geolocation database as a primary source of detecting TVWS in the developing world by comparing model outputs with real measurements and studying their accuracy in predicting signal attenuation in different types of terrain environment.(Fratu et al., 2015; Lazaridis et al., 2014)

5.2 Propagation models

When carrying out planning of wireless communication systems and designing wireless networks, the accuracy of the prediction of propagation characteristics of each environment should be taken into account. One of the most significant parameters, which can be provided by propagation predictions is large-scale path loss, which can affected directly the coverage of a base station placement and its performance. However, using field measurements to obtain real-world propagation parameters without depending on propagation models, it is very time-consuming and costly. The following subsections provide a brief explanation of general empirical propagation models (Iskander & Yun, 2002). The models discussed are the Extended-Hata, Davidson- Hata , and Egli models.

5.2.1 Extended Hata Model

The Hata-Okumura model was presented by Yoshihisa Okumura in 1980 as an empirical formulation for propagation loss in Land Mobile Radio Services within limited regions less than 20 km and valid from 15 MHz to 1500 MHz. This model consists of a set of equations which use the curves derived by Okumura for obtaining its measurements and extrapolations. Hata presented three types of area propagation loss, urban, suburban and rural areas; the urban area is taken into account as a standard formula, but in other cases such as suburban and rural area, additional correction factors are required. The main advantage of this model is that the computation time is very short due to the few number of parameters are needed. The model does not take into account terrain condition between the transmitter and receiver such as mountains, hills, and other obstacles (Singh, 2012b). Due to the limited distances of this model which is less than 20 km, it has been taken into consideration that our measurements have been conducted in various locations within a particular region with distances up to 100 km. Therefore, the extension of the Hata Model has been used. This extension was developed by ITU-R, based on the Hata model to extend to longer distances from 20km up to 100km. The extended equations are given in the following (Fratu et al., 2015):

$$L(dB) = 69.55 + 26.16\log_{10} f_{MHz} - 13.82\log_{10} h_t - a(h_r)$$

$$+ (44.9 - 6.55\log_{10} h_t)(\log_{10} d_{Km})^b - K \quad \textbf{(5.1)}$$

Table 5.1: Correction factor of the receiver antenna height

Area	$a(h_r)$	K
Open	$(1.1\log_{10} f_{MHz} - 0.7)h_r$ $-(1.56\log_{10} f_{MHz} - 0.8)$	$4.78(\log_{10} f_{MHz})^2 -$ $18.33\log_{10} f_{MHz} + 40.94$
Sub urban		$2[\log_{10}(f_{MHz}/28)]^2 + 5.4$
Medium –small city		0
Large city $fMHz$>300	$3.2(\log_{10} 11.75h_r)^2 - 4.97$	0
Large city $fMHz$<300	$8.29(\log_{10} 1.54h_r)^2 - 1.10$	0

Where

$$\begin{cases} 1 & d_{km} < 20 \\ 1 + (0.14 + 0.000187 f_{MHz} + 0.00107 h'_t)(\frac{log_{10} d_{km}}{20}))^{0.8} & d_{km} \geq 20 \end{cases} \quad \textbf{(5.2)}$$

$$h_t' = \frac{h_t}{1+7\times10^{-6}h_t^{\,2}} \qquad \textbf{(5.3)}$$

Where h_t is base station antenna height (meter). f denotes the carrier frequency in the range 150 MHz to 1500 MHz. while hr is the height of receiver. The distance between transmitter and receiver is denoted as d. The correction factors a(hr) and K, which depend on the type of environment are listed in Table 5.1. The strength of this model is its ability to deal with long distances of up to 100 km and a frequency range of 150 MHz to 1500 MHz.

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5.2.2 Davidson Hata Model

The Davidson model was derived from Hata's formulas by adding several correction factors for extending the appropriate distance to 300 km. It was created by The Telecommunications Industry Association (TIA), described in their publication TSB-88A (Hata & Davidson, 1997) and includes some modification of the correction factors in the Hata model. It should also noted that Hata-Davidson has not taken into account some of the adjustment factors, such as the rough terrain and street orientation. The area type (Urban, Suburban, Quasi-open, Open) is one of the main factors which has been included in the Davidson model. The frequency range (from 30MHz-1500MHz) and the path range (20-2500 m) have also been extended in this model. The path loss equations of the Davidson model can be illustrated (Kasampalis et al., 2014) as follows:

$$PL_{Davidson}=PL_{Hata}+A(h_t,d_{km})-S_1(d_{km})-S_2(h_t,d_{km})-S_3(f_{MHz})-S_4(f_{MHz},d_{km}) \qquad \textbf{(5.4)}$$

Where

$$PL_{Hata}=69.55+26.16\ log_{10}\, f_{MHz}-13.82\ log_{10}h_t-a(h_r)+(44.9-6.55\ log_{10}h_t)log_{10}d_{km} \qquad \textbf{(5.5)}$$

$a(h_r)$ denotes a correction factor for receiver antenna height, show in Table 5.1 (as in the Okumura-Hata Model).

Table 5.2: Correction factors for extended distance

Distance d_{km}	$A(h_t, d_{km})$	$S_1(d_{km})$
$d_{km} < 20$	0	0
$20 \le d_{km} < 64.38$	$0.62137(d_{km} - 20)[0.5 + 0.15\log_{10}(h_t/121.92)]$	0
$64.38 \le d_{km} < 300$	$0.62137(d_{km} - 20)[0.5 + 0.15\log_{10}(h_t/121.92)]$	$0.174(d_{km} - 64.38)$

$$S_2(h_t, d_{km}) = 0.00784 \mid log_{10}\left(\frac{9.98}{d_{km}}\right) \mid (h_t - 300) \qquad d_t > 300m \qquad \textbf{(5.6)}$$

$$s_3(f_{MHz}) = (f_{MHz}/250)log_{10}\left(\frac{1500}{f_{MHz}}\right) \qquad \textbf{(5.7)}$$

$$s_4(f_{MHz}, d_{km}) = [0.112\, log_{10}\left(\frac{1500}{f_{MHz}}\right)](d_{km} - 64.38) \qquad d_{km} > 64.38km \qquad \textbf{(5.8)}$$

The factors which extended distance up to 300km are denoted by A and S_1 as shown in the previous Table 5.2 ; S_2 is a correction factor to extend the height of base station antenna to 2500m, while the factors S_3 and S_4 extend the frequency range to 30MHz-1500MHz.

5.2.3 Egli

This model was first introduced in 1957 by John Egli, it is considered as a terrain-based model and commonly was used for point to point links to predict propagation path loss in an urban or rural area. The frequency range was VHF and UHF, between 40MHz and 900MHz with linking distances less than 60Km. The diffraction losses have not been included, which would cause random propagation fluctuations as the Rx moves over irregular terrain. Thus, rough terrain environment has not been taken into consideration when designing the model, due to the variety of significant obstructions which might hinder the received signal. The equations for the Egli's propagation loss are illustrated below (Mauwa et al., 2015):

$$PL_{Egli} \begin{cases} 20\ log_{10}f_{MHz} + P_0 + 76.3 & h_2 < 10 \\ 20\ log_{10}f_{MHz} + p_0 + 83.9 & h_2 < 10 \end{cases} \quad \textbf{(5.9)}$$

$$p_0 = 40\ log_{10}\ d_{km} - 20\ log_{10}h_t - 10\ log_{10}h_r \quad \textbf{(5.10)}$$

Where h_t is the height of transmitter antenna (m), h_r is the height of receiver antenna (m), the distance between transmitter and receiver is represented by d in km, while the frequency transmission is denoted as f_{MHz}.

5.3 Field Measurement and Data Collection:

The main aim of conducting the measurements is to identify signal strength behaviour in different receiving locations, at various distances from the transmitter.

5.3.1 Measurement Geographical Location

The measurements have been taken within 50 km² in 23 various locations were distributed randomly around Hull city as illustrated in Figure 5.1. Hull is a medium sized city characterized by fairly smooth terrain. Outside of the metropolis, routes are covered with moderate vegetation and there are some hills present. The Belmont TV Transmitter is located on the other side of the Humber Bridge nearby. Measurement locations have been positioned in different places randomly , for identifying the impact on the reception of the signal and assessment of the amount of path loss, compared with other sites that are cited as having direct line-of-site from transmitters and taking into account all transmitters signals. Most of the channels in the City of Hull can be received from Belmont and Emley Moor transmitters; the measurement locations have a different distance from both transmitters as shown in Table 5.3 below.

Table 5.3: Data Measurement Locations around Hull

Data Record	Post code	Latitude	Longitude	Belmont Transmitter	Emley Moor Transmitter
1	LN8 6GY	53.349776 N	-0.182547 E	1.7km	102.7Km
2	LN8 6JA	53.4172222 N	-0.2386111 E	10.1km	97.1km
3	LN7 6SP	53.4741667 N	-0.2961111 E	17.5km	92.1km
4	DN37 8JU	53.5508333 N	-0.2841667 E	25.2km	91.7km
5	DN39 6YH	53.5844444 N	-0.3494444 E	30.1km	87.2km
6	DN20 0PA	53.584146°N	-0.421635°E	32.3km	82.4km
7	DN18 6EH	53.623660 N	-0.430293 E	36.4km	81.7km
8	DN16 3WE	53.5447667	-0.6434167	39.1km	68.1km
9	DN18 5FG	53.68002 N	-0.46068 E	42.9km	80.1km
10	HU13 0HB	53.714768 N	-0.4434872 E	45.9km	81.6 km
11	HU2 8JY	53.7466667°N	-0.3505556°E	47.3km	88.2km
12	HU3 6JR	53.7483333°N	-0.3747222°E	47.9km	86.6km
13	HU5 1AG	53.76503°N	-0.34697 °E	49.2km	88.8km
14	HU6 7RU	53.7716667°N	-0.3716667°E	50.3km	87.3km
15	HU6 7TS	53.7736111°N	-0.3675°E	50.5km	87.6km
16	HU15 1PW	53.73075°N	-0.55015°E	50.6km	74.9km
17	DN17 4BZ	53.5706167°N	-0.8293167°E	50.9km	55.6km
18	HU6 9BP	53.7869444°N	-0.3644444°E	51.8km	88.2km
19	HU6 9DT	53.7883333°N	-0.3858333°E	52.4km	86.8km
20	HU15 2RA	53.7706167°N	-0.6928333°E	59.5km	66.7km
21	DN7 6HQ	53.5911167°N	-0.9664167°E	59.9km	46.3km
22	DN14 7UW	53.7355167°N	-0.8641°E	63.9km	54.7km
23	DN14 8SR	53.6721°N	-0.9645167°E	64.6km	46.9km

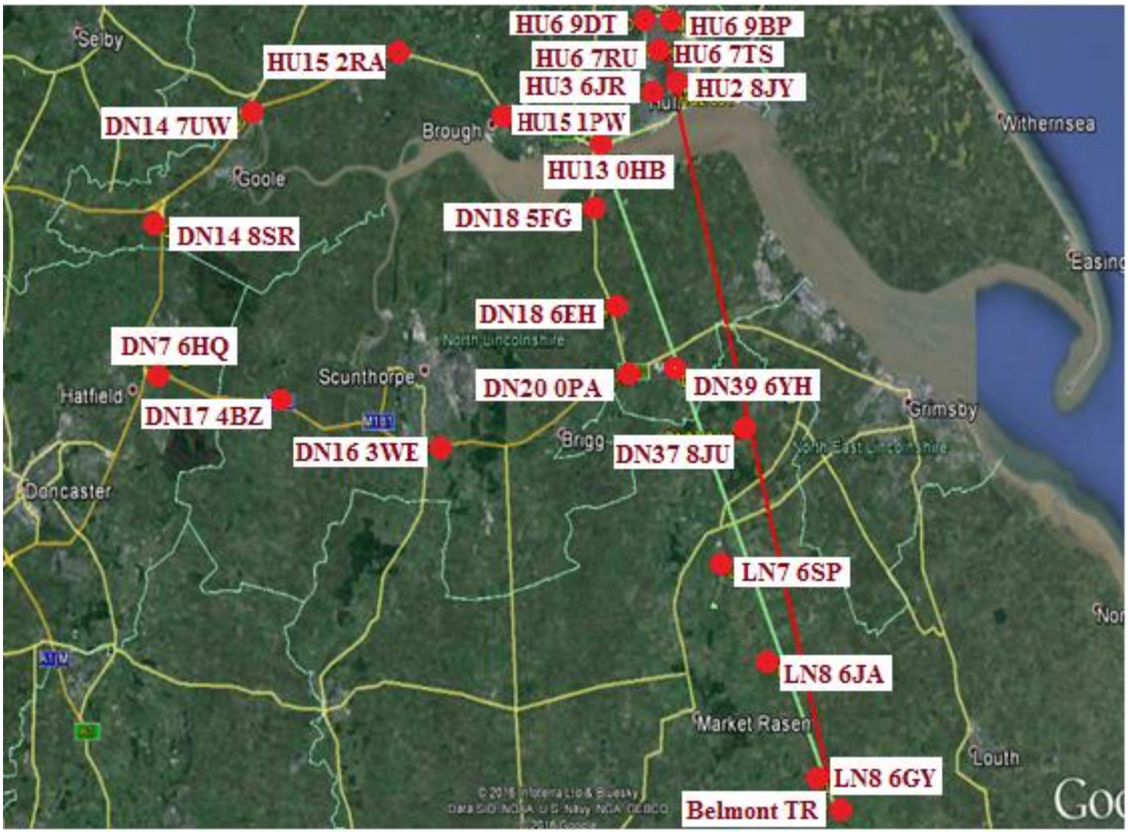

Figure 5-1: Measured Sites in Hull and suburban

5.4 Measurement Installation

The equipment employed in this study consisted of the Yagi TV antenna (RX20A/B/T) which at each measurement location was placed on the top of our car at a height of 1.5 m, having a frequency range 470-862 MHz, Gain High/ 12.5dBi, and with directional antenna pattern as shown in Figure 5.2. The received signal is fed to the spectrum analyser and read as received power. A mobile GPS application is used for identifying the measurement locations. The spectrum analyser is an Agilent E4407B, with Frequency Range 9 kHz - 26.5GHz, with -167 dBm of display average noise level (DANL). The received signal can be collected from the spectrum analyser via a General Purpose Interface Bus (GPIB) connection with a laptop, where the raw data was stored into Bin files. Data analysis was processed offline using MATLAB 2014b to produce the occupancy results and then path loss is extracted for each channel, on the assumption that the signal was transmitted by Belmont or Emley Moor transmitters only.

5.5 PERFORMANCE ANALYSIS

5.5.1 Base station parameters

The path loss was calculated taking into account the same characteristics as used in the measurements for the simulation program. These charcteristics include transmitter information as shown in Table 5.4 and receiver information as shown inTable 5.5. The measurement locations were as indicated in Table 5.3. MATLAB 14b was used for creating separating functions to calculate different propagation models (free space, Okumura-Hata, Davidson, Egli) for the 23 measurement locations around the City of Hull.

Figure 5-2: Measurement Installation

Table 5.4: Transmitters characteristics

No	Parameters	Belmont	Emley moor
1	Transmitter power	150Kw	174Kw
2	Transmitter Height	351m	329m
3	Longitude	-0.1720	-1.666
4	Latitude	53.3350	53.611
5	Cable loss	1dB	2dB
6	Frequency	530MHz	578MHz

Table 5.5: Received antenna characteristics

No	Parameters	value
1	Receive antenna height	1.5m
2	Receive location	As show in Table 1
5	Receive antenna gain	3.5dBi

5.5.2 Propagation path loss analyses

The main criterion for model assessment is path loss. A simulation program was implemented in Matlab, using channel 33 to conduct the comparison between the three propagation models and the measured results. In order to compare the real measurements with different propagation models, the path loss should be extracted from the real measurements by using the following equation in each location (Prajesh & Singh, 2012):

$$PL = TX + TX_{Gain} + RR_{Gain} - RP \quad \textbf{(5.11)}$$

Where TX denotes the transmitted power, transmitting antenna gain is represented as TX_{gain}, PL is the path loss, receiving antenna gain is denoted as PR_{gain} and RP is the received power, dBm (Silva et al., 2013).

To evaluate the propagation models against real measurements, several equations might be used to identify the most accurate propagation model. The error between predicted and measured path loss values was calculated by equation (5.12) and mean square error (MSE) calculated by equation (5.13).

$$E_i = M_i - \Pr_i \qquad \textbf{(5.12)}$$

$$MSE = \frac{\sum_{i=1}^{n} (E_i)^2}{N} \qquad \textbf{(5.13)}$$

in which E_i denotes the difference between the predicted model path losses Pr_i and real measured path loss M_i derived from measured received power in each location. Equations 5.12 and 5.13 are then used to calculate the standard deviation (SD), equation (5.14), whilst root mean square error (RMSE) is calculated by equation (5.15), which also depends on MSE as calculated in equation (5.12). (Prajesh & Singh, 2012)

$$SD = \sqrt{\frac{\sum_{i=1}^{n} (E_i)^2}{N-1}} \qquad \textbf{(5.14)}$$

$$RMSE = \sqrt{\frac{1}{N}\sum_{i=1}^{n} (E_i)^2} \qquad \textbf{(5.15)}$$

5.5.3 Diffraction model base on terrain profile Database

One of the very common phenomena that exemplify, the wave property of Electromagnetic (EM) waves is known as diffraction, which is the bending of EM waves around obstacles. Diffraction is considered as a significant non-line of sight (NLOS) propagation mechanism, which can occur when barriers exist that block the line-of-sight path such as mountains, hills or the curved earth's surface on longer paths. Diffraction can also occur around man-made obstacles such as buildings. Diffraction is a significant cause of signal weakness at the reception site, due to the presence of some of the aforementioned barriers between the transmitter and receiver. There are two types of diffraction, "shadow diffraction", which mean the received signal is blocked by obstacles and the received field strength will be decreased when the reception site goes forward into a shadowed area. The second type of diffraction occurs if the impediment is underneath the LOS, causing diffraction called "lit diffraction," which, commonly causes multi-path interference. However, shadow diffraction is the main reason for increasing the path-loss. One of the common diffraction models is single knife edge, which can be explained by Huygens's Principle, which states that when the electromagnetic wave is obstructed by natural or man-made obstruction, the obstruction acts as a secondary source for creating a new wave-front which then propagates into geometric shadow region of the obstruction (Jang, 1997).

5.5.3.1 Terrain Profile Data

The US Defence Mapping Agency (DMA) has developed Digital Terrain Elevation Data (DTED) as a uniform matrix and distribution method for terrain elevation values. The name of DMA has been changed to National Imagery and Mapping Agency (NIMA) and recently it is called the National Geospatial-Intelligence Agency (NGA). DTED can be obtained at six different levels of height resolution, of which the first three levels are available for public access, and the rest of them are not available. The characteristics of each level are shown in Table 5.6 (John Pike,).

Table 5.6: Digital Terrain Elevation Data Resolutions levels.

DTED Level	Post Spacing	Ground Dist	Row x Column	Tile size	Av
0	30 sec	~ 1 km	121 x 121	1 x 1 degree	Yes
1	3.0 sec	~ 100 meter	1200 x 1200	1 x 1 degree	Yes
2	1.0 sec	~ 30 meter	3600 x 3600	1 x 1 degree	Yes
3	0.333 sec	~ 10 meter	900 x 900	5 x 5 minute	No
4	0.111 sec	~ 3 meter	540 x 540	1 x 1 minute	No
5	0.0370 sec	~ 1 meter	810 x 810	30 x 30 second	No

The level 0 elevation is available online in a different format to the public. Various nations have contributed to provide online elevation data including the United Kingdom, Denmark, France, Germany, Netherlands, Norway Italy, and Spain. The DTED0 is considered as general modelling level, widely used for many applications whether scientific or technical that need terrain information like elevation, slope and surface type but do not required a high resolution. This level is not used for some applications related to the safety of public like automated flight guidance, which required a high-resolution terrain model. DTED1 is regarded as the basic medium resolution terrain elevation data. It has been used for most of the military activities and applications that required this kind of resolution, which can post spacing each 3 arc second, equivalent to about 100 meters along the Earth's surface. The highest-resolution topographic data was created in 2000 by NASA's Shuttle Radar Topography Mission (SRTM). Since that year, it was not available for public although the White House announced on 23rd of September 2014 that highest resolution of terrain data would be launched globally at the end of 2015. Since that date, SRTM data have become available at level 2 with 1 arc sec resolution, approximately 30 meters, by using the USGS web application (SRTM, 2017).

Currently, demand for the higher resolution of digital elevation data has increased, which encouraged NIMA to develop a new strategy embracing more accuracy and has evaluated and tested by a specific technique, which can meet the customers' demand of DTED with better understanding of their particular requirements. The information of the level 3 and above is not available to the public. Thus the high and very high-resolution elevation data are available for all military activities only.

In view of the potentially huge amount of terrain data, one of the main challenges is to identify the suitable terrain data resolution that will be used for the radio communication simulation for VHF and UHF. The main aspect here is that it is not possible to use level 2, level 3 or level 4 or datasets including the entire world. Terrain data must be associated with the size of the selected operational area and the appropriate data extracted from the terrain profile as a matrix. Therefore, as consider of the terrain data resolution, the terrain variation over lower grid post space such as 3 meter or tenth meter are not much different compared with least resolution, such as elevation data at 30 meters or 100 meters post spacing, which considered the highest resolution can be used for radio propagation. In our work, it uses level 0 and level 1 of DTED by several steps. Firstly, it has determined the study region by identifying four coordinates as shown in Figure 5.3.

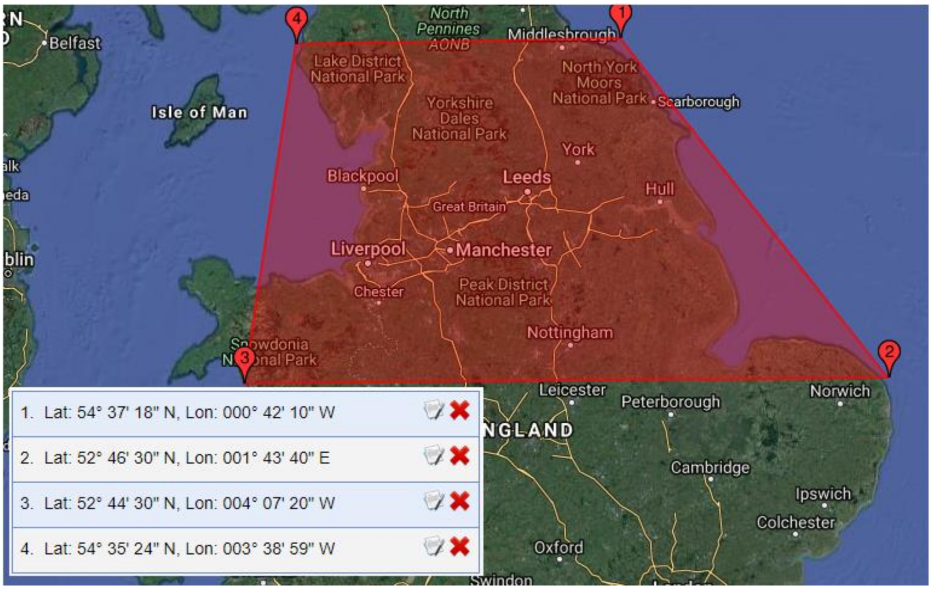

Figure 5-3: Region Selected of Terrain data

Using the resolution 30 arc second (level 0), it has downloaded all relevant files of DTED extension of the selected area, which are widely available online.

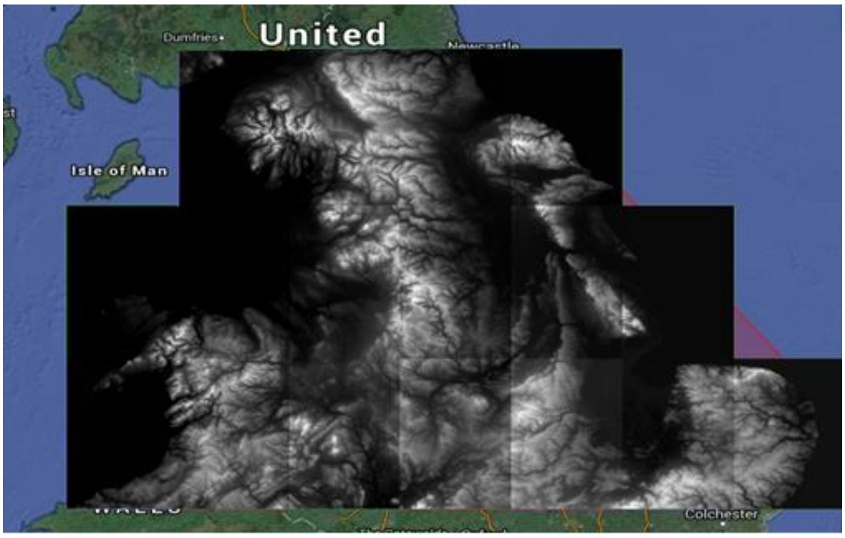

Figure 5-4: Research Region of Terrain Elevation Data by NASA's Shuttle Radar Topography Mission (SRTM) with Resolution 1 arc second (30 Meter)

Other resolutions that have been considered are (1 arc second approximately 30 meter and 3 arc second approximately 100 meter), for getting elevation data of this resolution, the USGS web application has been used for identifying research region, terrain tiles, and then downloading all relative DTED2 files, Figure 5.4 has classified all tiles.

The USGS WEB application "http://earthexplorer.usgs.gov/" has been used to download elevation data at various resolutions. Figure 5.5 illustrates the difference between two resolutions of 1 arc second and 30 arc second.

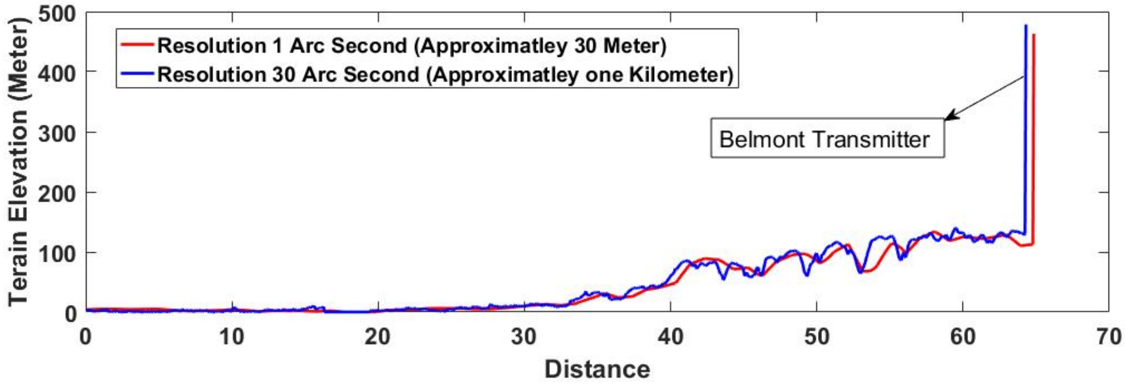

Figure 5-5: Terrain Elevation Data of path from university of Hull to Belmont Transmitter in different resolutions

The terrain resolution can use its effect on the diffraction calculation directly whether in terms positive or negative with more accuracy, such as, in the location of approximately 37km, the elevation data is about 85m when use 1 arc second resolution, while the 30 Arc second resolution estimated by 100 m. Also, some edges are not taken into account between receiver and transmitter compared with 1 arc second.

Figure 5-6: The path of Terrain Elevation Data from university of Hull to Belmont Transmitter

Furthermore, attempt to improve the previous results by investigating a third resolution value between 1 and 30 arc seconds to improve the compromise between accuracy and implementation time. Whilst calculating diffraction using the three different resolutions and investigating its effect on the received signal, it has noticed that in the location approximately 38 km along the path shown in Figure 5.7, in the 30 arc second resolution the elevation value is 100m, whilst when using 3 arc second and 1 arc second resolution, the elevation values are approximately 86 and 83 m respectively.

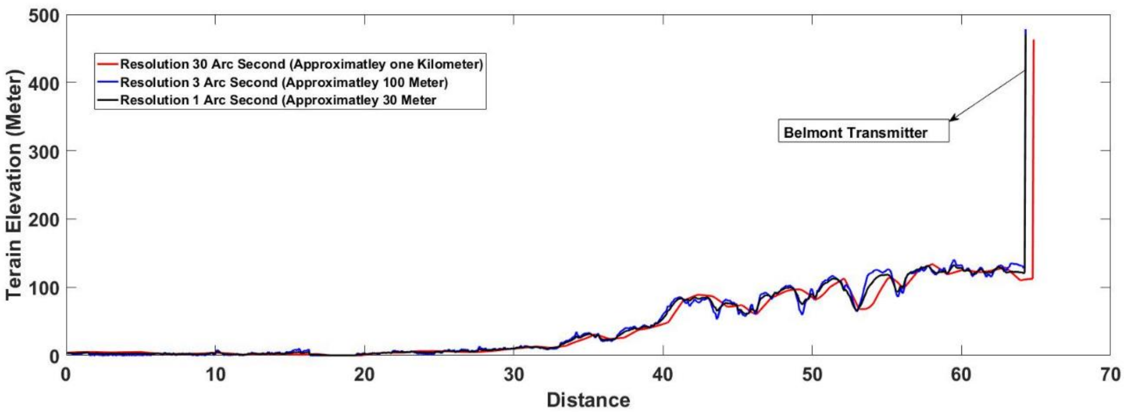

Figure 5-7: Terrain elevation data of the path from university of Hull to Belmont TV Transmitter in different resolutions.

Using 30 arc second resolution takes a short time for the implementation process but has less accuracy. When using 1 arc second, can get a good accuracy but a long time for the implementation process. However, using 3 arc second resolution produces the best results in terms of the compromise between accuracy and implementation time.

5.5.3.2 Diffraction model

Diffraction can be calculated by considering the single Knife Edge loss over the Earth as illustrated in Figure 5.8. Terrain profile database is used for calculating path elevation profile and identifying the highest point between transmitter and receiver by using the following equations (Mike Willis, May 5th, 2007).

$$h \approx h_n + \frac{d_{tn} d_{nr}}{2r_e} - \frac{h_t d_{nr} + h_r d_{tn}}{d_{tn} + d_{nr}} \tag{5.19}$$

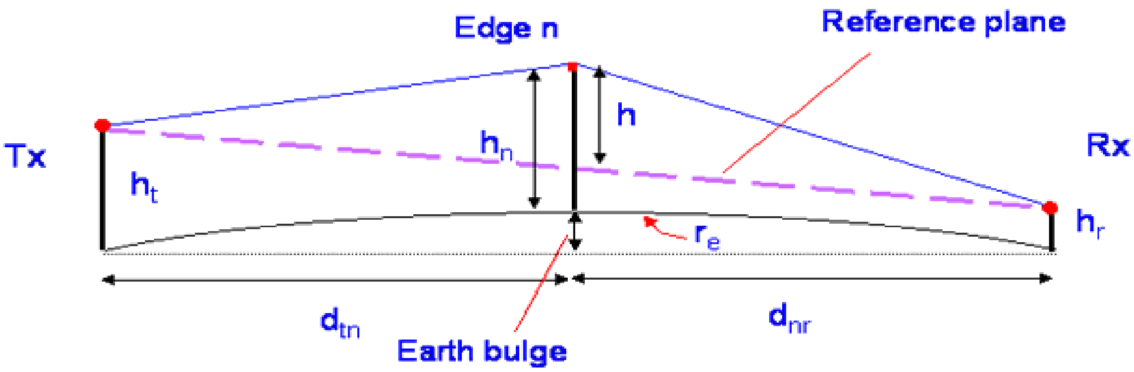

Figure 5-8: Path profile model for (single) knife edge diffraction.

If an obstacle of the single knife edge is situated above direct line-of-sight, with height h, d_{tn} is the T_x -obstacle separation, d_{nr} is the h_r -obstacle distances. define the following diffraction parameter v:

$$v = h\sqrt{\frac{2(d_{tn} + d_{nr})}{\lambda d_{tn} d_{nr}}} \tag{5.20}$$

The v parameters of diffraction can be used for calculating path loss by the following equation: (Mike Willis, May 5th, 2007)

$$\mathrm{Gd\ (dB)} = 20\, log\, \mathrm{F(v)} \quad \textbf{(5.21)}$$

$$Gd\ (dB) = 0 \qquad v <= -1 \quad \textbf{(5.22)}$$

$$Gd\ (dB) = 20 \log (\ 0.5 \text{ -}0.62) \qquad -1 \leq v \leq 0 \quad \textbf{(5.23)}$$

$$Gd\ (dB) = 20 \log(0.5 \exp(-0.95\ \mathrm{v})) \qquad 0 \leq v \leq 1 \quad \textbf{(5.24)}$$

$$Gd\ (dB) = 20 \log(0.4 - \mathrm{sqrt}\big(0.1184 - (0.38 - 0.1v^2)\big)) \qquad 1 \leq v \leq 2.4 \quad \textbf{(5.25)}$$

$$Gd\ (dB) = 20 \log(0.225/\mathrm{v}) \qquad v > 2.4 \quad \textbf{(5.26)}$$

5.6 Propagation models algorithm

The algorithm that was created depends on three variables: transmitter, receiver's location and transmitter's channels, which can be applying the changes, based on the information that is provided by data files, which have been stored in previously. Also, there are several functionality has implemented separately. The following algorithm explains the steps of the implementation in a sequential manner.

Constant Data: receiver height, receiver antenna gain

For selected transmitters do

Retrieve data: Transmitter gain, transmitter ERP, location (longitude, latitude)

For all receivers locations do

Calculate distance between TR and TX

Retrieve terrain path from terrain profile database

For all transmitter's channels

Retrieve channel's information : transmitter height, transmitter power, Frequency

Calculate different path loss (call Knife_Edge function)

Calculate path loss by Hata Extention model

Calculate path loss by Davidson model

Calculate path loss by Egli model

Calculate path loss by free space model

Calculate received power by using Hata Extension

End

End

Save calculated path and received power into database

End

Figure 5-9: Algorithm of Propagation models Calculation.

5.7 Diffraction path loss algorithm

This algorithm is considered as a part of the previous algorithm and is based on the single knife-edge model, which relies on a combination of parameters to calculate the diffraction path loss, as shown in Figure 5.10.

For selected transmitters do

Retrieve channel's information: receiver height (h2, transmitter_height(h1)

For all receivers location do

Retrieve terrain data: Obstacles height (hm) , distance from each obstacles to receiver and transmitter (d1,d2)).

For all transmitter's channels

Calculate the obstacles height above direct line of sight path between Transmitter and receiver

Calculate V parameter

Calculate diffraction path loss base on V parameter

End

End

End

Figure 5-10: Algorithm of Diffraction Calculation

5.8 Comparison and Results

The measurement study covered the area around the city of Hull, which was represented to measure the UHF TV band from 470 to 790 MHz with consideration of all radio and TV stations that feed the whole Hull area. Most of the channels transmitted into the area originate from the Belmont and Emley Moor transmitters. The results of comparison of predicted path loss with measurements for two cases (excluding and including terrain modelling) are presented by using the previously defined criteria average error, standard deviation and RMSE. Figure 5.11 shows an example of the results including path loss curves for each propagation model and a table of calculated parameters. This example is for the case with no terrain model.

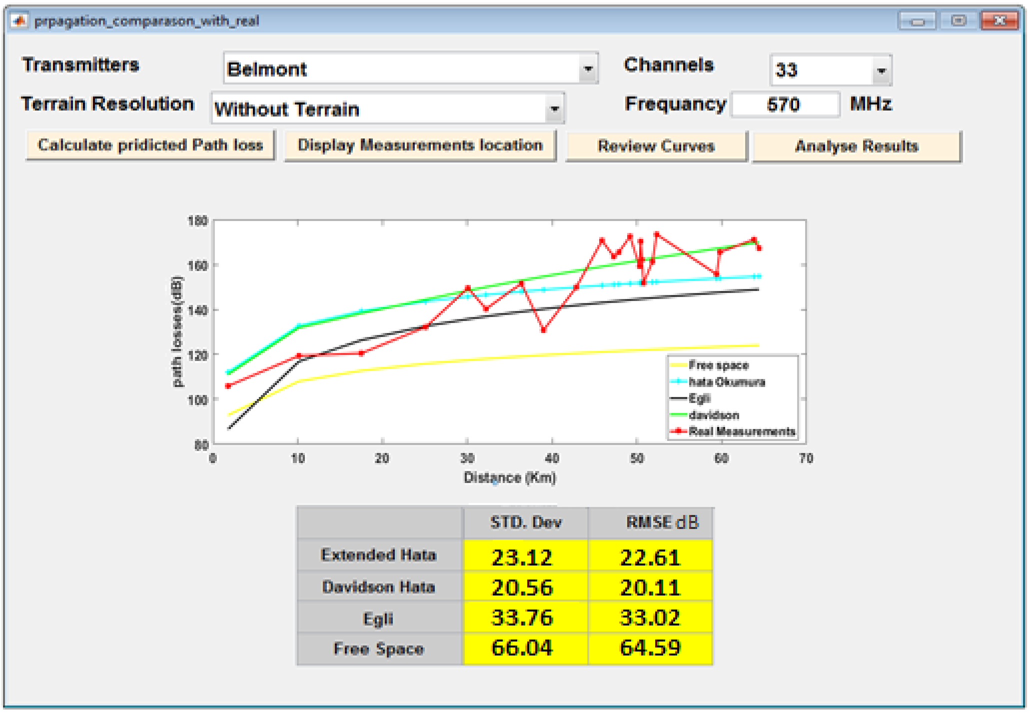

Figure 5-11: Example of propagation model comparison in the selected measurement locations

This analysis may be undertaken for all selected measurement points, by flexible selection of the transmitter name, terrain resolution and transmitted channel. Results corresponding to all measurement locations and comparison of the three propagation models with real measurements along with parameter analysis, are dicussed and classified in the following sections.

5.8.1 Comparison of Propagation Models without Terrain

The propagation modelling, excluding diffraction path loss factor are compared with measured data as shown in Figure 5.12. It is seen that the Davidson model provides the best comparison with measured data. The calculated parameters for this case are presented in Table 5.7. The Extended Hata model compares well with the Davidson model for distances less than approximately 35km, but at larger ranges path loss increases slightly less than in the value Davidson model. The Egli model produces results consistently 8-10 dB less than the Extended Hata results. The difference of the path loss between measurement and proposed models was increasing slightly until approximately 47 km with a difference ranging between 30 and 40 dB. After this distance, the difference was very variable between about 0 and 30 dB. It is therefore suggested that several factors should be included in the propagation modelling such as diffraction, Earth radius, reflection and clutter each of which can impact significantly on the behaviour of the propagation models.

Table 5.7 shows the error statistics for each propagation model results by using the evaluation criteria mentioned above. Davidson Hata gives the best result among other

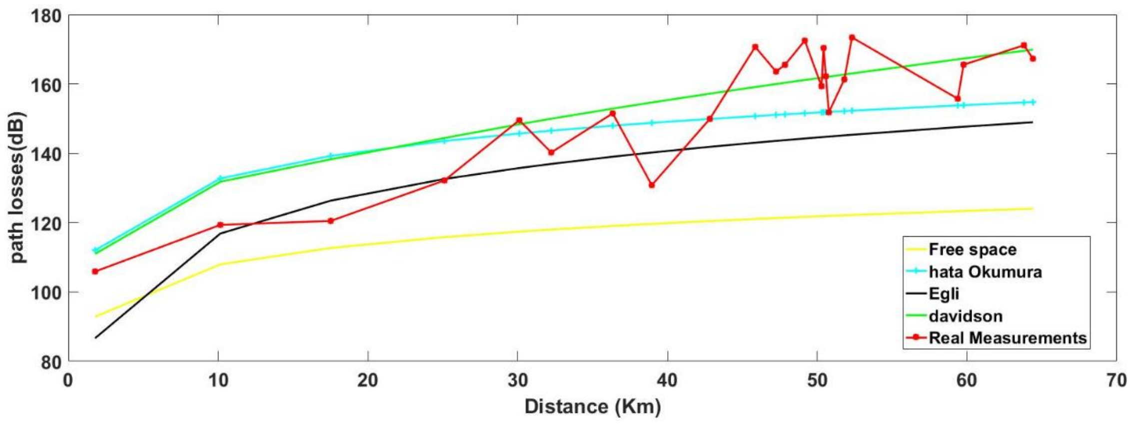

Figure 5-12: Propagation Models without Terrain

models with RMSE of 20.11 dB, which is however not considered as a good result, while the Extended Hata model gives slightly worse results with RMSE 22.61 dB. The main reason is likely to be that their equations were derived from the Hata Okumura model.

Table 5.7: Fitted propagation models without terrain at Hull-UK

Model	STD. Dev	RMSE
Extended Hata	23.12	22.61
Davidson Hata	**20.56**	**20.11**
Egli	33.76	33.02
Free Space	66.04	64.59

The worst performance was presented by the Egli and free space models with high values of RMSE. In summary the lowest value of RMSE is 20.11 dB, which is nevertheless not considered as a good enough result to be the basis of spectrum occupancy decision making. Thus, to improve RMSE results, it is necessary to include a terrain model when calculating the path loss in the propagation models.

5.8.2 Comparison of Propagation Models with Terrain Data Resolution 30 Arc Second

In this and following sections, terrain profile databases with various spatial resolutions and equivalent single knife edge diffraction have been used to calculate the diffraction factor and then evaluate their impact on the performance of the propagation models.

The results in Table 5.8 indicates that Egli model can be considered the best fit to the measured data with low error when applying the diffraction factor on the propagation models. It can be clearly seen in Figure 5.13 that the behaviour of path loss was influenced by diffraction, compared with the path loss derived from measured data.

Thus, the propagation behaviour has been affected in most measurement locations when applying the terrain variation with 30 arc second (1 km) resolution. The impact of the propagation model is obvious after the third measurement point, where the first three points might be situated within the line of sight or the 1 km resolution results might have missed terrain features situated along the path which might cause destructive or constructive diffraction. Thus, using 1 km resolution might not give accurate results.

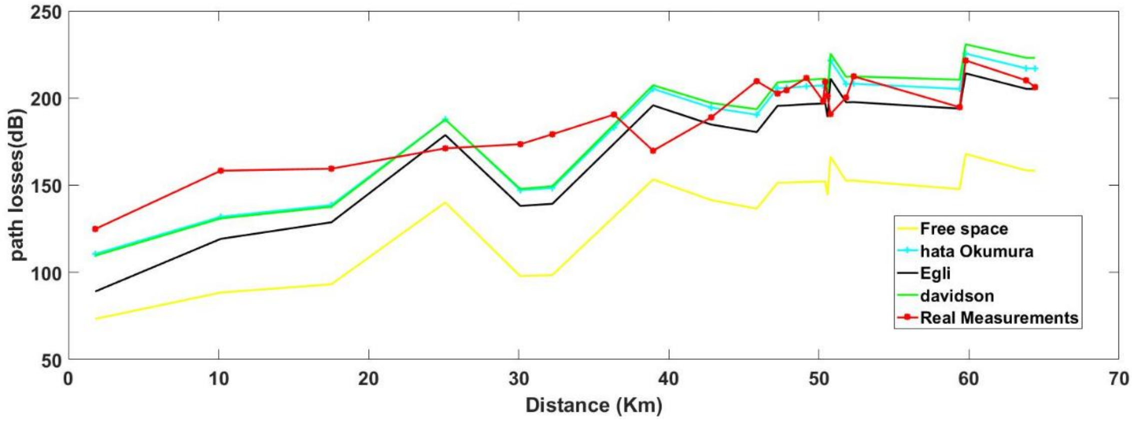

Figure 5-13: Propagation Models Including Diffraction by using Terrain Profile with Resolution 30 Arc Second (1 Km).

In the Table 5.8, it can be observe how the error statistics have been impacted by the diffraction factor and how the RMSE value are decreased in Egli and invreased in other propagation models. The results indicate that the Egli has the best results of the RMSE at 22.71 dB. On the other hand, the Egli model is seen to have less error compared with Davidson by about 2.6 dB.

Table 5.8: Fitted propagation models including Terrain 30 arc second aT Hull-UK

Model	STD. Dev	RMSE (dB)
Extended Hata	22.77	22.27
Davidson Hata	25.31	24.76
Egli	**22.71**	**22.19**
Free Space	51.66	50.53

5.8.3 Comparison of Propagation Models with Terrain Data Resolution 1 Arc Second (30 m).

Due to the nature of the terrain profile near the transmitter sites, which includes rough terrain and hills, the use of 1 arc second resolution (about 30 m) will clearly affect the propagation predictions, as illustrated in Figure 5.14. Here it may be seen clearly that there are large changes in the diffraction value at the distance of 48 km and that other locations such as the fifth location have less variation which might be placed in the line of sight of the transmitter.

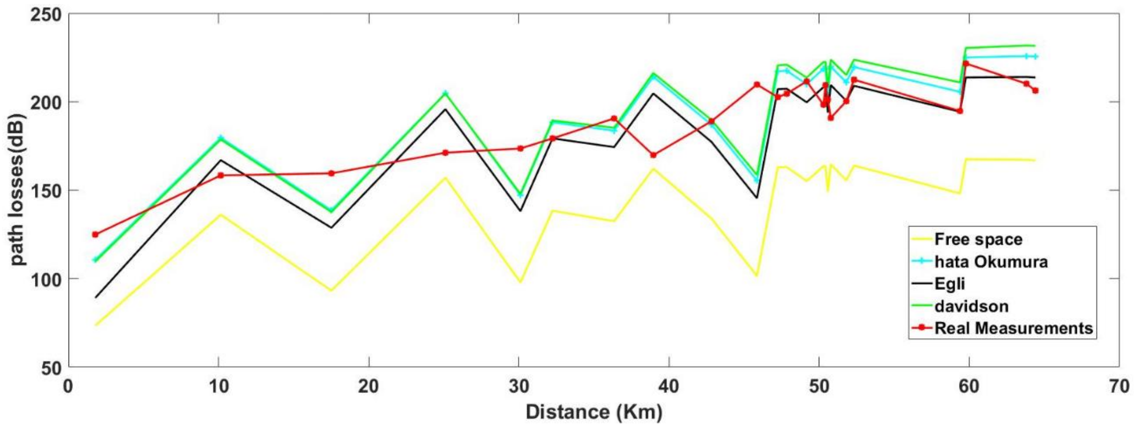

Figure 5-14: Propagation Models Included Diffraction by using Terrain Profile with Resolution 1 Arc Second

Therefore, it can be seen, when the resolution value of the terrain profile has increased, the error of the RMSE for the all models is decreased as observed by comparison of Tables 5.8 and 5.9.

Table 5.9: Fitted propagation models included Terrain 1 arc second AT Hull-UK

Model	STD. Dev	RMSE
Extended Hata	26.26	25.69
Davidson Hata	28.88	28.24
Egli	**24.01**	**23.48**
Free Space	46.27	45.25

According to the advantage and disadvantage of both previous results in terms of accuracy and time implementation, it can be observed that, 30 arc second has short time and less accuracy, while 1 arc second has high accuracy and long implementation time. Therefore, the author proposed extra results which can improve the implementation time whilst maintaining reasonable accuracy by utilising a compromise between 30 and 1 arc second resolution.

5.8.4 Comparison of Propagation Models with Terrain Data Resolution 3 Arc Second (100 m).

In the development work, it has been selected and download terrain data profile of 3 arc second, approximately 100 m resolution, which has less variation of the terrain data compared with 1 arc second, as shown in Figure 5.15.

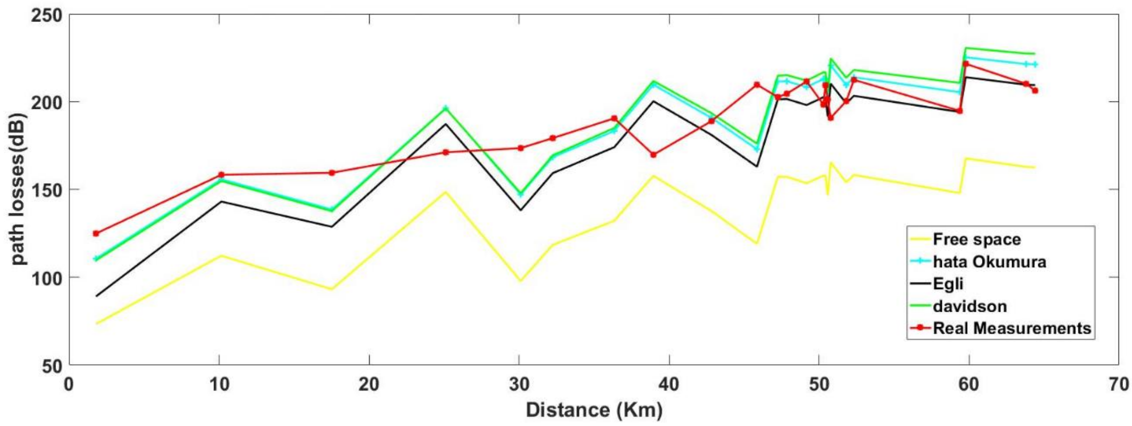

Figure 5-15: Propagation models included diffraction by using terrain profile with resolution 3 Arc second

It can be observed in statistics of Table 5.10 that the use of 3 arc seconds, whilst giving a clear improvement in the implementation time 1.005 sec, also impacts only slightly on the accuracy of the results compared with use of 1 arc second terrain data.

Table 5.10: Fitted propagation models included terrain 3 arc sec

Model	STD. Dev	RMSE
Extended Hata	23.07	22.56
Davidson Hata	25.80	25.23
Egli	**22.22**	**21.73**
Free Space	48.30	47.24

Hence, according to these results, it observes clear sequences of the RMSE values for all models based on the terrain resolution, where the RMSE of Egli model have slightly different (22.19, 21.73, 23.48) (30Arc, 3Arc, 1Arc) respectively and has the lowest error compared with other propagation models in all terrain resolutions as illustrated in Table 5.8, 5.9 and 5.10.

5.9 Conclusion

In this chapter, TV signal strengths are calculated using various propagation models and then compared with real measurements that have been conducted in various locations. Using a single knife edge model to calculate the diffraction factor with consideration of terrain profile data at different resolutions, investigate and prove how the terrain data resolution impacts the accuracy and implementation time of the propagation models. It has improved and extended the results that were published in our 2016 conference paper (Fanan et al., 2016). RMSE is the main criteria taken into account to assess the performance of the propagation models. The results summarized in Tables 5.8, 5.9 and 5.10 show that the Egli model still gives the best results when account is taken of the terrain profile data at a resolution of 3 arc second (100m), providing lower values of RMSE compared with other propagation models, with shorter computation time and similar accuracy compared with 1 arc second. The other models all display relatively poor performance in terms of RMSE when terrain data at any resolution is considered. It may be seem that, for the terrain examples considered (which are all relatively smooth paths) the terrain resolution of 30 arc seconds is at least as good as the higher resolutions and it is therefore concluded that, in view of the much shorter computation time, this resolution will provide useful input to create a system for the cognitive radio decision process. However, should more irregular terrain be considered, the 3 arc second resolution may provide a better compromise between accuracy and computational time. In the next chapter, will design a flexible system for creating a TVWS database for a specific area, by selecting the specific pixel size, adding appropriate transmitter information and choosing a suitable propagation model.

Chapter6: Implementation of combined geolocation database and infrastructure sensing in TV bands using different spectrum devices

6.1 Introduction

In the present day, the TV Band has become a realistic option and has attracted much attention due to the potential to exploit underutilised TV white space for other communications, based on time and location. In this chapter, design a flexible system which uses a combination of geolocation database and spectrum sensing in the TV band, comparing the performance of different spectrum Analysers (Agilent E4407B, Agilent EXA N9010A and a low cost RTL-SDR) in the real environment.

6.2 TV White Space and possible solutions for the rural broadband

The term white space originally referred to the underutilised frequency bands in the VHF and UHF that are traditionally allocated to terrestrial TV broadcast services, which deliberately left blank among analogue TV channels to avoid interference between them. In most area of the world, the white space is in the frequency range of 470-790 MHz and it varies widely in size and location from area to area and also from one country to another. In most countries, when they started to transition from analogue to digital TV broadcast, the White space term became more reminiscent of the nature of the TV spectrum. These resulted in wide ranges of the bands being unused in most countries. Usually it is referred to as the “Digital Dividend”, where in some countries, the mobile service uses some of the Digital Dividend as these frequencies are considered unutilised. Depended on the nature of TV broadcast planning and frequency use, the secondary devices (SUs) still have opportunity to access these bands without causing harmful interference to the TV broadcasters.(Marţian et al., 2013)

One of the main advantages of unused TVWS is that it is characterised with the superior properties of the VHF and UHF bands. A communication device transmitting in the VHF and UHF range does not require high power to transmit the signal over moderate ranges. As such, the signal can travel longer ranges without infrastructure, specifically in rough terrain, when compared to the higher frequencies for instance the 2.5 GHz used for WiMax. The current standards of IEEE802.22 WRAN, that have started to implement TVWS, are still looking to provide improved coverage of the signal from the base station up to 100 Km.

In addition, the superior propagation properties of the VHF and UHF frequencies, whether indoor or outdoor has good reception, and does not required the line-of-sight. These advantages can make TVWS technologies a good candidate to addressing broadband wireless information services with possibility to provide it to rural areas with minimum infrastructure investments. In theory, by depending on spectrum sensing, the CRs have the capability to detect the PU activity without interference. On the other hand, in practice, much work is still required to be done to test the CRs’ capability with more accuracy. For that reason, regulators around the world such as Ofcom, FCC and ECC are not yet allowing secondary use of the spectrum based on CR technology alone. As a result, they started to take the TVWS geolocation database approach as more accurate in preventing harmful interference to PUs.

6.3 TVWS Applications

The radio spectrum is widely used, literally by everybody, in applications in our personal environment including remote keys, remote controls, microphones, burglar alarms and cordless headphones. Some users might not be aware that these are considered as radio applications. Interference is of particular concern when affecting security services using radio such as police, ambulance, air traffic control and armed forces. Some issues of the radio spectrum for modern societies has been extensively discussed and improved. In contrast, spectrum monitoring is considered of vital importance for supporting the spectrum management process to find suitable solutions to address the interference problem, which is still considered the main issue in investigating TV white space applications. There are many radio applications which might be developed by using TVWS technology such as “super Wi-Fi” which can extend wireless hot spots to many kilometres depending on the location and extended wireless back-haul which can be established over white space to connect regular Wi-Fi access points to provide service to unserved areas. Also, there many other applications still under investigation for using TV licensed spectrum without harmful interference (Abognah, 2014).

6.4 TVWS Regulation

Due to increased demands on the radio spectrum, most of which has been licensed to the PUs by government, nowadays TVWS is considered the best solution to avoid the scarcity problem, offering a paradigm shift towards spectrum sharing. The suggested mode of operation of cognitive radio networks, being license-exempt in the spectrum bands assigned for TV broadcast service, fits very well with this requirement. Many regulators around the world have adopted a geographic database containing TV channel information to avoid interference at a particular site by using WSDs, and this kind of scheme is considered the main requirement for devices wanting to operate in the TVWS. The following is a summary of efforts to accommodate TVWS devices in the plans and regulatory policies of ITU, Ofcom, FCC and others.

- The Responsibility of regulating CR and TVWS devices has been transferred to the national regulatory bodies by the International Telecommunications Union (ITU). The summary of World Radio Communication conferences (WRC12) is that SDR and CR systems should be accommodated by the international regulatory framework and national regulators in each country should have the control of development of systems for implementing this concept in TV white spaces. Also, WRC12 provides the further recommendation, which encourages more investigation of the impacts of employing CR.

- The Federal Communications Committee (FCC) in the United States has many regulatory efforts for enabling the CR technology and TVWS for SUs by building the grounds for a geo-database of TVWS to protect the PU. This technology has since been globally recognized as the main contender for giving opportunity to new applications operating in such TV bands. Hence, many databases have been created on behalf of FCC by various companies such as Spectrum Bridge, Google and others (Yang, 2014).

-In August 2011 in Canada, the 700 MHz band has been set to be auctioned for cellular mobile service, which might limit use of TVWS applications in the future in Canada. Some consultations have been issued by Industry Canada to explore the extent of potential for sharing the TV broadcast spectrum below 698 MHz with SUs.

-In 2007, the regulatory body in the United Kingdom (Ofcom) has allowed for the SUs to operate TVWS in the range 470 to 790 on a license-exempt basis provided that there is no effect on the PU. In 2011, Ofcom held consultations regarding the implementation of the geo-location database. In 2015 there are seven organisations that have been signed off by Ofcom to provide database services for WSDBs in the UK, including Fairspectrum Oy

(Finland), Google UK Limited, Microsoft Ireland Operations Limited, Nominet UK, Sony Europe Limited, Spectrum Bridge Incorporated and others.

The technical and regulatory conditions are considered the main criteria to be investigated, according to the European Union CEPT and ECC, to enable the cognitive radios to operate in the UHF TV white spaces. The ECC report 159-53 is considering the technical and operational requirements which might give more protection to the digital broadcasting by using CR systems in the white spaces of the frequency band 470-790 MHz. This report proposed the potential benefit in using a combination of sensing and geo-location database to provide adequate protection to DTT receivers (Electronic Communications Committee, 2011). In additional, further definition of technical and operational requirements are represented in ECC Report 185 for the operation of white space devices in the band 470-790 MHz (Electronic Communications Committee, 2013), while ECC Report 186 suggests some technical and operational requirements to operate WSDs with the geo-location technique (Ecc, 2013).

6.5 Design of Cognitive Radio database system

In the spectrum sharing environment, SUs can be permitted to access licensed frequencies, which are not fully used by the PU. Therefore, to provide suitable protection for the PU, the white space database is essential to protect the PU from harmful interference. The Geolocation database approach will contribute to ensure coexistence among PUs and secondary users from one side, and spectrum sensing and database learning from other side. For this purpose, design and develop a Cognitive Spectrum Management System to efficiently and effectively allocate available channels to secondary users as illustrated in the Figure 6.1.

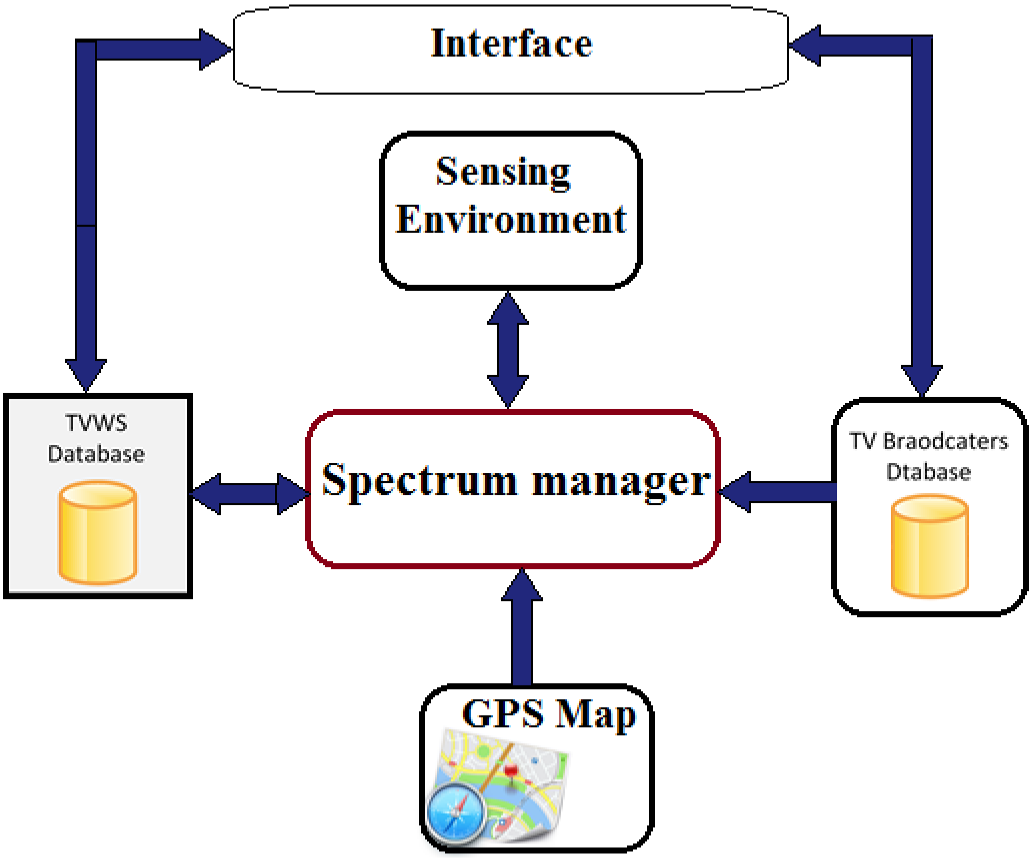

Figure 6-1: Cognitive Spectrum Management System

6.5.1 TVWS Database

The TVWS Database is considered as a key component of the system and where the information of channels availability is stored. The database can received a query from spectrum manager that comprises of a certain location in order to determine which channels are free (white) and which channels are not, and then reply with appropriate information such as the number of available channels for secondary use, and allowed transmission power in each channel. The regulator or a licensed administrator can maintain the TVWS-DB. The WSD can be granted permission to access to database by the administrator for provision of only selected information for the receiver location. The main role of the regulator is to maintain oversight of the whole process to ensure compliance of the TVWS- DB administrators and accuracy of its data. Figure 6.2 illustrates the relationship between the regulator, the database administrator or spectrum broker, the PU, and the SUs in TVWS applications.

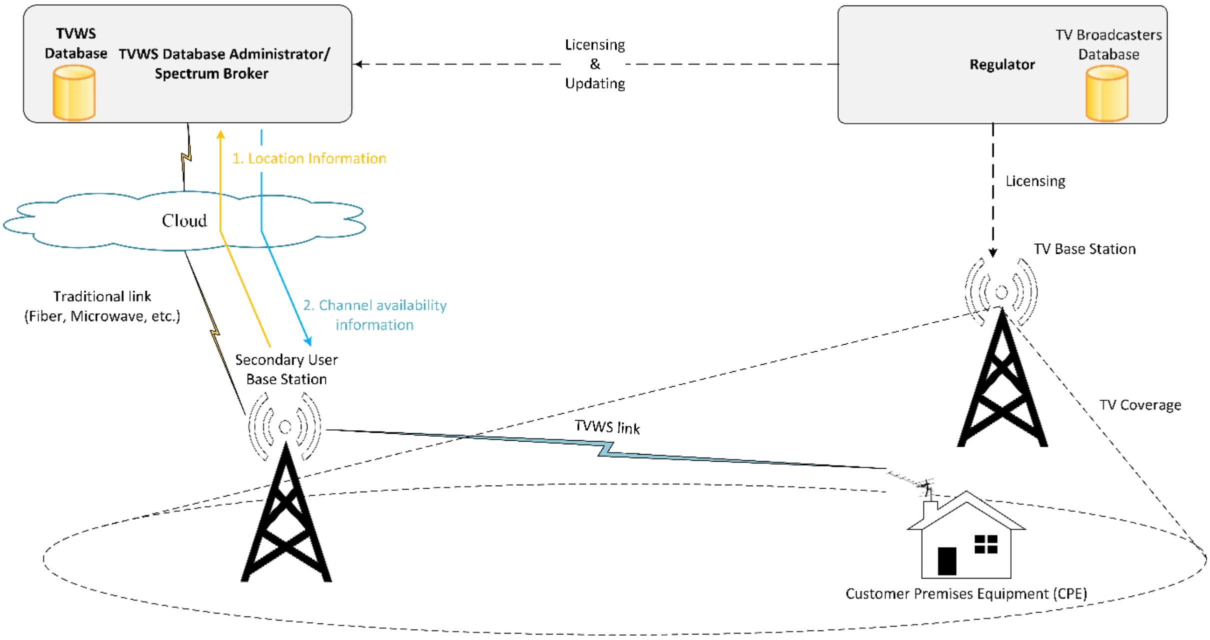

Figure 6-2: TVWS Geo-Location Database Model

6.6 Design of Flexible System for Creating TVWS Database by Using Different Propagation Models

Based on the previous results, which indicated that the Egli model is the best among the models that have been chosen for comparison with the real measurements, a flexible system has been built that performs many functions related to propagation modelling and calculation of signal strength in each pixel. A pixel is user-defined rectangular area which sets the special resolution of the simulation. Among these tasks, it is possible to determine any geographic area based on latitude and longitude between two concentric points. In addition, it can be determined that the size of each pixel will affect the implementation time and propagation accuracy. Also, the system can perform three major operations at the same time to create a database for a selected geographic region that can be easily used when connected to the white space devices (WSD). In this work, for illustration, it has considered only six transmitters, but more can be added using the “Add Transmitter Detail” button, as shown in Figure 6.3.

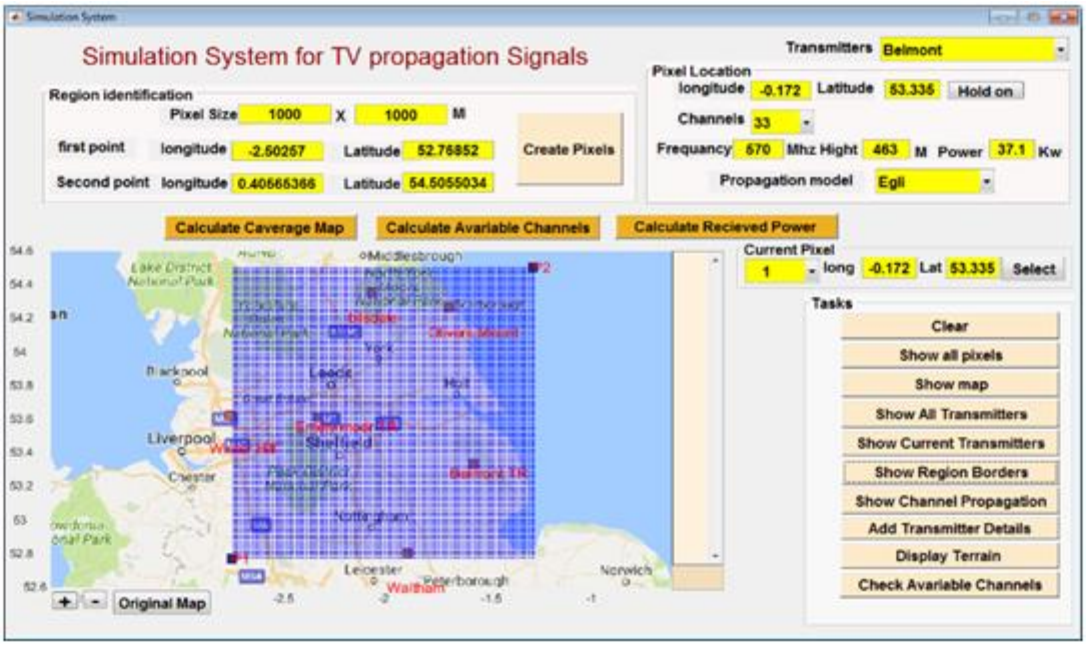

Figure 6-3: Display of all pixels in the selected region in the flexible simulation system for creating TVWS database

6.6.1 Methodology for Creation of pixels

To set up the simulation, the user selects the area over which calculation will be performed by drag and drop on the map and inputs several parameters such as pixel size in meters. Pixel set-up is illustrated in Figure 6.4.

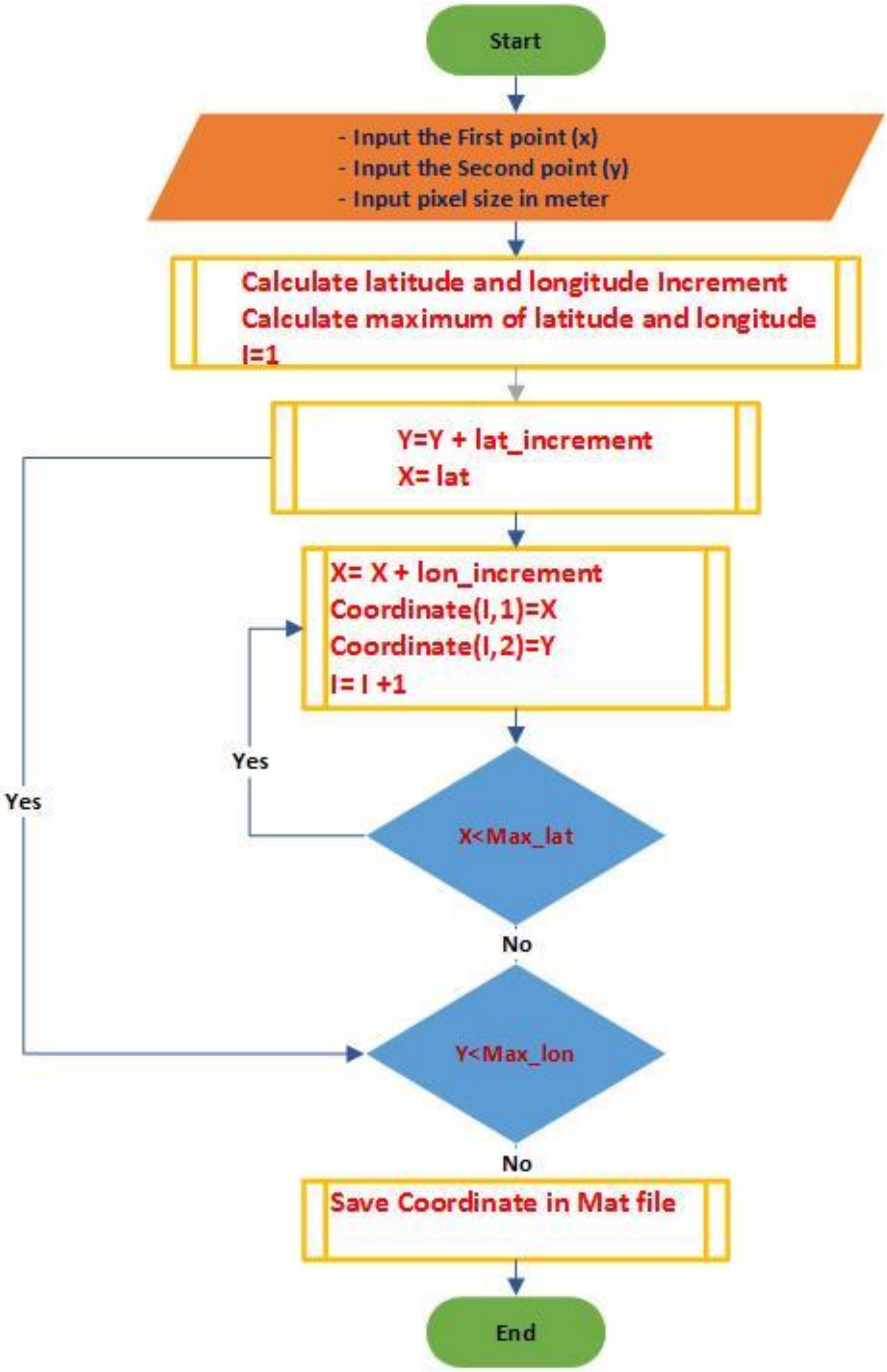

Figure 6-4: Algorithm of the Pixels Calculation

6.6.2 Configuring Calculation of Received Power

The second methodology to be implemented after creating the pixel file is to calculate the receiver power in each pixel in the frequency range 470 to 790 MHz, by considering the selected transmitters. The processing time depends on the number of pixels, propagation model and also the terrain resolution level. The process will be conducted only once to create a complete database of all the predicted TV signals in each pixel, as shown in Figure 6.5, which can be used for the next stages.

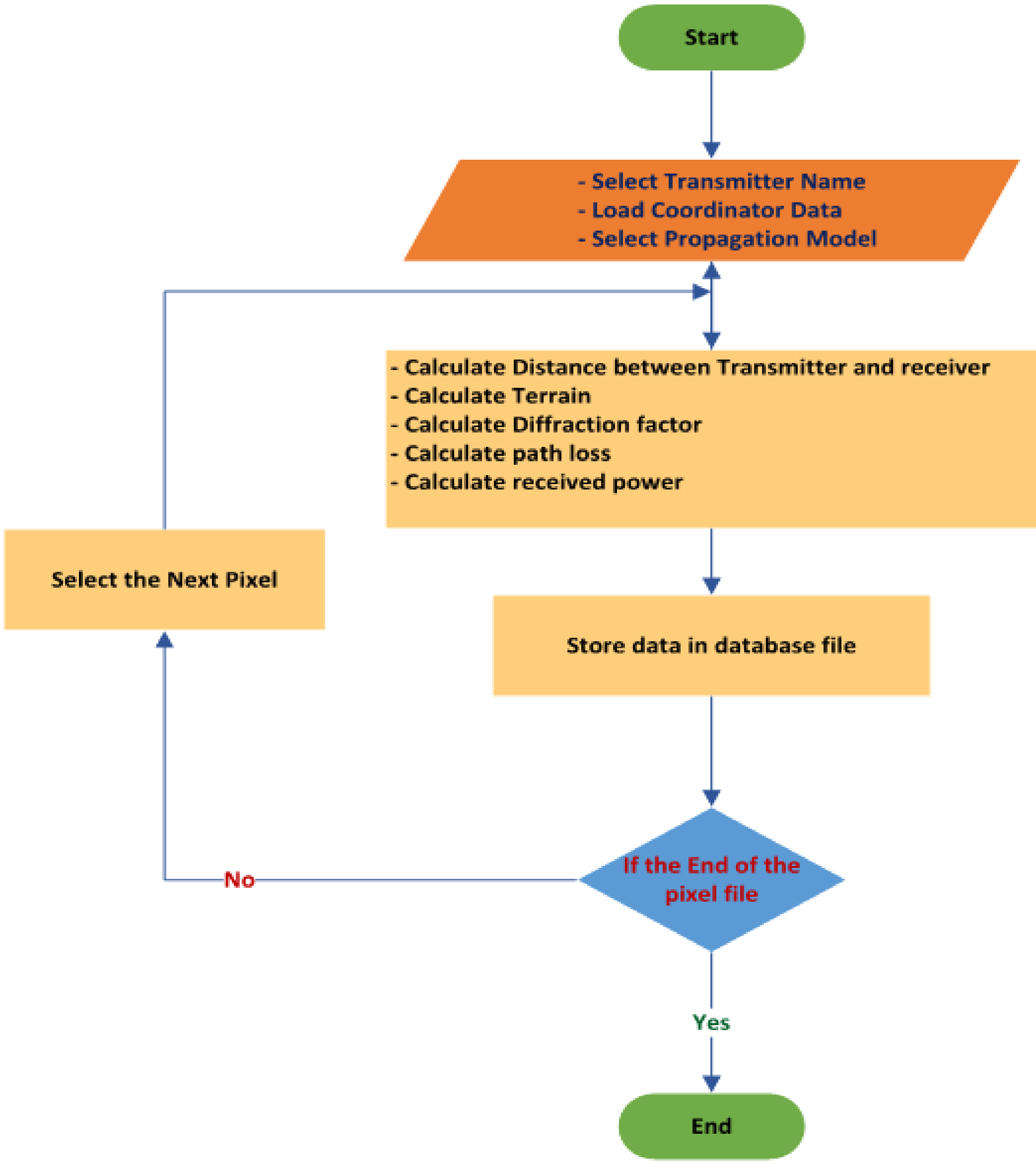

Figure 6-5 Algorithm of the received power calculation

6.6.3 Methodology for Calculation of Available Channels

The main goal of the system is to calculate available channels with high accuracy and then store all available channels of each pixel in the database, in a way which makes it easy for WSDs to retrieve the data. All of the transmitter information, such as height, channels and transmitted power, is stored previously in the database. The process takes into account all channels of the selected transmitters that might be received in a specific pixel, considering the weak signals as well.

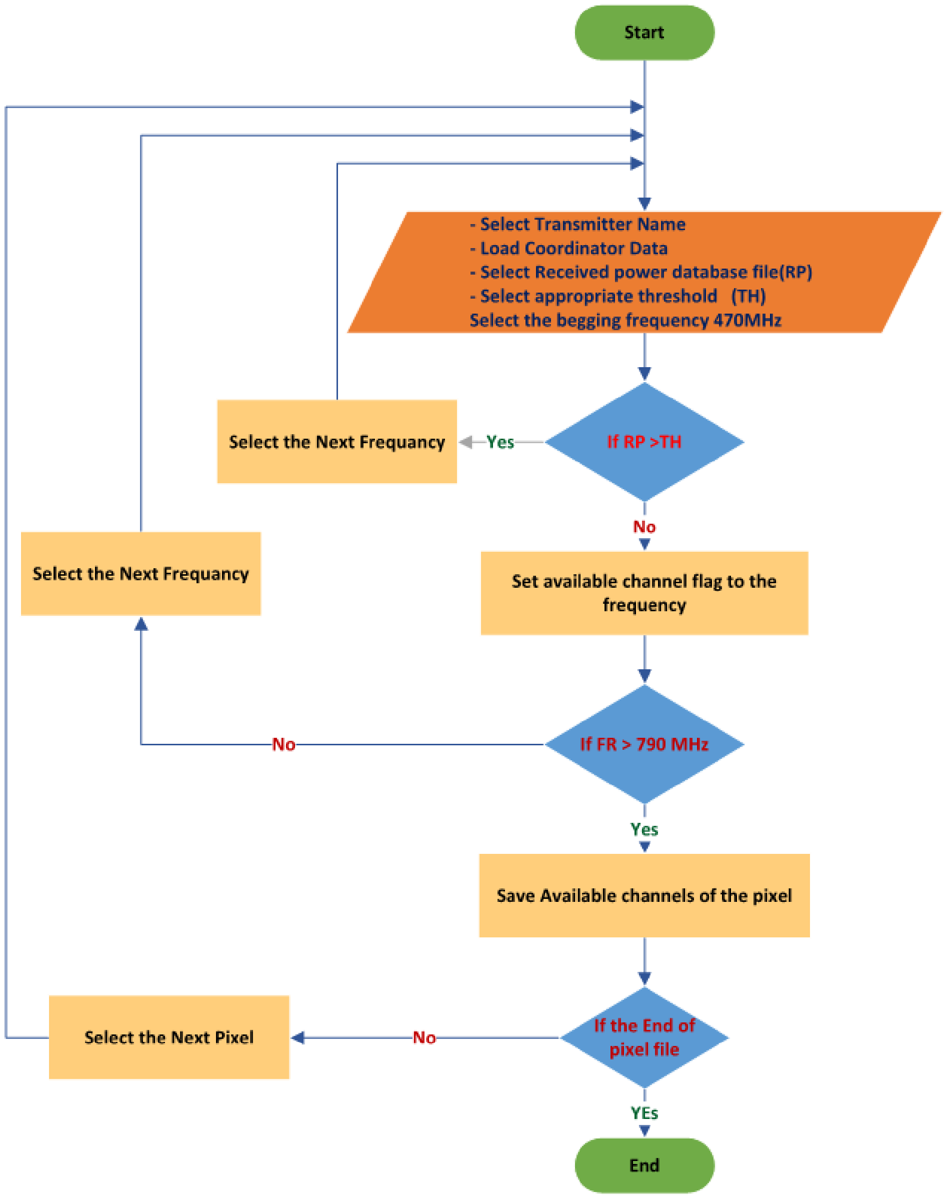

Figure 6-6 Available Channels Algorithm

6.6.4 Methodology for Calculation of Coverage Map

This methodology must be used to translate the database that has been stored to show as a visual map of different levels of signal strength in the selected region for each transmitter, which are then stored in different files in the database as shown in Figure 6.7.

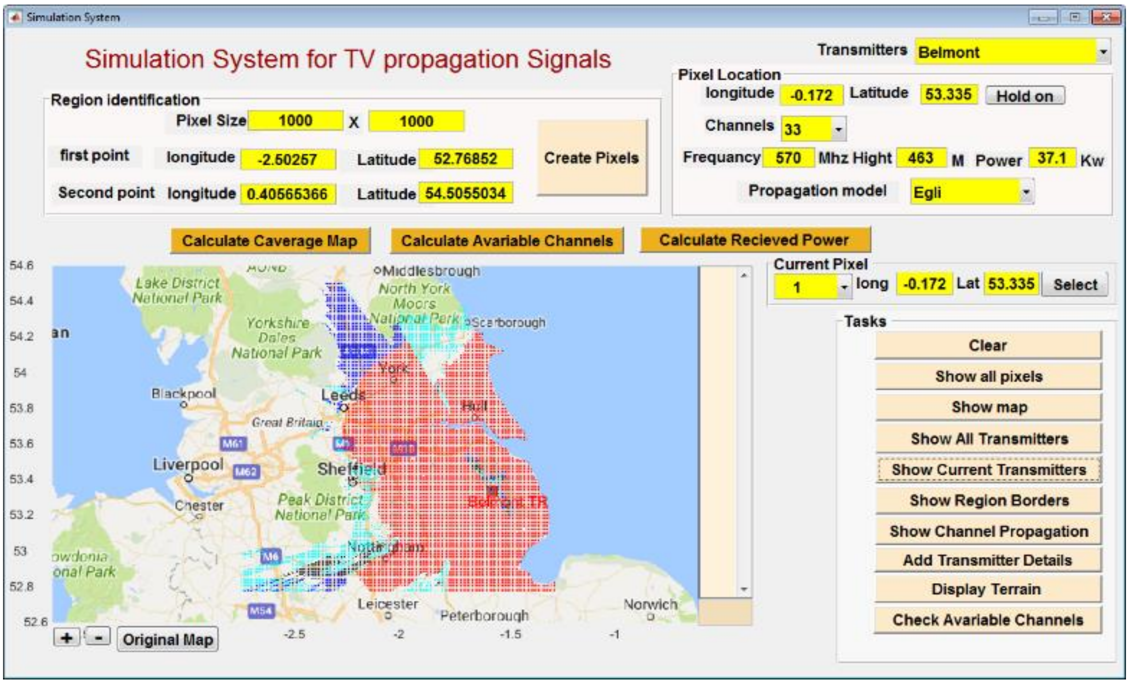

Figure 6-7: Display of the propagation signals for channel 33 using Egli model

Through this algorithm, the strength of the receiving signal can be categorized by four colours (red, blue, black, yellow) depending on the signal strength that the receiver can receive in each pixel. For example, the red colour represents the strength signal less than -60 dBuv/m The main benefit for designing this algorithm is to be easy for representing by drawing signal using the previous signal reception data and it is stored in a concise manner as shown in Figure 6.8.

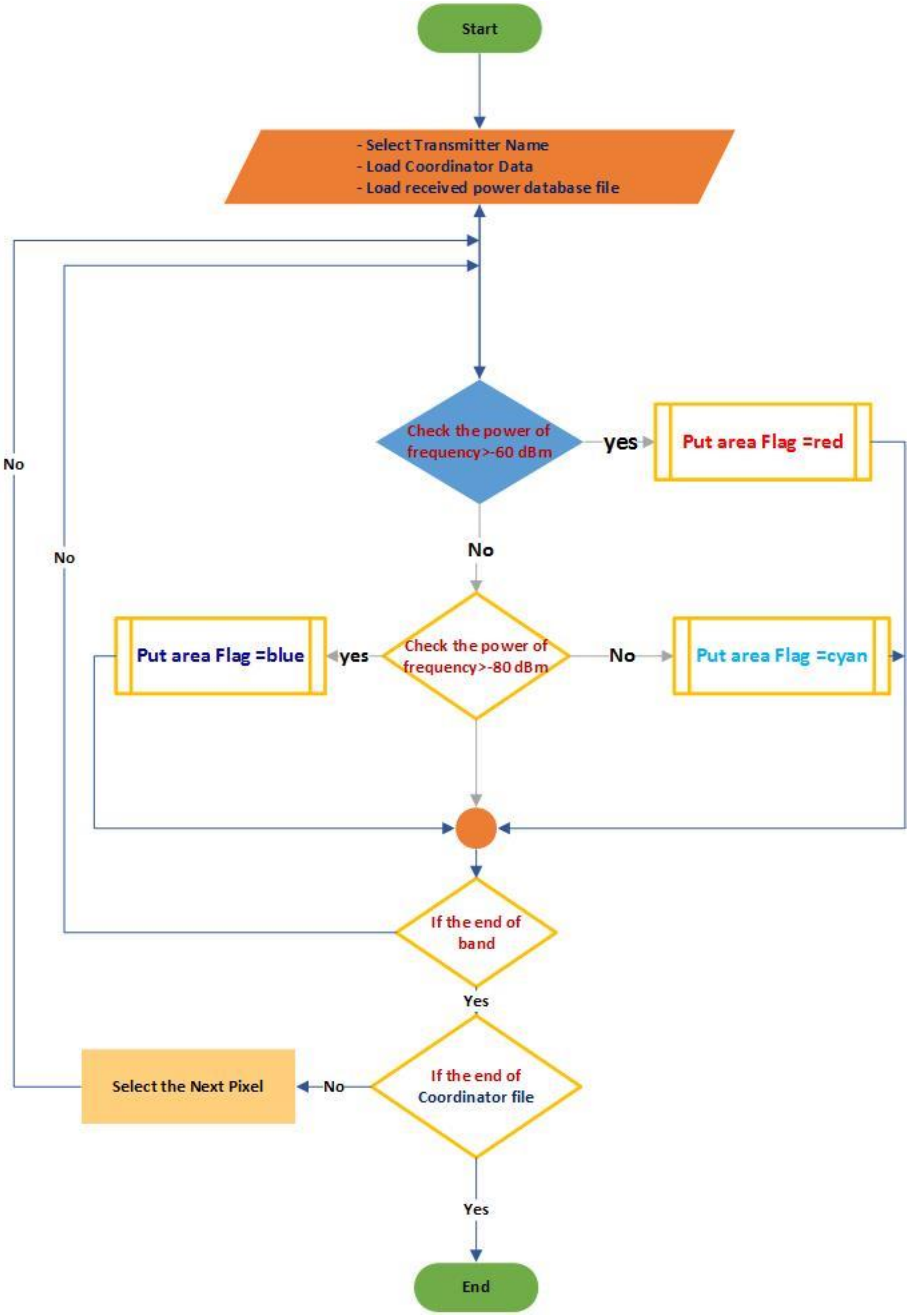

Figure 6-8: Coverage map Algorithm

6.7 Combination of a geolocation database with infrastructure sensing in TV bands by using different spectrum devices.

The WSD system queries a centrally managed database, referred to as the geolocation database, containing information regarding available channels for SUs. Our experimental white space system undertakes multi-tasking and works simultaneously with three spectrum analysers. Also, the system has the flexibility to build different scenarios for more investigation as illustrated in the following sections.

6.7.1 Algorithm to check available channels in a specific location

The accuracy of this algorithm relies on several factors including pixel size selection and the correct implementation of subsequent algorithms to determine parameters such as received power, available channels and coverage maps. These calculations will contribute to produce a TV white space database that contains the channels available at the centre of each pixel of given size. Figure 6.9 indicates four pixels of size 1000m x 1000m, where the red points represent the main locations of the available channels that have been calculated and can be used by the secondary user. It is unlikely that the secondary user will be located at the exact centre of any pixel but may fall into three possible categories: within the geographic range of any pixel; on the border between two pixels; or on the border of four pixels as shown by the green spots. Therefore, the system will adopt the available channels of the nearest pixel to the secondary user. When the pixel size is smaller the accuracy of the available channel information will be increased, in contrast the pixel size will impact the implementation time of the received power calculation algorithms, which depend on the percentage of the increment.

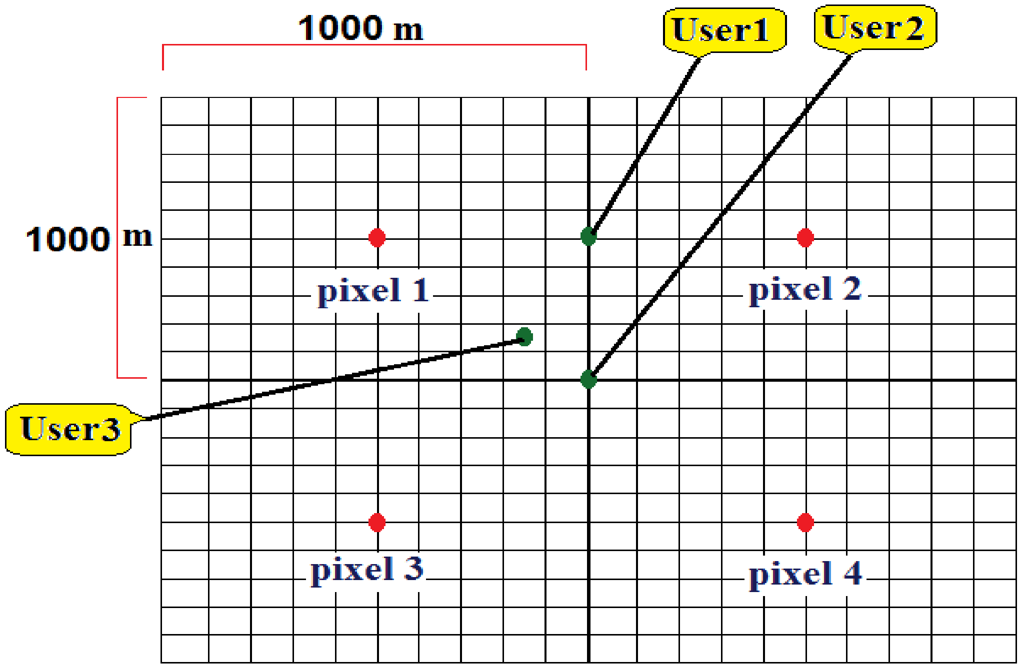

Figure 6-9 : Status of available channels for the secondary user

Furthermore, the white space device system is designed to include different scenarios with multi tasks. The secondary user location can be selected by drag and drop on the map and then click on the "check available channels" for connecting with the TV white space database by sending the user location and then retrieving a list of available channels, the example being based on pixel size 1000 m x 1000 m.

It can be seen from Figure 6.10 that after selecting the user location, a list of available channels at this location will be provided, available for use by a secondary user, the red point (p1) represents the real user location, whilst the green point (p2) represents the nearest pixel centre, used for calculation of the available channels, where in this example the distance appears about 274.24 m between them. In this example the database gives 14 channels that are available at this location.

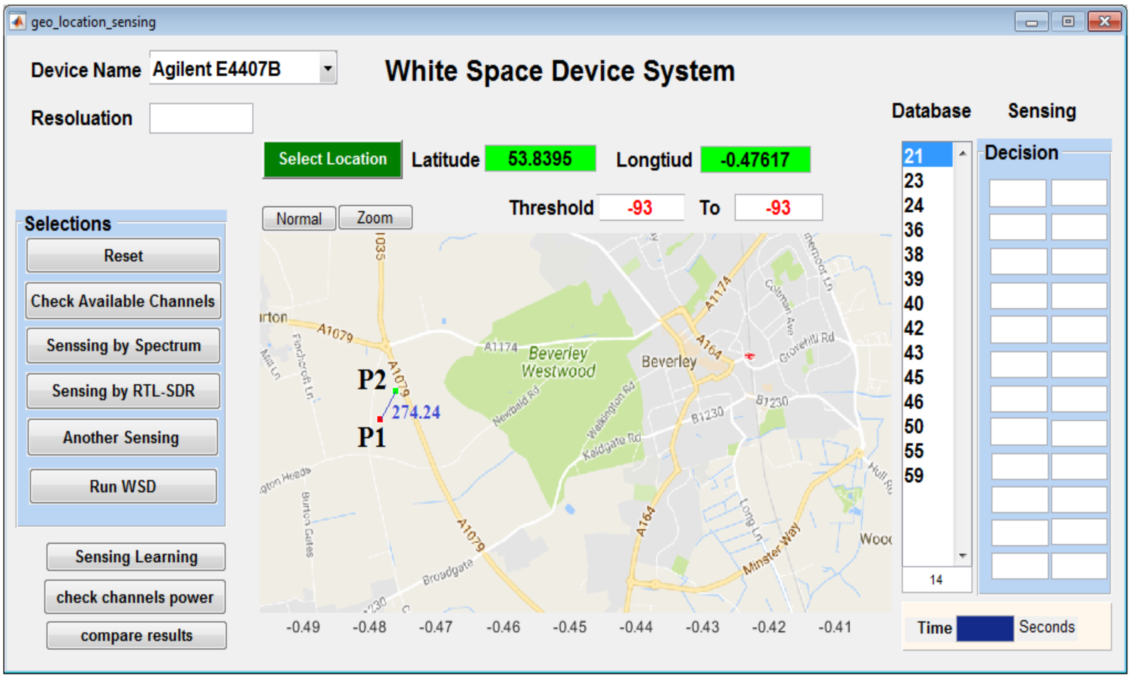

Figure 6-10: Retrieve available channels from TV white space database

6.7.2 Combining geolocation database and sensing techniques.

In this section, will describe the design of an efficient technique for combining the geolocation database and spectrum sensing results by using different spectrum analysers in various resolution bandwidths along with dynamic thresholding and investigate how the chosen threshold impacts on the number of available channels at different resolutions. The work divides into two scenarios. In the first scenario an RF screened chamber is used, allowing transmission of various imitated TV signals on the same frequencies as the available channels that have been provided by the database, allowing investigation of their effect on reporting of available channels and testing the efficiency of the system. The second scenario involves running the white space device system for combining the geolocation database and spectrum sensing in a real environment. The processing of the scenarios was conducted at the University of Hull Wireless Communication Laboratory (second floor of the Engineering building, latitude 53.771, longitude -0.368) and at the top of the Applied Science building (latitude 53.772, longitude -0.369). Equipment employed in this study consisted of a Bilog antenna, two spectrum analysers (Agilent E4407B and Agilent EXA N9010A), the RTL-SDR double and a signal generator. The received signals were loaded from the spectrum analyser via a general purpose interface bus (GPIB) connected to a laptop PC where they were sensed directly and compared with database results using the white space device system that has been created in Matlab 2014b, to provide the final decision on available channels, as shown in Figure 6.11.

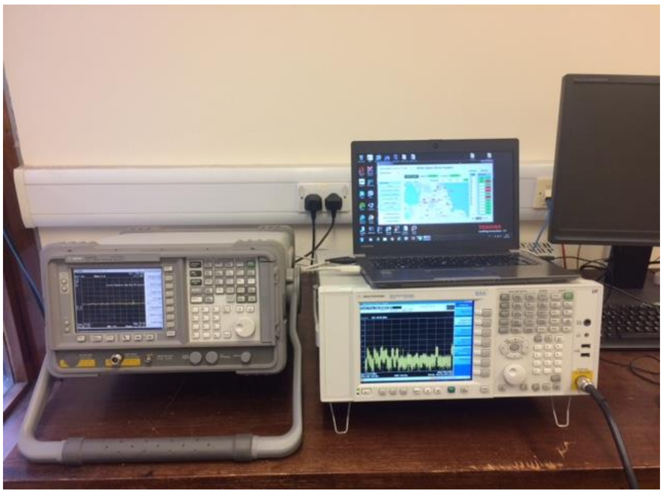

Figure 6-11: Equipment used for geolocation database and spectrum sensing techniques

6.7.2.1 Generation of TV signal and sensing at the same time by using the simulation system

The WSDB simulation system will send a query requesting a list of available channels and then perform spectrum sensing to find the frequencies that may be used by a secondary user, by trying to detect primary transmissions on the same database frequencies. In the first part of the experiments, using the signal generator to represent the transmitted TV signals for a few seconds at various frequencies in the wireless laboratory (RF screened chamber), and then run the white space device system continuously by using a spectrum analyser for sensing the database channels. This simulation system is used to evaluate the accuracy of the white space device system and investigate how it deals with any of the database channels that might be occupied by a PU at a specific time.

Figure 6.12 shows that the signal generator transmits a signal at 626 MHz at a level of - -40 dBm during each 2 seconds and then receives it using the TV antenna and Agilent spectrum analyser and monitors the sensing by the WSD system at same time.

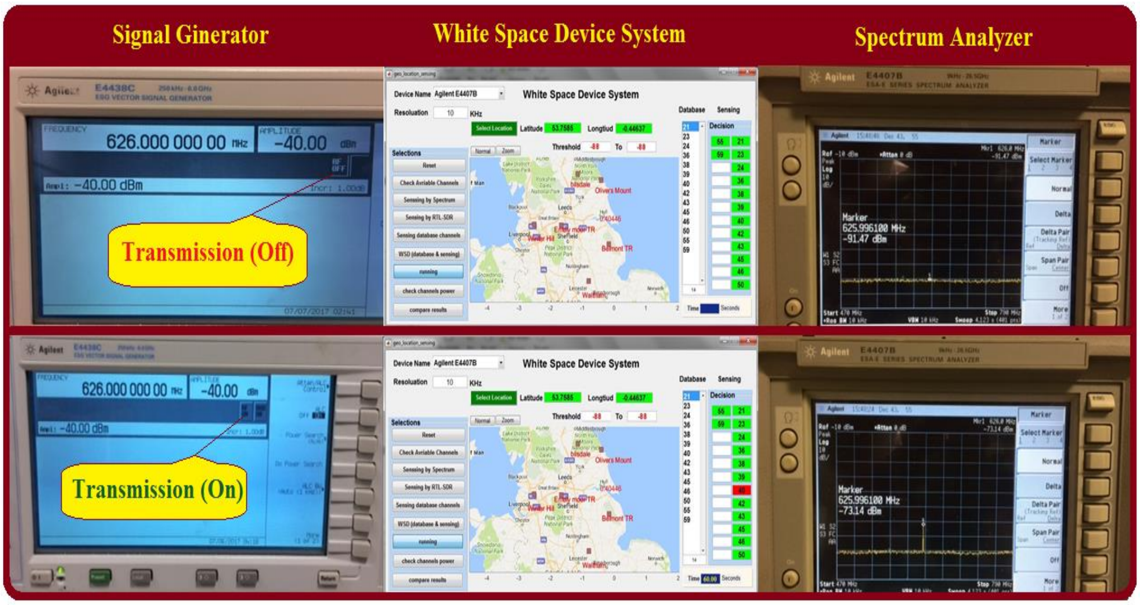

Figure 6-12: The white space system status before and after transmitting a test TV signal

The results show that channel 40 is colored red as soon as the test transmission is switched on, which means the PU is present and this channel is not available for the secondary user. In contrast, when the transmission is off, the channel 40 responses colored green and becomes available for the secondary user.

6.7.2.2 Geolocation database and spectrum sensing in a real environment

In the second part of the testing and validation process, an elevated receiver site has been chosen for detecting TV signals by using the geolocation database and sensing of the real environment. Figure 6.13 and Figure 6.14 shows the decision of the TV signal detection process by using both spectrum analysers (Agilent E4407B, Agilent EXA N9010A) with

RBW 10 kHz and threshold -95 dBm. The results illustrate that the database gives 10 available channels while the real sensing shows that 4 of these 10 channels are occupied and only 6 are available when using Agilent E4407B. Here the detection threshold has been set at 4 dB above the noise floor.

On the other hand, when use another spectrum analyser (Agilent EXA N9010A) with same parameters, the results show that 9 channels are available and one is occupied. The main reason for the different results is noise floor of the Agilent EXA differ the noise floor of Agilent E4407B (Ecc, 2013).

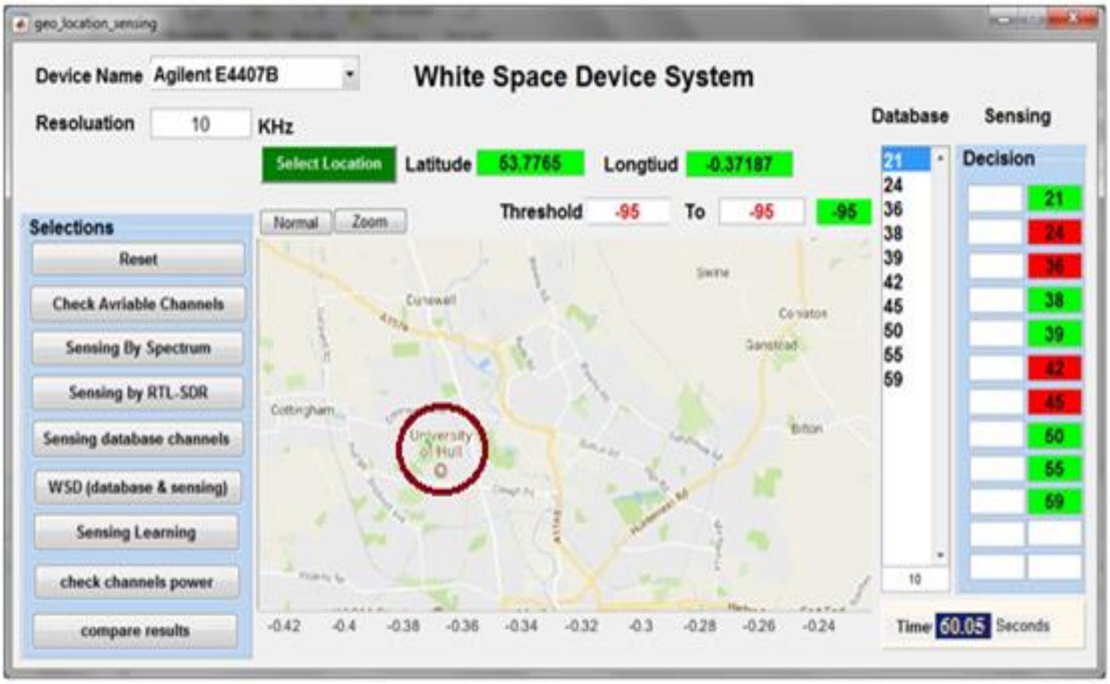

Figure 6-13: Result of combining techniques by using Agilent E4407B with threshold

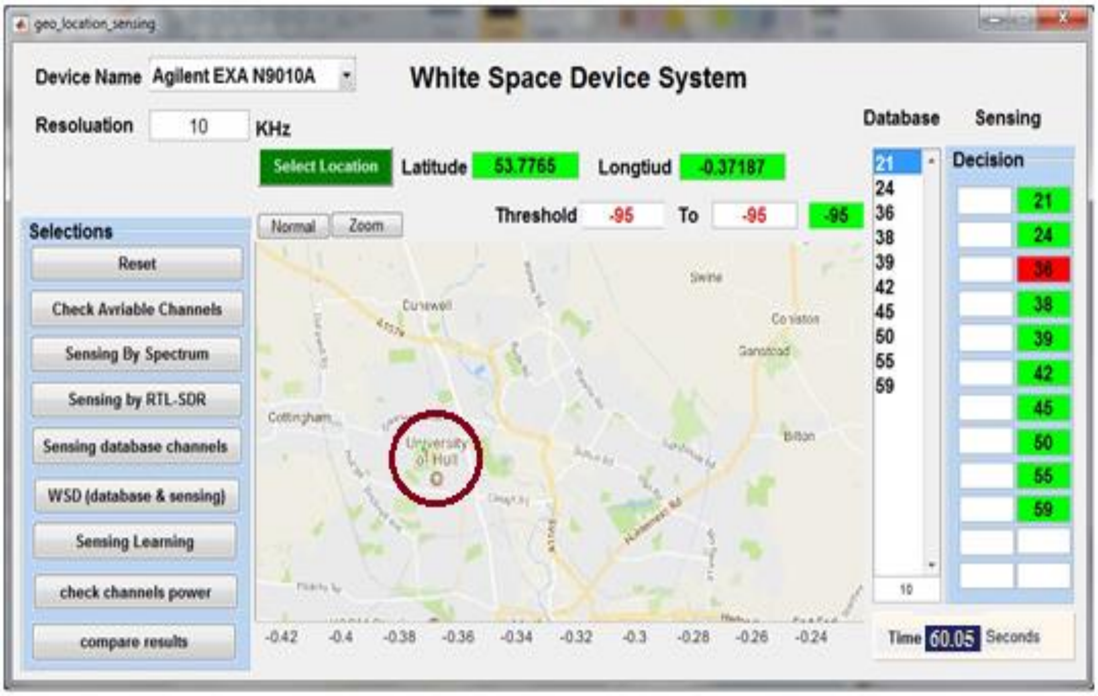

Figure 6-14: Result of combining techniques by using Agilent EXA N9010A with threshold

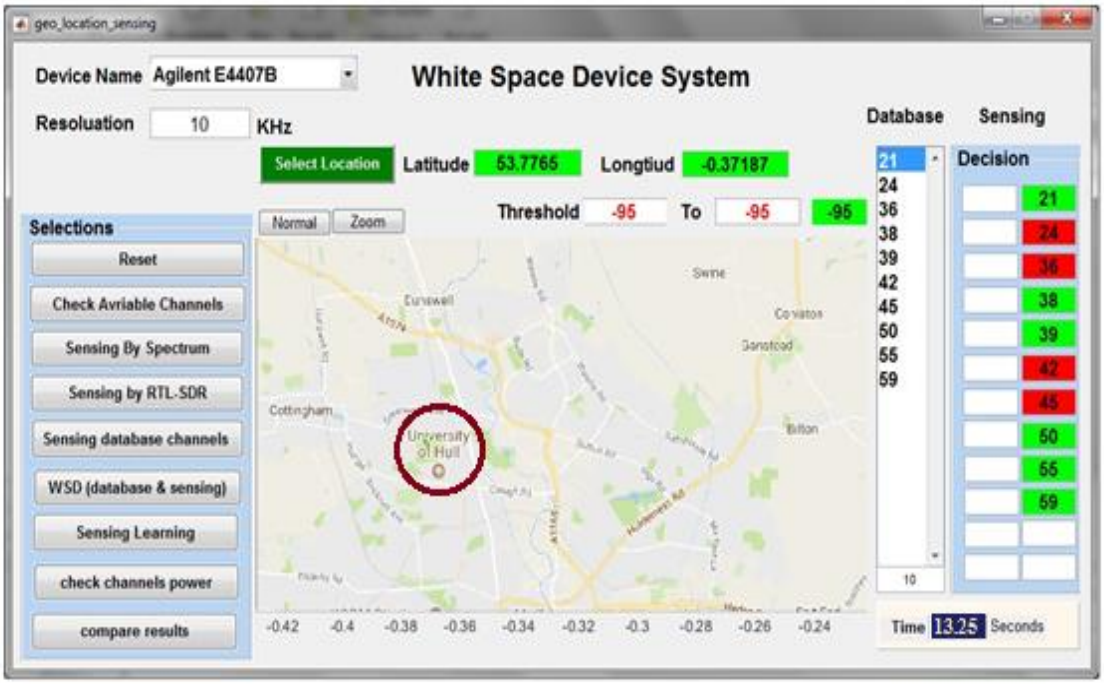

Figure 6-15: Results of combining techniques by using Agilent E4407B for sensing only database channels

In the previous sensing, the whole TV band has been sensed within one minute for multi sweep, to investigate the sensing time and compare with other sensing techniques that will only sense database channels instead of all channels as illustrated in Figure 6.15.

The time needed to sweep the whole band 470-790 MHz when using the Agilent E4407B spectrum analyser is 4.123 seconds, when the selected resolution bandwidth is 10 kHz, which means each channel will take about 0.103 seconds. Furthermore, the sweep time is different from one device to another depending on the resolution bandwidth as seen in Figure 6.16.

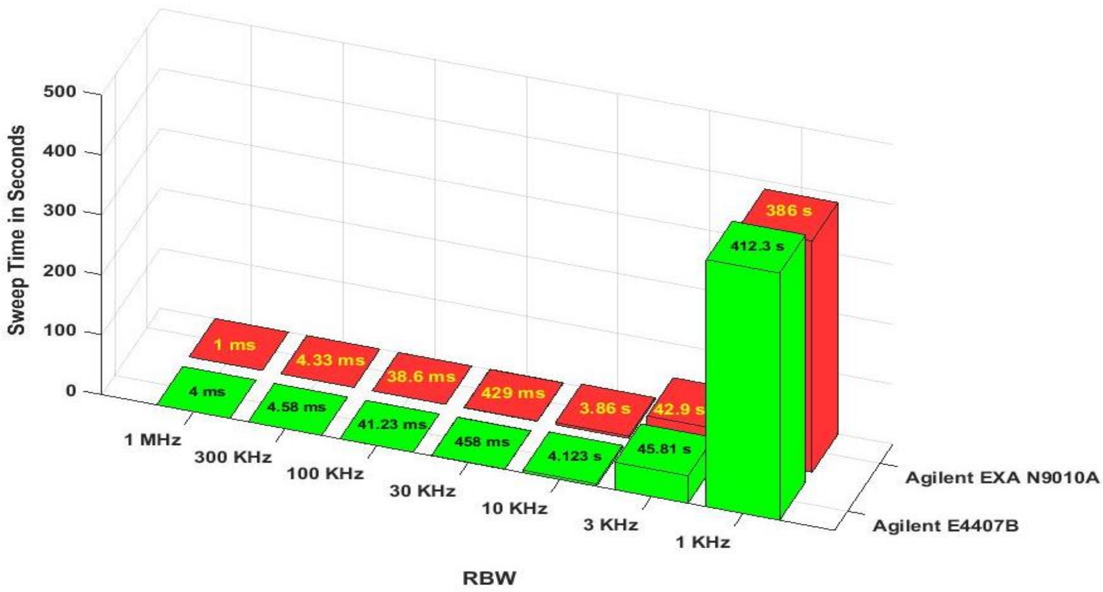

Figure 6-16: Sweep time of the Spectrum Analysers

The chart shows that the sweep time is increased when the resolution bandwidth (RWB) is decreased. Further investigation has been conducted to find the most suitable RBW and threshold. Using the white space system by selecting the location of the Humber Bridge as an example, it has applied both techniques (geolocation database and spectrum sensing) using different resolution bandwidths and thresholds. The database gives 14 available channels, which can be used in that location, whereas, the spectrum sensing gives different numbers of available channel, depending on both parameters RBW and the selection threshold as illustrated in Table 6.1.

Table 6.1: Calculated Thresholds, RBW and corresponding available channels for both spectrum analysers.

Threshold / RBW	-80 dBm		-85 dBm		-90 dBm		-95 dBm		-100 dBm		-105 dBm		-110 dBm	
	E4	EX	E4	EX	E4	EX	E4	EX	E4	EX	E4	EX	E4	EX
1 KHz	**10**	**13**	**10**	**13**	**9**	**13**	**8**	**12**	**7**	**9**	**0**	**7**	**0**	**0**
3 KHz	**10**	**13**	**10**	**13**	**9**	**12**	**9**	**11**	**6**	**7**	**0**	**0**	**0**	**0**
10 KHz	**10**	**13**	**9**	**12**	**9**	**11**	**6**	**10**	**0**	**3**	**0**	**0**	**0**	**0**
30 KHz	**9**	**12**	**9**	**11**	**7**	**11**	**0**	**5**	**0**	**0**	**0**	**0**	**0**	**0**
100 KHz	**9**	**11**	**7**	**11**	**0**	**5**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**
300 KHz	**9**	**11**	**6**	**7**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**
1 MHz	**3**	**10**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**

E4 =spectrum Analyser E4407B **EX** =spectrum Analyser EXA N9010A

The results show how the different RBWs and thresholds affect the apparent number of available channels, and which suitable value of RBW and threshold should be selected to avoid adversely affecting the sensing time, giving sufficient detection accuracy for TV signals whilst guaranteeing to find available channels. So allowing for the differing sensitivity of the two devices, the difference in the number of detected available channels can be clearly seen.

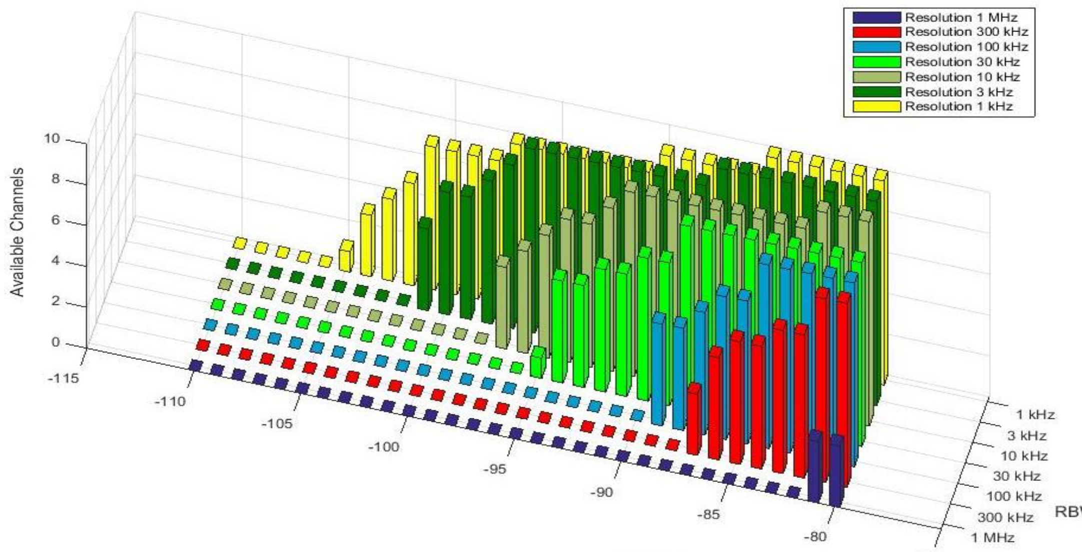

Figure 6-17: Calculation Thresholds, and RBW with Corresponding Available channels in spectrum Analyser E4407B.

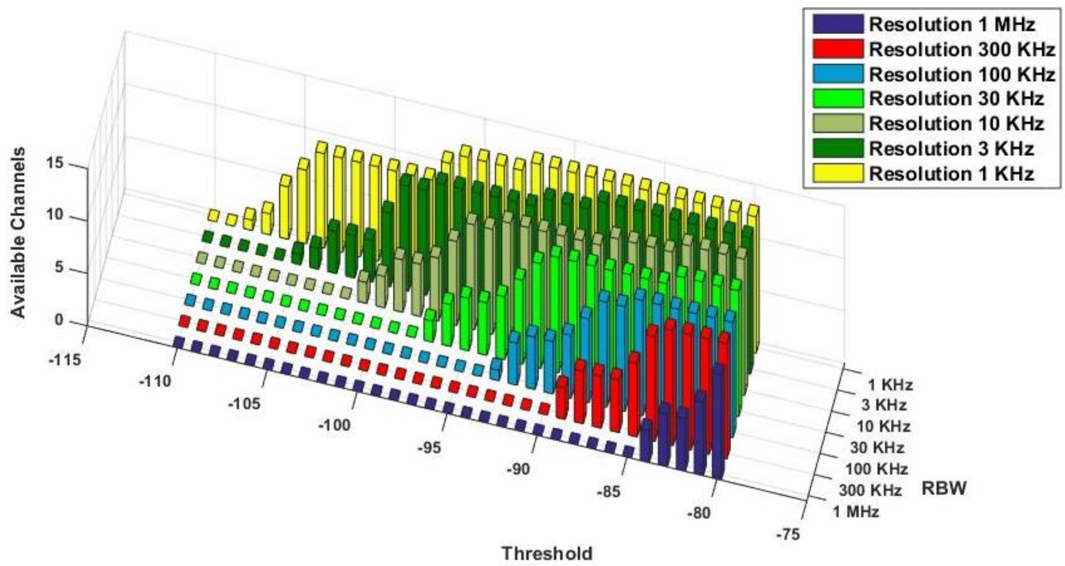

Figure 6-18: Calculation Thresholds, and RBW with Corresponding Available channels in spectrum Analyser EXA N9010A

In Figure 6.19 shows how the sensitivity differs from device to another, from -100 dBm up to -98 dBm the Agilent EXA gives three available channels whereas the Agilent E4407B indicates no channels available for secondary user.

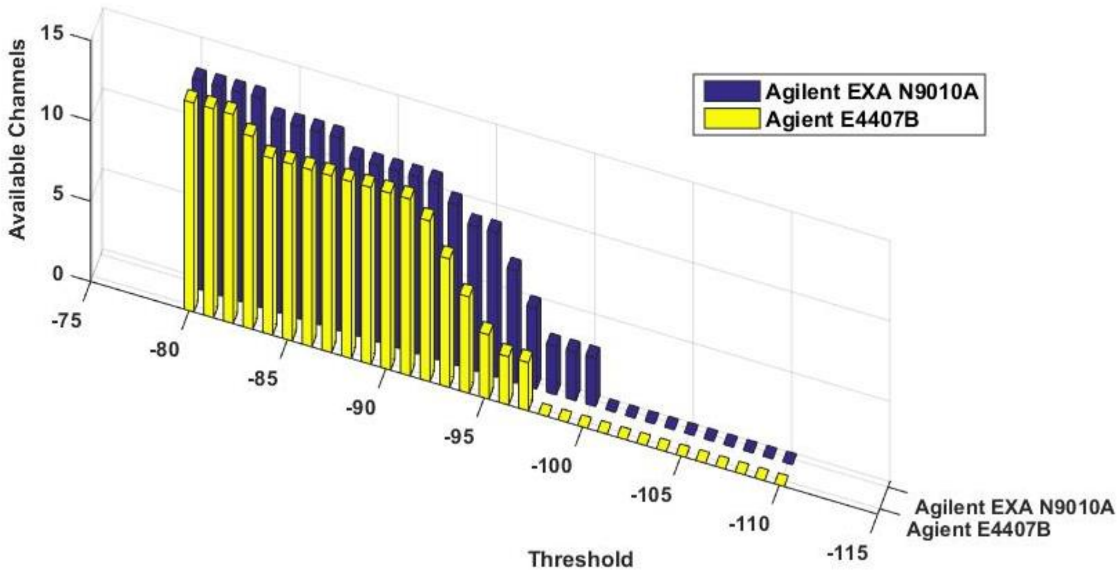

Figure 6-19: Calculate Thresholds, and Corresponding Available channels in both devices

Due to their compatibility, the parameters of both of the Agilent spectrum analysers can be controlled easily either manually or under program control, although their noise floors are slightly different. In contrast, the type of RTL-SDR dongle that has been used has a noise floor about -60 dBm. Results for the same Humber Bridge location show seven available channels from 10 channels that are provided by the database as shown in Figure 6.20.

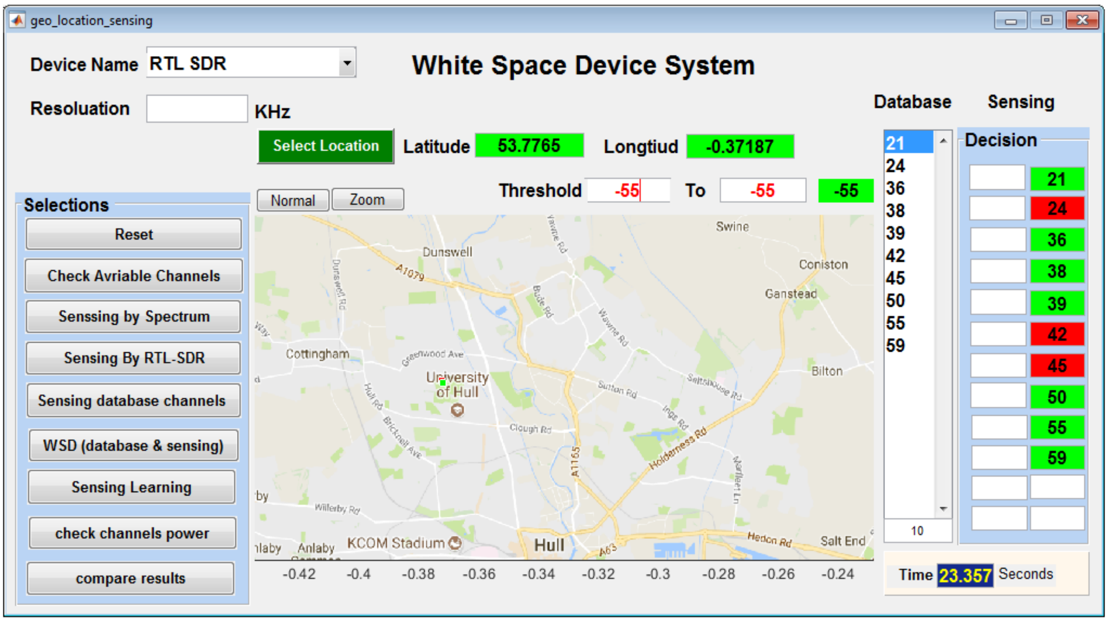

Figure 6-20: Results of combining techniques by using RTL-SDR for sensing only database channels

Therefore, when comparing the previous results, which were conducted using Agilent spectrum analyser, with the low cost RTL-SDR device results for geolocation database and sensing in different locations in a real environment, it may be seen that the results are slightly different between the two types of devices for the first ten locations, which are situated in flat terrain within the city of Hull, whilst the rest of the sensing is conducted in the surrounding area which is characterised by rough terrain in most locations as illustrated in Figure 6.21.

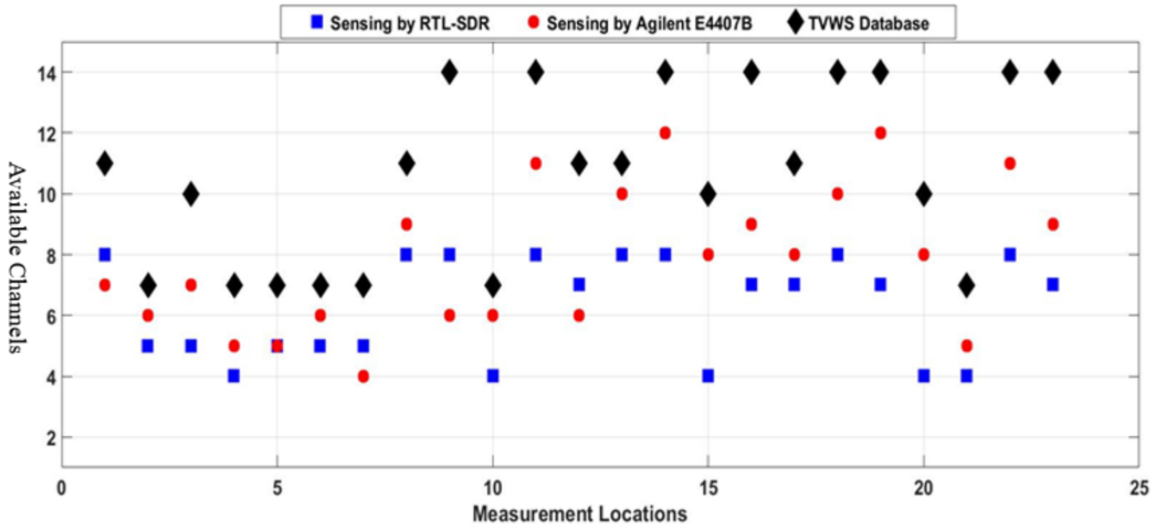

Figure 6-21: Comparison of combining techniques by using RTL-SDR and spectrum Analyser E4407B in different locations

Despite the high sensitivity of the spectrum analysers to detect the weak signals, the RTL-SDR can sense most of the TV signals that are indicated by the database. Therefore, the RTL-SDR is considered the best way to detect in terms of cost efficiency. Also, improving sensitivity of the RTL-SDR will contribute to improved performance of the white space device system. Recently a new high quality RTL-SDR called Airspy has been introduced(Gray et al., 2016), with the digital down-converter increased from 8 bits to 18 bits, which contributes to increased resolution of the digitised RF signal, so that weak signals are less likely to be lost when converted from analogue to digital.

6.8 Conclusion

In conclusion, it has shown that is possible to obtain good quality results when using the RTL-SDR as part of a TV white space device system to sense the radio environment in a cost-effective manner, combining appropriate spectrum sensing techniques with use of a geolocation database and sensing the environment with minimum external hardware. Results obtained have been shown to be comparable with those obtained using a high cost spectrum Analyser.

Chapter7: Conclusion and Future Work

7.1 Conclusion

The scarcity of radio spectrum and improvement of its utilisation efficiently have been a major focus of research effort over many years. A new perspective is required for spectrum management based on shared, dynamic spectrum access. Spectrum regulators and wireless network operators need to adopt new frameworks for shared and dynamic spectrum management in order to ensure continuing improvement of information and communications services essential to national and international economic growth. TV White Space is considered to offer the first real possibility for such shared spectrum access with supporting geo-location databases to ensure the harmonious coexistence of SUs with existing PUs within TVWS.

Through the several investigations carried out and results that have been reported within this thesis, the main conclusions can be summarised in several stages.

The first stage of this thesis has presented an overview of various aspects related to radio spectrum and methods to improve spectrum utilisation efficiency for meeting the stakeholders' requirements. This stage gives a clear understanding of the importance of the interdependence between the concepts which contribute to better use of under-utilised spectrum for economic growth particularly in developing countries. Therefore it can be concluded that use of white space devices (WSDs) is potentially one of the most significant methods for achieving more efficient utilisation of radio spectrum without causing harmful interference to licensed users, by using several features of CR, sensing environment capability and connecting with a geolocation database to determine the available usable channels. Furthermore, various dynamic spectrum access models have been presented and cognitive radio functions have been discussed. Consequently, this first stage paved the way towards the comparative study of several spectrum sensing techniques and their capability to facilitate adaptive SDR as the main part of the cognitive radio system.

The second stage of this thesis has compared three channel sensing techniques (ED, matched filtering and CFD detection) and given a clear vision of the relationship of criteria such as processing time, cost, necessary prior knowledge and complexity, and their impact on both accuracy and performance for each technique. It has been found that the performance and accuracy are very reliant upon the availability of prior knowledge of the PU signals. Furthermore, the complexity is also increased when spectrum sensing techniques require more prior knowledge to detect PU. In contrast, increasing knowledge causes increased cost and takes a longer time to reach spectrum usage decisions. Therefore, to mitigate the impact of these issues, the combining of two different techniques will provide the optimum compromise, involving possession of minimum prior knowledge of PU, low cost, short processing time and minimum complexity.

The next stage of the thesis proposed a practical solution by using spectrum sensing and Geolocation database by using a suitable spectrum monitoring device to sense the radio environment and choosing a suitable propagation model to create a Geolocation database.

The third stage of this thesis has presented and investigated the spectrum occupancy of the UHF TV band using a low cost software defined radio (RTLSDR) and to compare the results with those derived using a Spectrum Analyser (SA, Agilent E4407B) which is considerably more expensive. The findings of the aforementioned studies have shown that is possible to use the RTL-SDR software defined radio dongle with minimum external hardware as an inexpensive spectrum monitoring device instead of a high cost spectrum analyser. This opens the door for the development of efficient collaborative cognitive radio systems, where many geographically-dispersed terminals need to sense the radio environment in a cost-effective manner.

Stage four involved a comprehensive study to investigate the best empirical propagation model for predicting TVWS by examining the performance of three propagation models (Extended-Hata, Davidson-Hata and Egli) in the TV band 470 to 790MHz and then compared with a set of propagation measurements taken in selected locations around Hull, UK. The results shows that the Egli model is the best model giving a consistently good fit to measured data among other selected models and, with appropriate terrain data, will provide useful input to a system for facilitation of the cognitive radio decision process. In addition, designing the flexible system to create a TVWS database for a specific area, by selecting the optimum pixel size, adding appropriate transmitter information and choosing a suitable propagation model, this system gives potential applying the Geolocation database practically in the next part of the thesis.

In stage five a flexible system is proposed, which uses a combination of geolocation database and spectrum sensing in the TV band, comparing the performance of different spectrum analysers (Agilent E4407B, Agilent EXA N9010A and a low cost RTL-SDR) in the real environment, in order to investigate the potential usefulness of an inexpensive RTL-SDR in sensing geolocation database channels when compared with high cost spectrum analysers. The results show that is possible to obtain good quality results when using the RTL-SDR as part of a TV white space device system to sense the radio environment in a cost-effective manner, combining appropriate spectrum sensing techniques with use of a geolocation database and sensing the environment with minimum external hardware. Results obtained have been shown to be comparable with those obtained using a high cost spectrum analyser.

7.2 Future Work

Due to resource limitations and time constraints, some aspects of the system design and are left for future work, which may be considered as an extension of this thesis, focusing on either the Geolocation Database System, Low Cost RTL-SDR dongle or propagation models.

In the Geolocation Database direction, improvements could be made to the white space device system by adding the technique "Geolocation Database Learning", Here the ability to learn spectrum behaviour from the real environment can be developed. As this is a complex problem involving a large amount of data and lots of variables, machine learning would be the best approach. Machine learning is able to deal with data that is messy, incomplete, or in a variety of formats. For this application it could be employed to choose the right model for data measurement and contribute to improving the accuracy and performance of sensing the primary user. Using the Airspy Low Cost High Performance SDR (instead of the old version of the RTL-SDR) and trying to include this in the white space device system that has presented in this study. It would continue to investigate further results and attempt to increase the accuracy of the sensing whilst reducing in cost and shortening sensing time.

In the propagation models direction, it would investigate the use of other propagation models to improve our system and to increase the geolocation database accuracy and efficiency, such as Longley rice model and cost Hata model.

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Appendices

Appendix A- Measurement System using RTL-SDR in TV band

The software can measure and display TV band signals by using both the RTL-SDR spectrum analyser dongle and a high cost spectrum analyser. There are several stages to running the measurement system and displaying the measured signals.

1- Input suitable parameters as mentioned in the right-hand boxes (measurement parameters, measurement location) as shown in Figure 8.1.

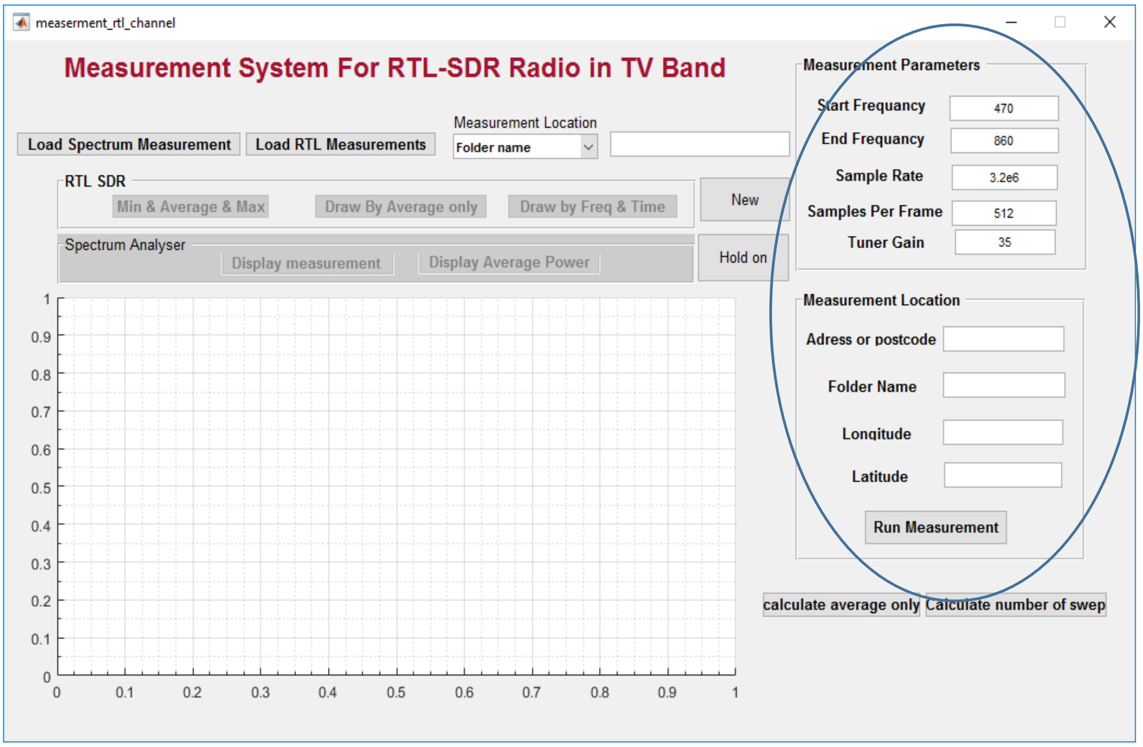

Figure 8.1: Measurement system – Input Measurement parameters

2- Connect the chosen spectrum analyser to the laptop.

3- Run the measurement by pressing “Run Measurement” as illustrated in the Figure 8.2.

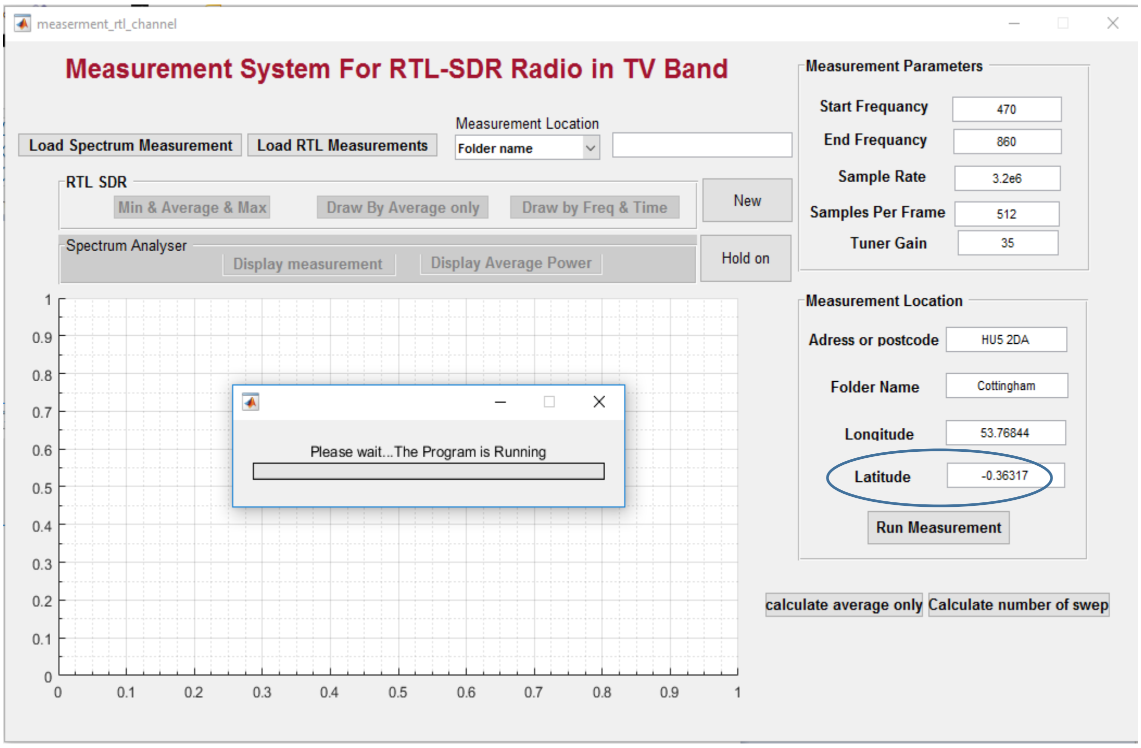

Figure 8.2: Measurement system - Measurement Implantation

4- To select the hop technique for the RTL-SDR only, press the button "calculate number of sweep" and then press button "calculate average only". as shown in Figure 8.3

5- For loading any measurement data from one of the spectrum analysers, press on the "load Spectrum measurement or load RTL measurement" for loading the list of measurement locations as shown in Figure 8.3

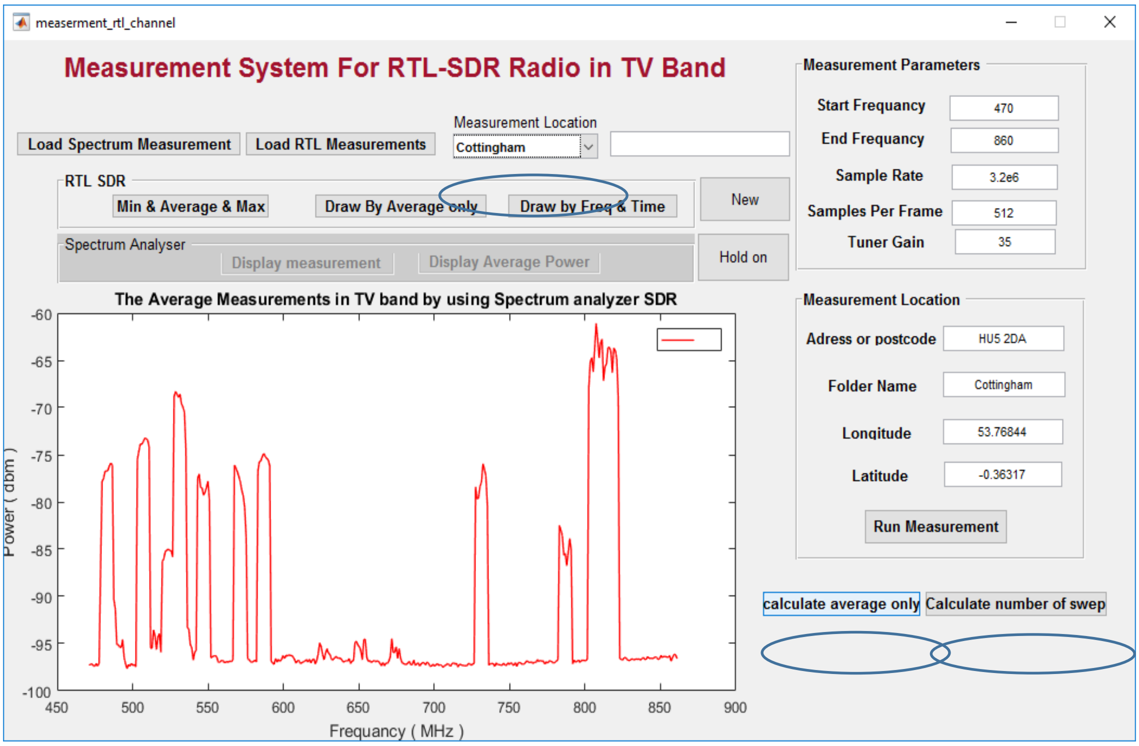

Figure 8.3: Measurement system - Display data Measurements

Appendix B- Simulation System for Creating TV white space database by using different propagation models

This software has various functions for creating a Geolocation database for different propagation models.

1- The first step for creating geolocation database is to select the geographical region for study by inputting the first point and second point (diametric opposite corners) of the specific area on the map as indicated in Figure 8.4.
2- Input the pixel size in metres and then press on the “Create Pixels” button.
3- The pixels that have been created can be shown by using the on the “Show all pixels” button.

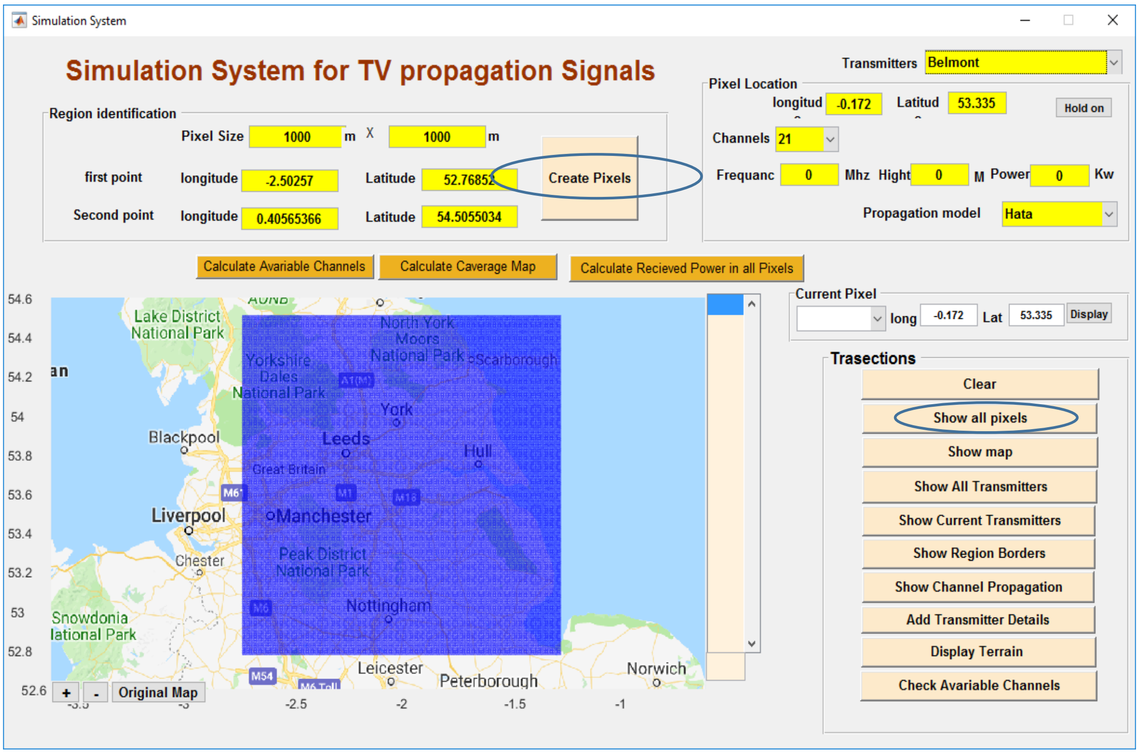

Figure 8.4: TV white space database system- Create Pixels

4- Calculate received power in all pixels for each transmitter and select one of the propagation models, and then click on the “Calculate Received power in all pixels” button, as illustrated in Figure 8.5.

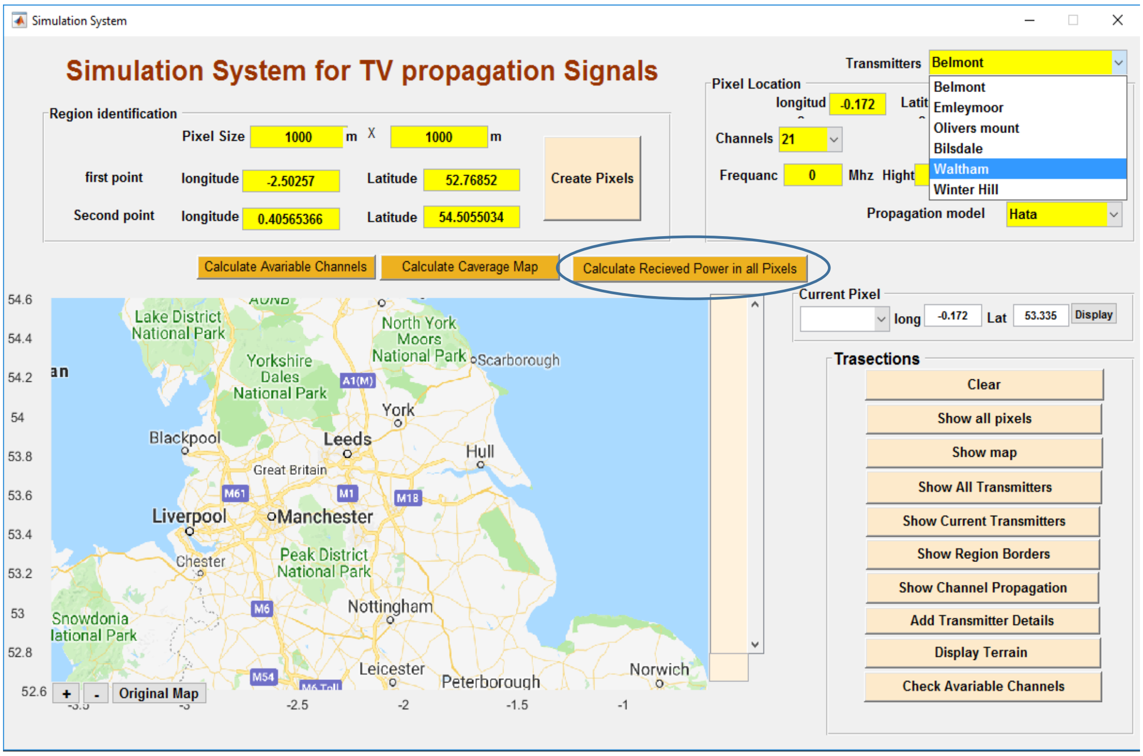

Figure 8.5: TV white space database system- Received power calculation

5- When the calculation of the received power has finished for all transmitters, the next step should be click on the “Calculate Coverage Map” button, this process has the ability to show the propagation results for each channel on the map.

6- The next process is to calculate the variable channels in each pixel, by clicking on the “Calculate Available channels” button. For testing the available channels on the specific location on the map, the location should be selected by clicking the “Display” button and then selecting any point on the map, as shown in the Figure 8.6.

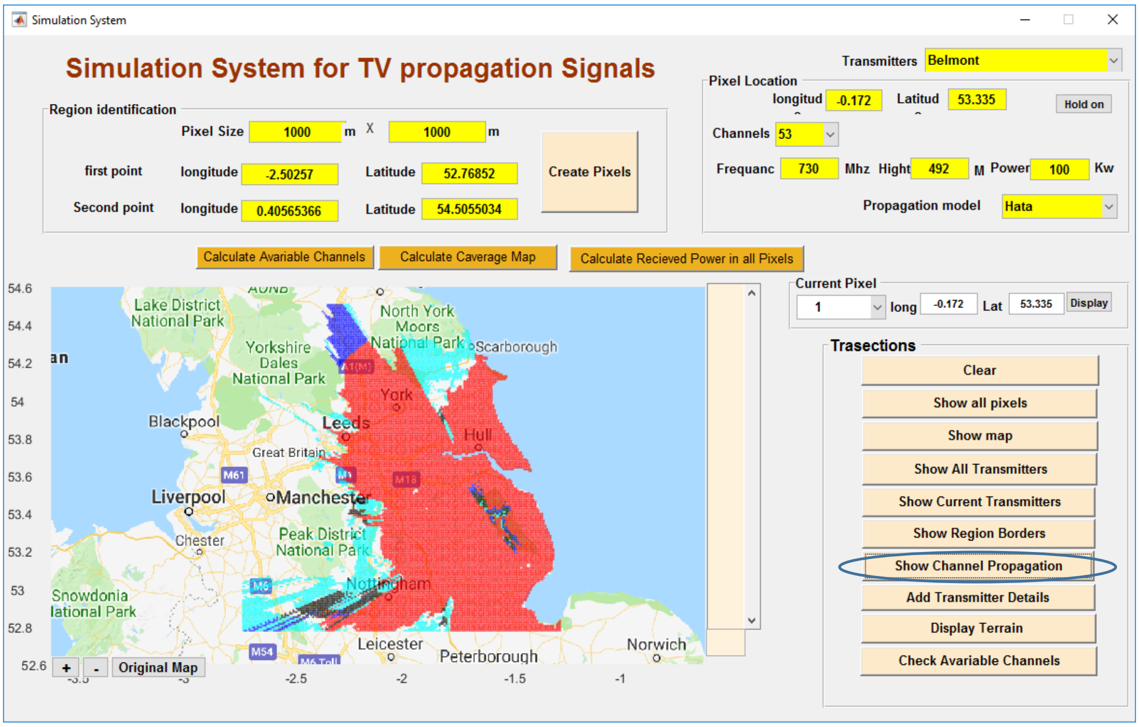

Figure 8.6: TV white space database system- Display channel propagation

Also, when selecting a point on the map, the information of the selected location will be displayed including Pixel number, longitude and latitude. The list of available channels in the location will then appear as illustrated in Figure 8.7.

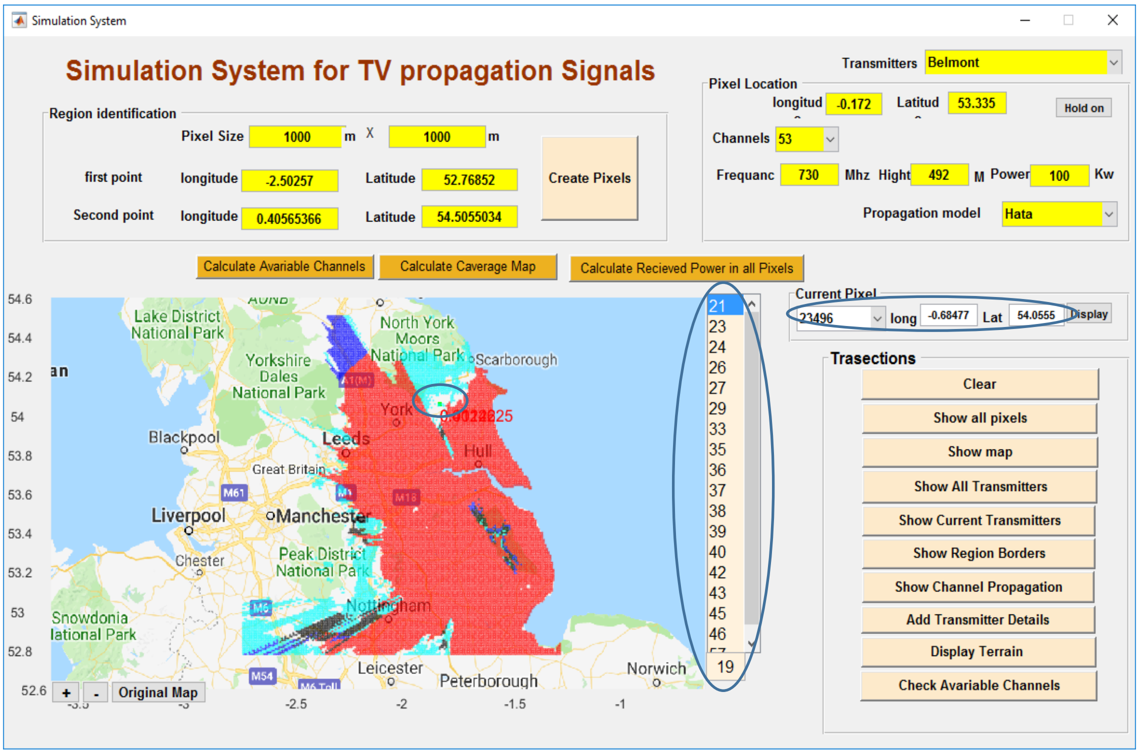

Figure 8.7: TV white space database system- Display Available channels

7- This system has the ability to show all transmitters on the map that have been stored on the database system as shown in the Figure 8.8.

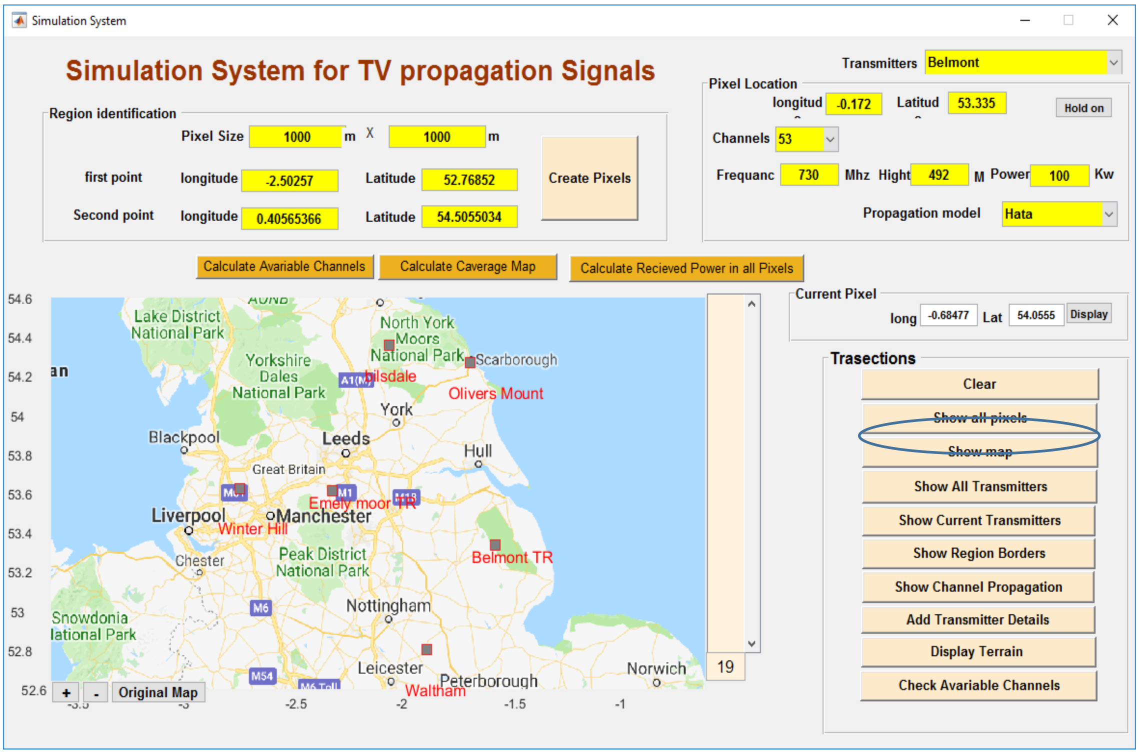

Figure 8.8: TV white space database system - Display all transmitters

8- The terrain profile between a selected point and transmitter may be plotted as shows in Figure 8.9, Figure 8.10.

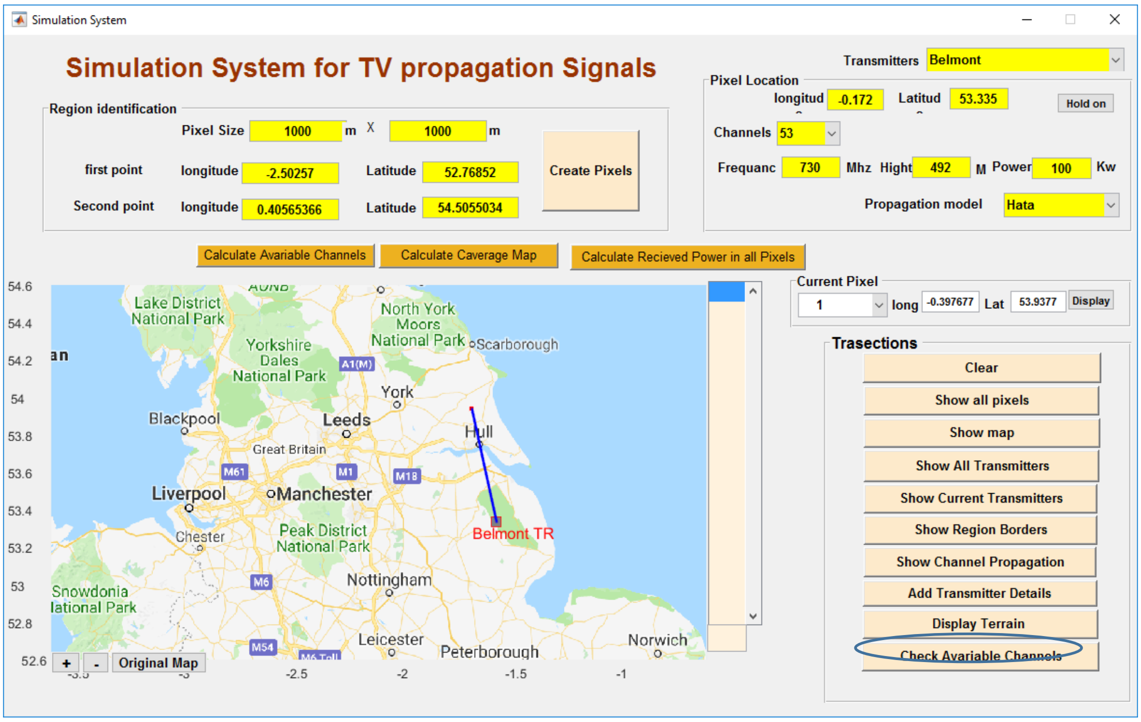

Figure 8.9: TV white space database system- Display the path from university of hull to Belmont transmitter

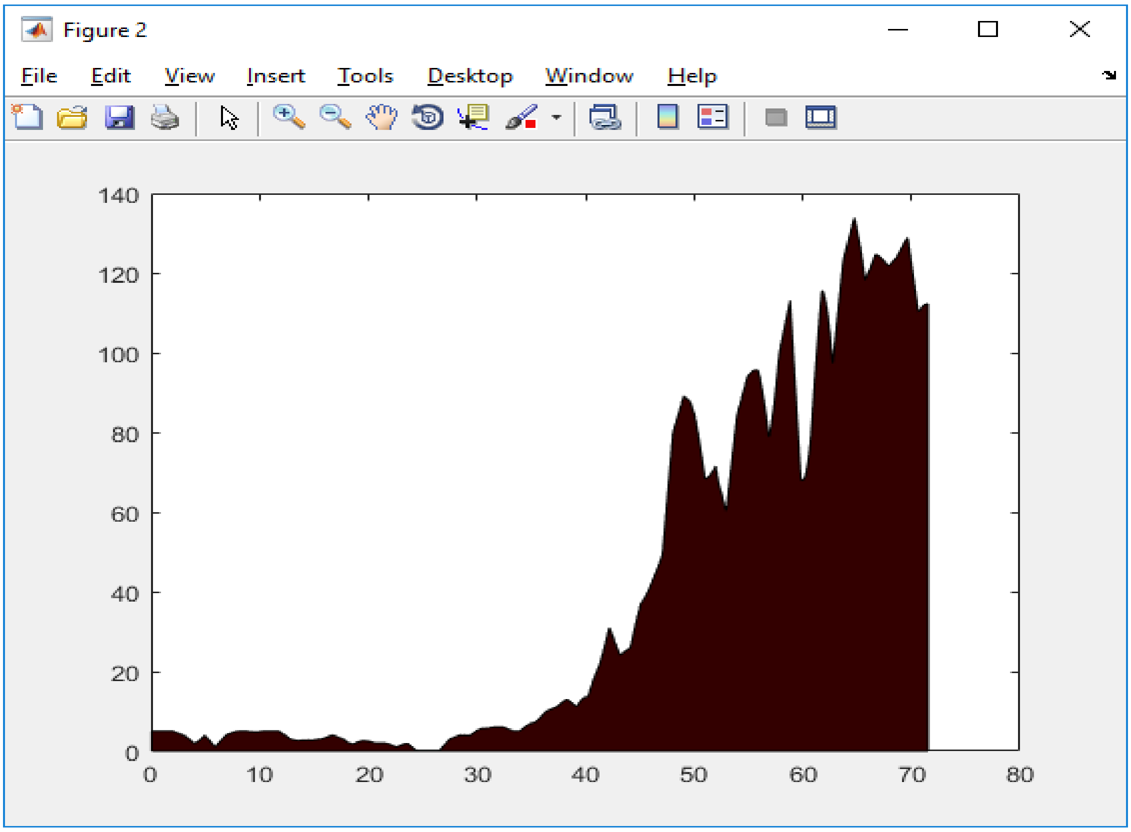

Figure 8.10: Display Terrain Elevation data from university of hull to Belmont transmitter

Appendix C- Algorithm for comparison of propagation model results with real measurements.

This algorithm is based on the terrain resolution data, which relies on a combination of parameters to calculate the diffraction path loss in each propagation, and then compared with the path loss of the real measurement as shown in Figure 8.11.

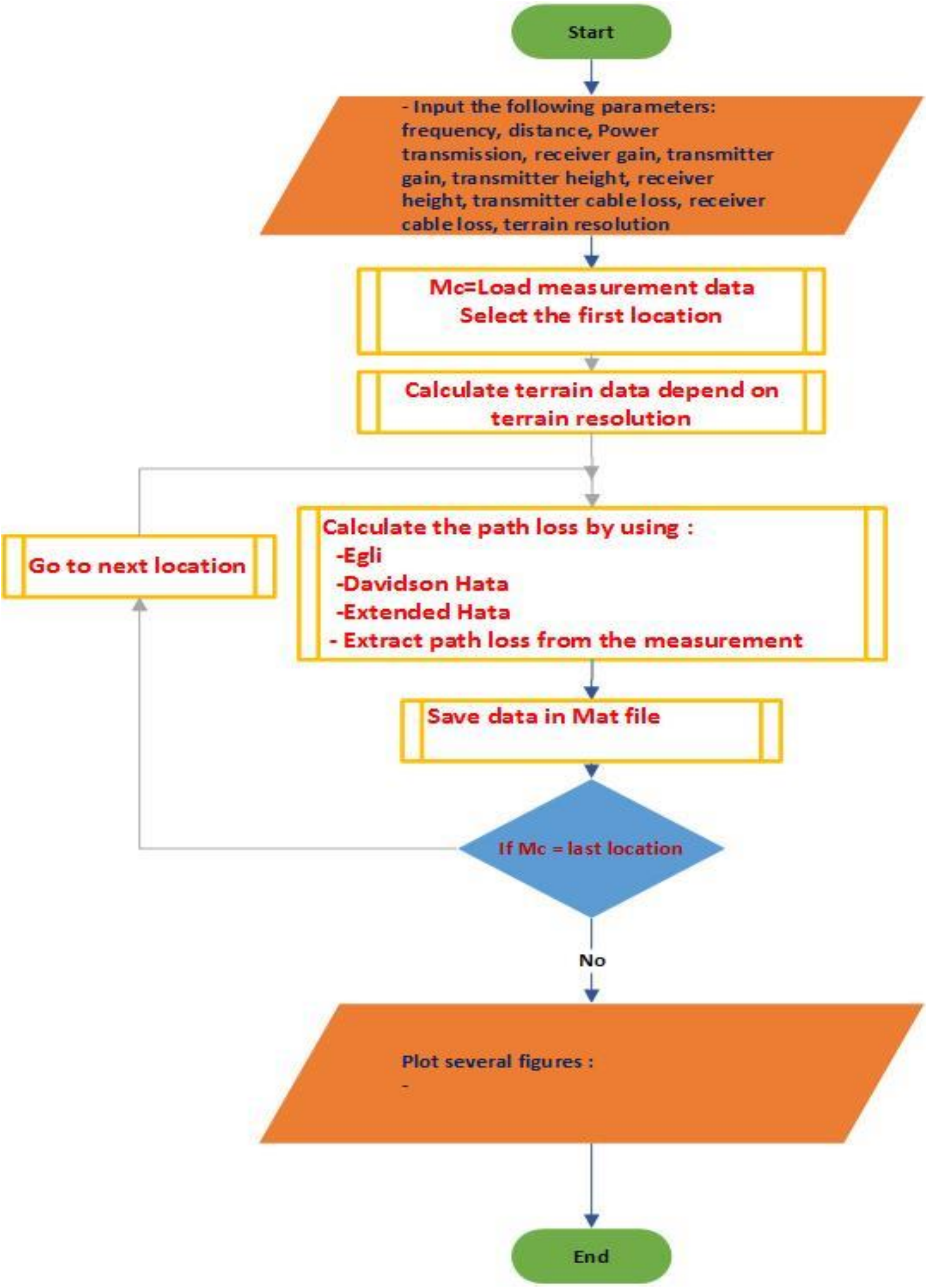

Figure 8.11: Comparison of propagation models algorithm

Appendix D- White Space Device System

This system has the ability to sense a primary user by using two techniques: geolocation database and spectrum sensing. There are several stages to run this system.

1- One of the spectrum analyzers or RTL-SDR should be connected with the system.

2- Select the location where you would check available channels by using latitude and longitude and then pointed on the map, as shown in Figure 8.12

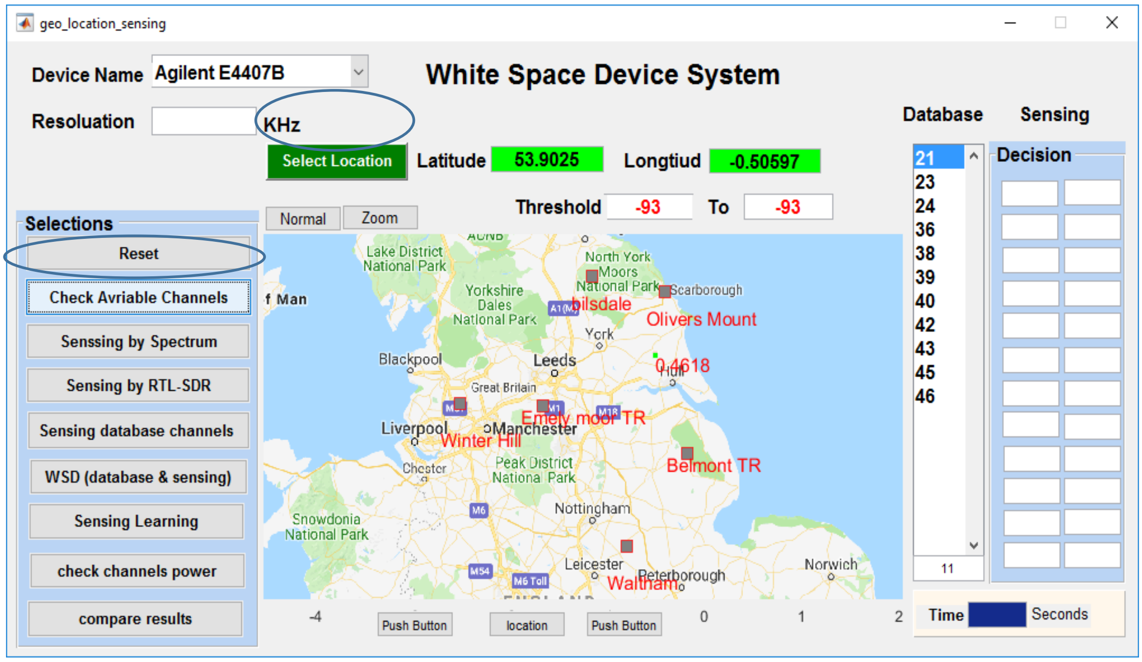

Figure 8.12: White space device system

3- Check available channels by using "check variable channels" button or click WSD button, which has ability to send the query to the database to retrieve available channels and also sensing by using a spectrum analyser.

4- In the same location, and after using different spectrum analysers, the system can compare between the results by clicking on the "compare results" in different resolution bandwidth (RBW).