DESIGN AND SIMULATION OF A SMART POWER GRID COMMUNICATION NETWORK OVER TV WHITE SPACE USING COGNITIVE MACHINE-TO-MACHINE NETWORKING

KENNETH KURIA KIMANI

MASTER OF SCIENCE

(Telecommunication Engineering)

JOMO KENYATTA UNIVERSITY OF

AGRICULTURE AND TECHNOLOGY

2019

Design and simulation of a smart power grid communication network over TV white space using cognitive machine-to-machine networking

Kenneth Kuria Kimani

A thesis submitted in partial fulfillment for the Degree of Master of Science in Telecommunication Engineering in the Jomo Kenyatta University of Agriculture and Technology

2019

DECLARATION

This thesis is my original work and has not been presented for a degree in any other University.

Signature: ____________________ Date: ______________________

Kenneth Kuria Kimani

This thesis has been submitted for examination with our approval as the university supervisors:

Signature: _____________________ Date: ______________________

Dr. Kibet Langat

JKUAT, Kenya

Signature: _____________________ Date: ______________________

Prof. Vitalice Oduol

University of Nairobi, Kenya

DEDICATION

I dedicate this thesis to my loving father James Kimani Mwangi and Mother Nancy Wanjiku Kimani for the great support and training and upbringing in my life and for support throughout my education. Above all, thanks to the almighty God.

ACKNOWLEDGEMENTS

I would like to express my deep gratitude to God the almighty and all those who supported me. In particular, I offer my sincere gratitude to my supervisors, Dr Kibet Langat and Prof Vitalice Oduol who introduced me to research, gave me the opportunity to pursue my research ideas, supervised me and kept me on the right track. I also want to thank the telecommunications department at JKUAT for providing me with a conducive environment to conduct my research. Finally, I would like to thank my Father and my Mother who bought me up, took me to good school and supported me through prayers in this walk of research. God bless you all and take good care of you.

TABLE OF CONTENTS

DECLARATION ..... **ii**

DEDICATION ..... **iii**

ACKNOWLEDGEMENTS ..... **iv**

TABLE OF CONTENTS ..... **v**

LIST OF TABLES ..... **ix**

LIST OF FIGURES ..... **x**

LIST OF APPENDICES ..... **xii**

LIST OF ABBREVIATIONS ..... **xiii**

ABSTRACT ..... **xvi**

CHAPTER ONE **1**

INTRODUCTION **1**

1.1 Background 1

1.2 Problem Statement 3

1.3 Justification 3

1.4 Research Objectives 4

1.4.1 Main Objective 4

1.4.2 Specific Objectives 4

1.5 Scope of Research 4

1.6 Organization of the Thesis 5

CHAPTER TWO **6**

LITERATURE REVIEW **6**

2.1 TV White Space (TVWS) 6

2.1.1 Analogue Switch-off 6

2.1.2 Digital dividend 7

2.1.3 TVWS as Shared Spectrum 8

2.1.4 Benefits of exploiting TVWS 9

2.1.5 Spectral co-existence 10
2.2 Interference 11
2.2.1 Interfering modes (unwanted and blocking) 12
2.2.2 Co-channel Interference 13
2.2.3 Adjacent Channel Interference 14
2.3 Cognitive Radio Technology 15
2.3.1 Dynamic Spectrum Access 16
2.3.2 Major Functions of Cognitive Radio 17
2.3.2.1 Spectrum Sensing 18
2.3.2.2 Spectrum Management 18
2.3.2.3 Spectrum Mobility 19
2.3.2.4 Spectrum Sharing 19
2.4 Classification of Spectrum Sensing Techniques 19
2.4.1 Primary Transmitter Detection 20
2.4.1.1 Matched Filter Detection 20
2.4.1.2 Energy Detection 21
2.4.1.3 Cyclostationary Feature Detection 23
2.5 Machine-to-Machine (M2M) communications 25
2.5.1 Requirements of the M2M communication in SG. 26
2.5.2 Cognitive M2M 28
2.5.3 CM2M network architecture for the smart grid 29
2.5.3.1 Wide Area Networks (WANs) 30
2.5.3.2 Home Area Networks 30
2.5.3.3 Neighborhood Area Networks 30
2.6 Review of Existing Systems in Smart Grid 31
2.6.1 Review of Existing Communication Technologies 31
2.6.1.1 Wired Communication 31
2.6.1.2 Wireless Communication 31
2.6.1.3 Comparison Between Various Communication Technologies 32
2.6.2 Gaps in Existing Grid Networks 34
2.6.3 Load Balancing 37
2.7 Channel Propagation Model for TVWS Devices 39
2.7.1 Path-Loss models 39

2.7.1.1 Free Space Path Loss Model ... 40
2.7.1.2 Okumura-Hata Path Loss Model ... 41
2.7.1.3 Hata-Okumura Extended Model (ECC-33 Model) ... 42

CHAPTER THREE ... 44

DYNAMIC SPECTRUM ACCESS FOR PROPOSED COMMUNICATION NETWORK ... 44

3.1 Interference analysis for coexistence ... 44
3.1.1 Interference Modelling ... 44
3.1.2 Interference Simulation ... 47
3.1.2.1 Simulation Scenario 1: ... 47
3.1.2.2 Simulation Scenario 2: ... 49
3.1.2.3 Simulation Scenario 3: ... 50
3.2 Comparison Between the Various Spectrum Sensing Techniques ... 52
3.2.1 Receiver operating characteristics (ROC) curves ... 52
3.2.2 Choice of detection method. ... 58

CHAPTER FOUR ... 59

THE DESIGNED COMMUNICATION NETWORK ... 59

4.1 CM2M Communication in Smart Power Grid ... 59
4.2 Designed Network Layout ... 60
4.3 Designed Detection Mechanism ... 61
4.3.1 Operational Design ... 62
4.3.2 Cooperative Transmitter Sensing ... 63
4.3.3 Using history for prediction ... 64
4.3.4 Frame Structure for SG Communications ... 66
4.3.5 Principle of Operation of the Detection Mechanism ... 67
4.4 Designed SG Communication Network ... 69
4.4.1 Network Simulation ... 69

CHAPTER FIVE ... 74

RESULTS AND DISCUSSION ... 74

5.1 Path-Loss Analysis ... 74
5.2 Power Consumption ... 76

5.3 Throughput Analysis 78
5.4 Results Validation 79
CHAPTER SIX 83
CONCLUSION AND RECOMMENDATIONS 83
6.1 Conclusion 83
6.2 Recommendations and Future Work 84
REFERENCES 86
APPENDICES 97

LIST OF TABLES

Table 2.1: Comparison between different potential communication technologies for the smart grid..33

Table 3.1: Simulation modelling parameters 46

Table 3.2: Simulation parameters (Same Channel)...48

Table 3.3: Simulation parameters (Adjacent Channel)...49

Table 3.4: Simulation parameters (2nd Adjacent Channel) 50

Table 5.1: Parameters to calculate path loss 75

Table 5.2: Sensing Requirements for IEEE 802.22 standard....................................80

LIST OF FIGURES

Figure 2.1: Spectrum Occupancy Measurements. 6

Figure 2.2: Coexistence between Primary Users and Secondary Users. 11

Figure 2.3: Power levels used to determine presence/absence of interference......... 12

Figure 2.4: Interference due to the unwanted emissions.. 12

Figure 2.5: Blocking of the victim receiver 13

Figure 2.6: Combined unwanted emissions and receiver blocking mechanism. 13

Figure 2.7: Co-channel interference scenario. 14

Figure 2.8: The dynamic spectrum access by Cognitive Radio. 17

Figure 2.9: The cognitive cycle in detecting spectrum holes.................................. 18

Figure 2.10: Classification of spectrum sensing techniques. 20

Figure 2.11: Block Diagram for Matched Filter Detection...................................... 21

Figure 2.12: Energy detector block diagram. 22

Figure 2.13: Block diagram for cyclostationary feature detection........................... 25

Figure 2.14: Architecture of M2M Networks. 26

Figure 2.15: Hierarchical structure of CM2M architecture. 30

Figure 2.16: Average daily load profile curve. 38

Figure 2.17: Average weekly load profile curve.. 38

Figure 3.1: Overview of interference scenario in SEAMCAT. 44

Figure 3.2: dRSS and iRSS values of co-channel SU... 48

Figure 3.3: Probability of interference against transmit power of co-channel SU. .. 48

Figure 3.4: dRSS and iRSS values of 1st adjacent SU. 49

Figure 3.5: Probability of interference against transmit power of 1st Adjacent SU.. 50

Figure 3.6: dRSS and iRSS values of 2nd adjacent SU. 51

Figure 3.7: Probability of interference against transmit power of 2nd Adjacent SU. 51

Figure 3.8: Energy Detection ROC curve for P_D vs SNR with varying $P_{FA.}$ 54

Figure 3.9: Energy Detection ROC curve for P_D vs P_{FA} with varying SNR. 54

Figure 3.10: Energy Detection ROC curve for P_{MD} vs P_{FA} with varying SNR......... 55

Figure 3.11: Matched Filter Detection ROC curve for P_D vs SNR........................... 55

Figure 3.12: Matched Filter Detection ROC curve for P_D vs $P_{FA.}$ 56

Figure 3.13: Matched Filter Detection ROC curve for P_{MD} vs $P_{FA.}$.......................... 56

Figure 3.14: Cyclostationary Detection ROC curve for P_D vs $P_{FA.}$ 57

Figure 3.15: Performance Comparison of Transmitter Detection Techniques. 57

Figure 4.1: Proposed Network Layout. 61

Figure 4.2: Proposed network design.. 63

Figure 4.3: Effect of Cooperative Sensing on time factor. 64

Figure 4.4: Learning process utilized by the system. 65

Figure 4.5: Communication frame for secondary cognitive radio networks. 66

Figure 4.6: Flowchart of the proposed detection model 68

Figure 4.7: Secondary Node Architecture as modelled in Omnet++. 70

Figure 4.8: Simulation Environment Parameters 71

Figure 4.9: Simulated Smart Grid Communication Network. 72

Figure 5.1: Extended Okumura-Hata Path loss Comparison. 76

Figure 5.2: Power consumption in the designed M2M devices 77

Figure 5.3: Throughput Analysis on PU reappearance. 78

Figure 5.4: Validation of Spectrum Sensing Performance 79

Figure: 5.5: Cyclostationary detector performance. 80

Figure: 5.6: Comparative Procedure of Spectrum Sensing at SU nodes. 82

LIST OF APPENDICES

Appendix I: Matlab Pseudo-Code for Spectrum Sensing...……………….…..….106

Appendix II: Omnet++ Code for Communication Network Design.……..…..….109

Appendix III: List of Publications …………………………..………..……….112

LIST OF ABBREVIATIONS

A/D	Analogue to Digital
ACI	Adjacent Channel Interference
ACLR	Adjacent channel leakage ratio
ACS	Adjacent channel selectivity
AMI	Advance Metering Infrastructure
ASO	Analogue Switchoff
AWGN	Additive White Gaussian Noises
BS	Base station
BSD	Broadcast Signal Distributor
CA	Communications Authority of Kenya (Previously CCK)
CCI	Co-Channel Interference
CEPT	European Conference of Postal and Telecommunications Administrations
CM2M	Cognitive Machine-to-Machine
CPE	Customer Premises Equipment
CR	Cognitive Radio
CRN	Cognitive Radio Network
DD1	Digital dividend 1
DRM	Demand Response Management
dRSS	desired Received Signal Strength
DSA	Dynamic Spectrum Access
DSM	Demand Side Management
DSO	Digital Switchover
DTT	Digital Terrestrial Television
DTV	Digital Television

DTVB	Digital Television Broadcast
DVB	Digital Video Broadcasting
DVB-T	Digital Video Broadcasting – Terrestrial
DVB-T2	Digital Video Broadcasting –Second Generation Terrestrial
ECC	Electronic Communications Committee
EIRP	Effective Isotropic Radiated Power
ETSI	European Telecommunications Standards Institute
FC	Fusion Centre
FCC	Federal Communications Commission
GPS	Global Positioning System
GW	Gateway
HAAT	Height above Average Terrain
HAN	Home Area Network
IEEE	Institute of Electrical and Electronics Engineers
IoT	Internet of Things
iRSS	interfering Received Signal Strength
ISI	Inter Symbol Interference
ISM	Industrial, Scientific and Medical Band
ITU	International Telecommunication Union
LTE	Long Term Evolution
M2M	Machine-to-Machine
MPEG	Motion Picture Expert Group
MTC	Machine Type Communication
NAN	Neighbourhood Area Network
NLOS	Non-line-of-sight

OFCOM Office of Communications (United Kingdom communications regulator)

OFDM Orthogonal Frequency Division Multiplexing

OSA Opportunistic Spectrum Access

PLC Power Line-based Communication

PMSE Program Making and Special Event

PU Primary User

QoS Quality of Service

ROC Receiver Operating Characteristics

SCADA Supervisory Control and Data Acquisition

SDR Software Digital Radio

SEAMCAT Spectrum Engineering Advanced Monte Carlo Analysis Tool

SEM Spectral Emission Mask

SG Smart Grid

SINR Software to Interference and Noise Ratio

SNR Signal-to-Noise Ratio

sRSS sensing Received Signal Strength

SU Secondary User

SUN Smart Utility Network

TVBD TV Band Device

TVWS TV White Space

WAN Wide Area Network

WiMAX Worldwide Interoperability for Microwave Access

WLAN Wireless Local Area Network

WRAN Wireless Regional Area Network

WSD White Space Device

ABSTRACT

Most of the current power grid networks are coupled with lots of inefficiencies mainly due to constant outages, overloading during peak times, service disruptions that are never reported in time and a lack of customer usage data and patterns in order to better understand and serve the customers. This is mainly due to lack of a reliable communication infrastructure between the grid devices, the provider and the customers. Scarcity of available spectrum, limited range of most unlicensed spectrum frequencies coupled with human inefficiencies are the biggest hindrances to building an effective communication network that can span the wide geographical regions covered by most grid networks. However, with the coming of age of cognitive radio technology that allows for spectrum sharing and allows opportunistic access to unused spectrum, spectrum utilization can be enhanced. The migration from analogue to digital television transmissions has freed large portions of the spectrum in the UHF/VHF bands that can be used for long distance propagation while the emergence of cognitive machine to machine communications can help eliminate human related inefficiencies resulting in timely production, exchange and processing of information. In this thesis, a smart grid communication network is designed utilizing dynamic spectrum access and TV white space using cognitive machine to machine networking. The designed smart grid communication network is able to acquire and process real time data from the grid hence allowing for automatic control and operation of the various systems in response to the users' needs. This in turn allows the utility companies to effect dynamic pricing structures where they charge higher prices during peak times and lower prices during off-peak times. This can then be used as one of the mechanisms to achieve load balancing.

CHAPTER ONE

INTRODUCTION

1.1 Background

Radio spectrum is a finite resource. Demand for access to spectrum has been growing dramatically, and is likely to continue to grow for the foreseeable future. New services are being launched and existing services continue to grow at dramatic rates, thereby creating demand for access to additional spectrum. At the same time, most of the spectrum has been assigned, and it is becoming increasingly difficult to find spectrum that can be made available either for new services or to expand existing ones.

The current spectrum management policy typically gives exclusive and unlimited access to license-holders. Despite revisions aimed at ensuring greater flexibility, the current framework continues to rely significantly on centrally managed allocation and assignment, with government regulators deciding how and by whom wireless communications are to be used. The table of frequency allocations maintained by the ITU and other regulatory bodies contains the usable parts of the electromagnetic spectrum and the allocation of that spectrum to vast numbers of different users and uses. Spectrum utilization measurements have however shown that most of the allocated spectrum is actually underutilized (Ghosh, Das, & Chatterjee, Simulation and Analysis of Cognitive Radio System Using Matlab, 2014).

The traditional practice of clearing and reallocating portions of the spectrum used (existing users relocated to some other portion of the spectrum) to create room for new services is not a sustainable model as this is a process that can be time consuming (taking years) and expensive. Spectrum sharing however is possible without such radical change to better utilize the spectrum and make current wireless systems more spectrally efficient (Werbach & Mehta, 2014).

One of the most exciting new ways of spectrum sharing is called cognitive radio networking. Cognitive radio networking is a paradigm for wireless communications in which either a network or a wireless node changes its transmission or reception parameters to communicate efficiently while avoiding or mitigating interference with licensed or unlicensed users (Hossain & Bhargava, Cognitive Wireless Communication Networks, 2007).

Use of spectrum sharing instead of exclusivity has created new opportunities for new technologies such as a smart grid communication network. Most of the current grid networks in use today are not intelligent and they are prone to constant outages, overloading during peak hours, service disruptions that are never reported in time, human inefficiencies such as in meter transactions (meter reading in analogue meters and prepaid code generation and inputting in digital meters). These problems are mainly due to a lacking communication infrastructure between the network devices, the providers and the customers.

The recent migration from analogue to digital TV technology has freed up large portions of the spectrum in the UHF/VHF bands for reallocation to other licensed uses and also for opportunistic secondary access. These UHF/VHF bands have the ability to cover a greater area at a relatively lower cost, offer non-line-of-sight performance and low power consumption (Saeed & Shellhammer, 2011). These characteristics offer ideal conditions for deployment of a cognitive radio network especially in creating a Wireless Regional Area Network (WRAN) for the smart grid communication network.

Additionally, the key to eliminating the human errors and inefficiencies in the current grid networks is to integrate machine to machine communications (M2M) in the smart grid communication network. Machine to machine communications (M2M) are characterized by low power, low cost, and low human intervention (Antón-Haro & Dohler, 2015).

All these technologies combine dynamically adapting and utilizing the underutilized spectrum for communication to unlock the true potential of seamless smart grid systems. In this research, a smart power grid communication system utilizing TV white space and cognitive machine to machine communications is designed. Smart grid communications consist of multiple two-way, short data bursts transmissions of low bandwidth, delay-tolerant traffic that is well suited for communication in the designed communication network.

1.2 Problem Statement

One of the hindrances to developing a wireless smart grid communication network is the scarcity of available spectrum since in the current licensing scheme, spectrum bands are pre-assigned for fixed uses and certain bands can only be used for specified uses. However, worldwide spectrum occupancy measurements show that more than 70\% of the available spectrum is not utilized efficiently thus building a smart power grid communication network will require a dynamic spectrum access mechanism to opportunistically utilize unused spectrum without putting any more pressure on the current strained spectrum resources and without the current human inefficiencies associated with the current grid network.

1.3 Justification

The coming of age of the digital era has heralded a surge in number of smart end-to-end systems that require little or no human input. These smart systems however need to be in constant communication with each other in order for them to make timely decisions and for them to work effectively and efficiently.

Smart grid networks provide an intelligent monitoring infrastructure of the grid network and offers remote control of the various network devices in response to the changing needs of the users and the network. This requires a dynamic two-way communication system to be able to acquire and process real time data from the grid. Smart grid devices communication consists of small periodic bursts of traffic mainly in the uplink and utilizes battery operated devices designed for low power operations. Smart grid (SG) communications therefore needs to be designed to accommodate the current communication requirements as well as the potential demand of future applications as the grid network expands.

The application of Cognitive radio (CR) technology in smart grid communications has excellent capability to improve the spectrum usage. In addition, the application of cognitive radio network can also alleviate the burden of purchasing licensed spectrum for utility providers by utilizing the free, unutilized and underutilized spectrum.

With smart grid communication the utility providing companies will be able to monitor the consumption levels and patterns of their customers and hence be able to plan and serve the customers more effectively and efficiently. This will help them in carrying out grid upgrades and re-routing of the supply channels to maximize on their customer needs. Also, to cover for inconsistencies in demand and supply, companies using cognitive radio smart grids will be able to effect dynamic pricing structures where they will have different prices such as higher prices for peak demand time to discourage much consumption and lower prices for off-peak demand times to encourage more consumption. This can be used as one of the measures to try and effect load balancing.

1.4 Research Objectives

1.4.1 Main Objective

- ❖ The main objective of this research was to design a smart power grid communication system based on a cognitive radio network over TV White Space using Machine-to-Machine (M2M) communications.

1.4.2 Specific Objectives

To achieve this main objective, the following specific objectives were carried out:

i. Investigate the suitability of opportunistic use of the TV White Space (TVWS) in a smart grid communication network and analyze interference to the primary users from secondary users in TV White Spaces.

ii. Evaluate the various spectrum sensing techniques in a cognitive radio network using dynamic spectrum access to determine a suitable one for the smart grid transmitter nodes.

iii. Design a Cognitive Machine-to-Machine (M2M) communication network for the smart grid.

iv. Evaluate the performance of the designed communication grid.

1.5 Scope of Research

The application of TVWS and cognitive machine to machine communications in smart grid networks is a very wide area of research. However, for purposes of this research, the three main areas which pose the biggest challenges in implementation of the smart grid network have been concentrated on.

One of the main challenges in a TVWS network is how secondary users can communicate effectively over the network without causing interference to the incumbent primary users. This research investigates the suitability of TVWS and the measures taken to minimize interference to the primary users.

One of the most important aspect of cognitive radios is spectrum sensing as it enables a cognitive radio to detect which parts of a spectrum are currently underutilized and unutilised in real-time. In this research, the main spectrum sensing techniques have been compared to determine the most suitable for application in the smart grid system.

Machine-to-machine (M2M) communications have emerged as a cutting-edge technology for next-generation communications. This research presents an investigation of the application of M2M communication in smart grid in order to eliminate the aspect of human inefficiencies in the production, exchange, and processing of data in the smart grid network. The validation of the results is done through simulations and comparison with other existing technologies.

1.6 Organization of the Thesis

The thesis is organized as follows. Chapter Two gives overviews of the relevant TVWS and spectrum sensing literature and a review of current smart grid and M2M technologies. Chapter Three investigates the interference analysis of TVWS and the best spectrum sensing mechanism for dynamic spectrum access. The details of the designed communication network are given in Chapter Four. Chapter Five presents and discusses the experimental results in detail. The conclusions of the research are drawn in Chapter Six while Chapter Seven summarizes the recommendations and further work to be done to extend the research work.

CHAPTER TWO

LITERATURE REVIEW

2.1 TV White Space (TVWS)

According to research done by the IEEE 802.22 Working Group (IEEE 802.22 WG), less than 14\% of the spectrum is effectively utilized – 86% of the spectrum is not used or scarcely used (See Figure 2.1) (Mody, 2013). In Kenya, a study was done to determine the usability of 700 MHz frequency band previously allocated for TV channels 52-69 (Arato & Kalecha, 2013). The study showed that the spectrum occupancy is only 5.26%. This shows that although most of the electromagnetic spectrum has already been allocated to the different users, its utilization is quite low. A new approach is thus required to utilize this free spectrum without antagonizing the already licensed users of the spectrum in order to cater for the expanding wireless systems competing for the finite spectrum resource.

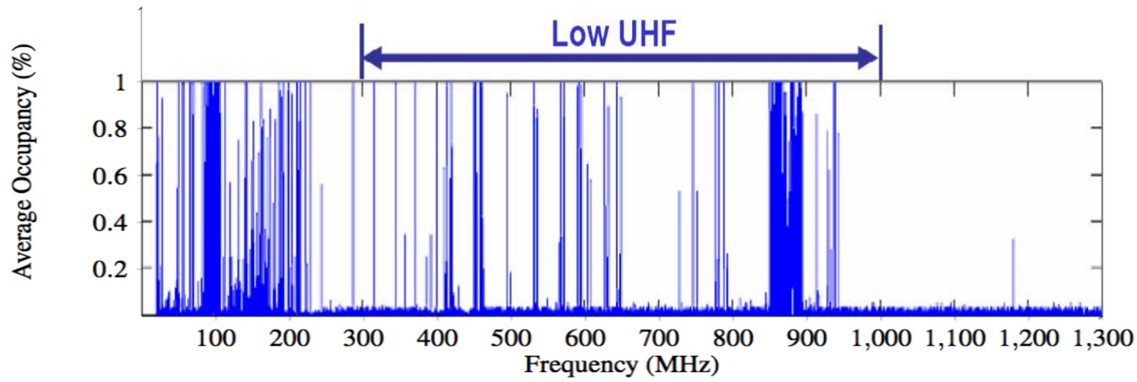


Figure 2.1: Spectrum Occupancy Measurements.

2.1.1 Analogue Switch-off

Prior to 17 June 2015, the bands 47 - 68 MHz, 174-230 MHz and 470-806 MHz were allocated to analogue terrestrial television broadcasting service. Analogue signals required more broadcasting spectrum than digital television and were more susceptible to interference and distortion and hence needed to be spaced far apart to avoid interference.

However, with the migration from analogue to digital transmission, digital transmissions are more spectrally efficient and hence can be compressed such that many more fit in the space of the original analogue channel width (International Telecommunication union, 2011). Digital TV in Kenya uses the MPEG 4 compression mode (Gbenga-Ilori & Ibiyemi, 2010) (Ndonye, Khaemba, & Bartoo, 2015). The adopted DVB-T2 MPEG-4 standard accommodates up to 20 standard definition television channels in the same amount of spectrum used to transmit one analogue television channel. This created better efficiency in spectrum management, allowed for more uniform broadcasting coverage, and reduced potential signal interference (Telecommunications Management Group, Inc, 2017).

2.1.2 Digital dividend

The migration to digital platform of broadcasting has produced what is known as digital dividend. Digital dividend refers to the radio spectrum which is freed when television broadcasters switched from analogue TV to digital-only platforms since digital television needs less spectrum than analogue television. One reason is that new digital video compression technology can transmit numerous digital sub-channels using the same amount of spectrum used to transmit one analogue TV channel. Another reason is that digital transmissions require much less of a guard band on either side, since they are not nearly as prone to RF interference from adjacent channels. Because of this, there is no longer any need to leave empty channels to protect stations from each other, in turn allowing stations to be repacked into fewer channels, leaving more contiguous spectrum to be allocated for other wireless services.

Planning for the analogue to digital television migration in Kenya began in 2006 and took nine years to achieve. The World Radio Communication Conference 2007 (WRC-07) allocated the upper part of the UHF band (790–862 MHz) to the mobile service in Region 1 as from 2015, under the condition that they protect broadcasting services against harmful interference. The migration allowed the government to recover 168 MHz in the 700 MHz and 800 MHz bands and repurpose these frequencies for provision of high-speed 4G mobile broadband services. Digital television channels are assigned channels 21-48 (470-694 MHz). The 800MHz frequency band (encompassing spectrum in 790-862 MHz frequency range) is referred to as digital dividend 1 (DD1) while the 700MHz frequency band (encompassing spectrum in the

694-790 MHz frequency range) is referred to as digital dividend 2 (DD2) (Kennedy, George, Vitalice, & W., 2015). It was agreed by African countries that DD1 be allocated to mobile services after the digital switchover (DSO) whose deadline was June 17, 2015.

In Kenya digital migration was completed in 2015 and Kenya was one of only 37 countries that completed their ASO by the global GE06 digital migration deadline of June 25, 2015. With the digital switchover the available spectrum for TV broadcasting reduced from 448 MHz to 224 MHz whilst the number of broadcasters increased from 14 to 65. However most African countries have yet to complete the digital migration process. As of January 2017, only seven of the 54 African countries have completed the ASO (Telecommunications Management Group, Inc, 2017). The transition to digital television has introduced unique opportunities for exploitation of locally underused portions of the TV bands.

2.1.3 TVWS as Shared Spectrum

TV White Space refers to low-power, unlicensed operation of communications services in unused portions of RF spectrum that fall within frequencies allocated by regulators to television broadcasters and wireless microphones. A TV white space channel is thus an unoccupied or unused TV channel in the Very High Frequency (VHF) and Ultra High Frequency (UHF), i.e. there is no active TV broadcasting on the channel. White spaces exist naturally between used channels, since assigning nearby transmissions to immediately adjacent channels will cause destructive interference to both channels. In addition to white space assigned for technical reasons, there is also unused radio spectrum which has either never been used or is becoming free as a result of technical changes and in particular the switchover from analogue to digital television frees up large areas between 54MHz and 694MHz. This is because digital transmission can be packed into adjacent channels while analogue ones cannot. This means that the band can be compressed into fewer channels while still allowing for more transmissions. The unused portions are referred to as spectrum white space.

The TV white spaces can arise from the following three aspects: -

a) Frequency domain - The electromagnetic spectrum is fragmented into sets of frequency bands most of which are licensed to different users or allocated for specific uses. If some band is not allocated to anybody, then that is a white space in frequency domain (often-called Spectrum hole). These spectrum holes have also arisen in TV bands due to analogue to digital migration and includes the guard bands that are left intentionally between two adjacent channels to guard against interference.

b) Time domain - If a user does not use the spectrum allocated to them for a period of time, that spectrum can be utilized by someone else for that idle period. In this case if the TV broadcasters are not using their allocated frequencies for a period of time, it is a TV white space in time domain.

c) Space domain - Any wireless transmission is limited by its range. White spaces therefore exist where there is no coverage or where there are holes in the geographical coverage provided by the primary licensee. For example, FM radio stations have a range of around 50 km radius beyond which you can't listen to the FM radio. Thus the same frequency can be used to transmit outside that radius without interfering with that station. This technique is usually applied in GSM, where frequencies are reused in every 7th cell (Tse & Viswanath, 2005).

For purposes of this paper the term TV white space has been used interchangeably to refer to any or various combinations of the above three domains. A first adjacent (white space) channel is a white space channel that is right next to an occupied TV channel. A second adjacent (white space) channel is a white space channel that is two channels away from an occupied TV channel. However, for purposes of this paper, the term second adjacent (white space) channel has been used to refer to a white space channel that is not neighboring any occupied TV channel.

2.1.4 Benefits of exploiting TVWS

With demand for wireless connectivity increasing, the exploitation of white space is an attractive way of making more efficient use of radio spectrum simply by sharing the spectrum such that if not used in one location of a country by the primary user, then in that geography it can be redeployed and used by secondary users as long as it will not interfere with the primary users (Electronic Communications Committee (ECC), 2008). FCC's recent ruling that allowed for unlicensed radio operation in the unused portions of the VHF and UHF spectrum has led to great interest in developing wireless communications in this spectrum as it benefits from great signal propagation and penetration properties, which allows for long transmission ranges (Fatemieh, Chandra, & Gunter, 2010).

According to Friis's law, the range of a radio depends on the wavelength where shorter wavelengths (higher frequencies) travel shorter distances for a given power level, receiver sensitivity, and antenna gains. Whereas a 2.4-GHz signal may travel up to several meters under the right conditions, a signal in the UHF range from 470 MHz to 698 MHz can travel many miles, up to 100 kilometres. By physical law, the coverage of a radio device is proportional to the square of the frequency (Xin & Song, 2015). Due to this lower frequency spectrum, it costs cheaper to build a wireless network in the TV band frequencies since it allows deployment of fewer antennas operating at lower power levels and hence the number of base stations are lower compared to other higher frequency spectrum. TVWS therefore permits more expansive reach than conventional Wi-Fi networks, which utilize higher frequencies that limit their range.

2.1.5 Spectral co-existence

Opportunistic Spectrum Access (OSA) enables wireless devices to identify and make use of spectrum that is unused at a particular location and/or at a particular time. Primary users (PU) are licensed incumbent users and have the exclusive rights in using certain frequency band for communications. Secondary users (SU) are allowed to use the frequency spectra momentarily but only if they do not interfere with the PU. The primary and the secondary users coexist together in the same wireless ecosystem allowing secondary users to exploit unused and under-utilized spectrum.

Primary users i.e. licensed TV broadcasters and wireless microphone users must certainly be protected against potential interference from the secondary users and, on the other hand, sufficient freedom must be given to secondary users to exploit the available spectrum while guaranteeing the quality of service of the secondary users. The architecture of a secondary network superimposed on a primary network operating in the UHF/VHF spectrum bands is as shown in Figure 2.2.

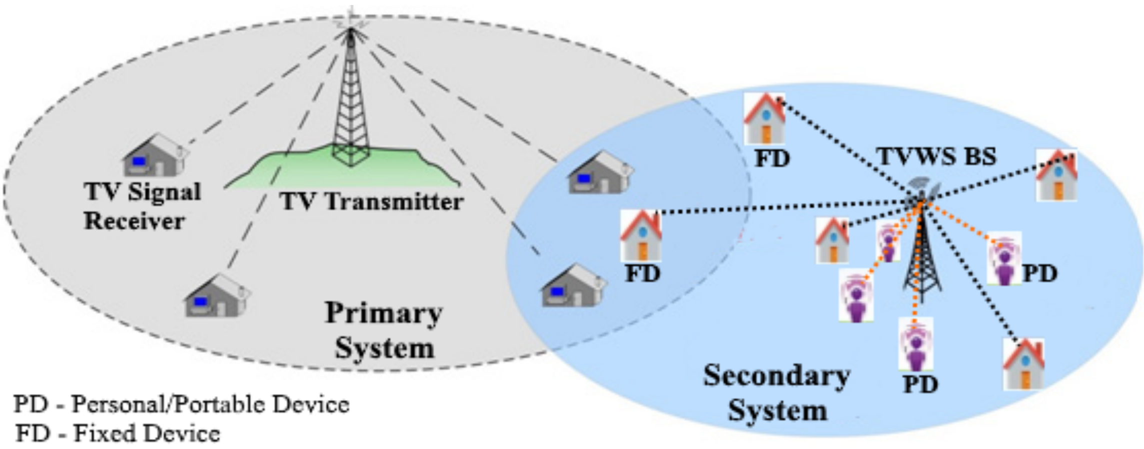


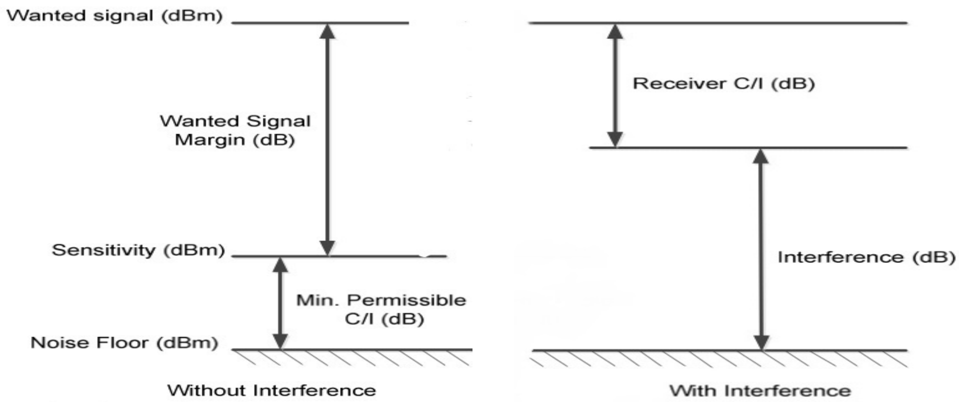
Figure 2.2: Coexistence between Primary Users and Secondary Users.

In recent years, available spectrum for this application has been reduced since some parts of the spectrum currently used by these applications have been targeted for other usages as a consequence of the digital dividend, and of the increase of bands designated for mobile broadband.

2.2 Interference

Interference is said to have occurred when the victim receiver has a carrier to interference ratio (C/I) that is below the threshold minimum value allowed (referred to as protection ratio) as shown in Figure 2.3. However, for us to calculate the victim's C/I it is imperative to determine the victim's desired Received Signal Strength (dRSS) in addition to the interfering Received Signal Strength (iRSS). The location of the victim's wanted signal transmitter is established and a link budget calculated. C/I is therefore the ratio of the power of the wanted signal to the total power of interfering signals and noise, evaluated at the receiver input.

Figure 2.3 illustrates the various signal power levels used to determine the presence or absence of interference.



(a) Without Interference **(b) With Interference**

Figure 2.3: Power levels used to determine presence/absence of interference

Figure 2.3 (a) represents a scenario where there is no interference and the victim is able to receive the wanted signal with some margin. In such a case the victim's C/I ratio can be obtained by the summation of the minimum permissible C/I and the wanted signal margin. Figure 2.3 (b) shows what occurs when interference is present. The interference adds to the noise floor and the victim's C/I ratio is decreased. The new C/I ratio is obtained by the difference (in dBs) between the increased noise floor and the wanted signal strength. If interference is to be avoided, then this ratio must be greater than the minimum permissible C/I.

2.2.1 Interfering modes (unwanted and blocking)

The level of unwanted emissions consists of the spurious emissions and out-of-band emissions of the interfering transmitter falling within the victim's receiver bandwidth. The unwanted emission is also referred to as the Adjacent Channel Leakage Ratio (ACLR) and is illustrated as shown in Figure 2.4 (European Communications Office (ECO), 2016).

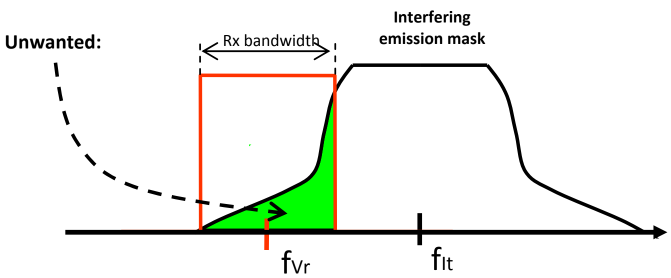


Figure 2.4: Interference due to the unwanted emissions.

The blocking power of the receiver is the power detected from the interferer's transmissions resulting from selectivity imperfections of the victim's receiver i.e. total emission power of interfering transmitter (It) reduced by the blocking attenuation (selectivity) function of the victim receiver (Vr) as shown in Figure 2.5.

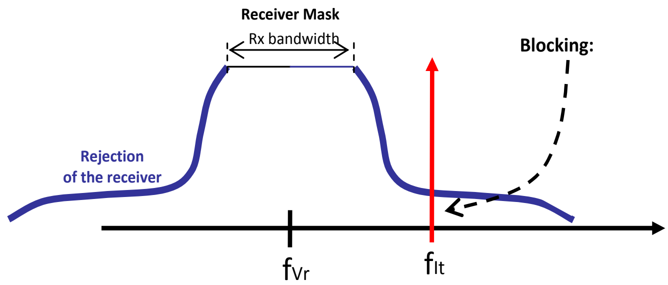


Figure 2.5: Blocking of the victim receiver

The main interference mechanisms to be analyzed are both the unwanted emissions and receiver blocking (European Communications Office (ECO), 2016) (Agrawal, Bhatia, & Bhadoria, 2016) shown in Figure 2.6.

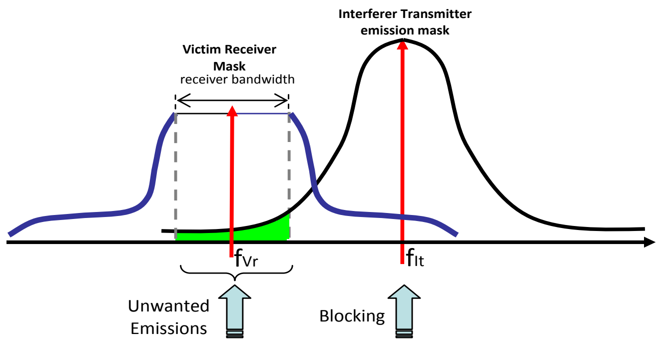


Figure 2.6: Combined unwanted emissions and receiver blocking mechanism.

The main types of interference between primary users and secondary users are:

2.2.2 Co-channel Interference

Co-channel interference refers to interference from the transmitter of the secondary system to the receiver of a licensed primary system and occurs if the secondary system transmits in an occupied TV channel as illustrated in Figure 2.7. This may be due to misdetection where the secondary user detects the primary user as absent due to fading and shadowing and attempts to transmit in the same frequency as the primary user or can also occur if the spectrum-sensing period is long enough that the secondary user is not able to detect the reappearance of the primary user fast enough in a previously unoccupied channel that it continues to transmit instead of vacating the channel.

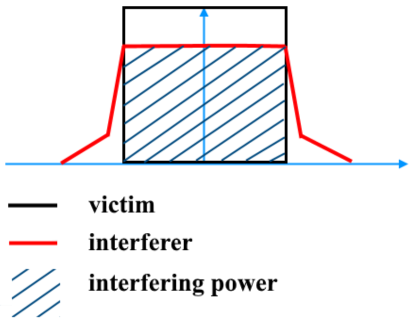


Figure 2.7: Co-channel interference scenario.

2.2.3 Adjacent Channel Interference

Adjacent channel interference occurs when the receiver of the licensed primary system is subject to interference in its channel from a secondary system operating in TVWS in an adjacent (neighbouring) channel. The cause of this is usually extraneous power originating from a signal in an adjacent channel mainly due to different power levels employed by the two systems and especially if the secondary system transmits at extremely high-power levels beyond those stipulated by the ITU and the regulators. Since TV receivers are not designed to tolerate interference, most of the TV receivers' filters have poor adjacent channel selectivity.

Adjacent channel power ratio (ACPR) is the power ratio of the transmitter average power centered on the frequency of the assigned channel to the average power centered on the frequency of an adjacent channel (Vieira, et al., 2010). The ACPR provides the amount of interference that a transmitter could cause to a receiver operating in the adjacent channel as shown in equation 2.1.

$$\text{ACPR} = 10\log_{10}\left(\sum_{k=1}^{k} 10^{\left(\frac{P_{SU}-L-ACPR_k}{10}\right)}\right) \tag{2.1}$$

Where,

k is the number of subbands of the SEM within an adjacent channel.

P_{SU} is the transmission power of the Secondary User,

L is the path loss between the SU and the PU,

$ACPR_k$ is the effective attenuation of the SEM in a given subband k.

Adjacent Channel Leakage Ratio (ACLR) is a measure of transmitter performance and is defined as the ratio of the transmitted power to the power measured in the adjacent radio frequency evaluated at the output of a receiver filter whereas Adjacent Channel

Selectivity (ACS) is a measure of receiver performance and is defined as the ratio of the receiver filter attenuation on the allocated channel frequency to the receiver filter attenuation on the frequency in an adjacent channel.

Adjacent Channel Interference Ratio (ACIR) is a measure of overall system performance and is defined as the ratio of the total power transmitted from an interfering source to the total interference power affecting a victim receiver, due to both transmitter and receiver imperfections. The relationship between these parameters (in linear domain) is given by Equations 2.2 and 2.3:

$$\frac{1}{ACIR} = \frac{1}{ACLR} + \frac{1}{ACS} \tag{2.2}$$

$$ACIR = \frac{PR(f_1 = f_W)}{PR(f_1 \neq f_W)} \tag{2.3}$$

2.3 Cognitive Radio Technology

According to ITU-R Report SM.2152 (International Telecommunication Union, 2009), a Cognitive Radio System (CRS) is defined as ‘a radio system employing technology that allows the system to obtain knowledge of its operational and geographical environment, established policies and its internal state; to dynamically and autonomously adjust its operational parameters and protocols according to its obtained knowledge in order to achieve predefined objectives; and to learn from the results obtained.’

Cognitive Radio provides a novel way to improve utilization efficiency of available electromagnetic spectrum by allowing secondary users to borrow unused radio spectrum from primary licensed users or to share the spectrum with the primary users by recognizing radio spectrum when it is unused by the incumbent radio system (Fatemieh, Chandra, & Gunter, 2010) (Mitola, 1993) (Nekovee, 2010). Spectral crowding problem where some frequency bands are heavily crowded, can be avoided using cognitive radio technology by introducing the opportunistic usage of frequency bands which are not heavily utilized by their licensed users. Primary users (PU) are licensed users and have the rights of priority in using certain stable frequency band for communications. Secondary users (SU) are allowed to use the frequency spectra momentarily but only if they do not interfere with the PU (Butler, et al., 2006). A cognitive radio must continuously sense the spectrum it is using in order to detect the reappearance of the primary user. Once the primary user is detected, the cognitive radio should instantly withdraw from the spectrum band so as to cede control back to the legacy user and migrate to another vacant channel in order minimize possible interference to the primary user (Joseph Mitola, 2006).

The main aim is to utilize the available spectrum in the most efficient way. An interconnected set of cognitive radio devices that share information is defined as a Cognitive Radio Network (CRN) (Krishn & Bhuvan, 2016). Opportunistic spectrum access creates the opening of underutilized portions of the licensed spectrum for reuse, provided that the transmissions of secondary radios do not cause harmful interference to primary users (PUs). Cognitive Radio (CR) is an important enabling technology for dynamic spectrum access (DSA).

2.3.1 Dynamic Spectrum Access

CR can help mitigate the spectrum scarcity problem by enabling dynamic spectrum access (DSA), which allows unlicensed users/devices to identify the un-/underutilized portions of licensed spectrum and utilize them opportunistically as long as they do not cause any harmful interference to the legacy spectrum users' communications. The temporarily unused portions of spectrum are called spectrum white spaces (WS) and they exist in time, frequency, and space domains. In the context of DSA, the legacy users are called primary users (PUs) and the CR users are called secondary users (SUs).

Traditionally, wireless networks are regulated by a spectrum assignment policy which makes fixed assignments of spectrum to license holders on a long term basis for large geographical regions. This fixed assignment leads to under-utilization of spectrum as is shown in the utilization graph on Figure 2.1 of section 2.1. Dynamic Spectrum Access (DSA) provides a solution to these spectrum inefficiencies. A DSA network is implemented with the help of cognitive radios (CRs). CRs use the existing spectrum through opportunistic access without interfering with the licensed users. CRs determine the available portion of the spectrum known as spectrum hole or white space. The best available channel is then used by the CR users if there are no licensed users operating in these licensed bands. The concept of dynamic spectrum access is therefore the identification of white spaces and exploiting them to communicate. Dynamic spectrum access is the most vital application of cognitive radios. The PU bands are opportunistically accessed by the SU networks such that there is no interference caused to the PUs (Yadav, Chatterjee, & Bhattacharya, 2012) as shown in Figure 2.8.

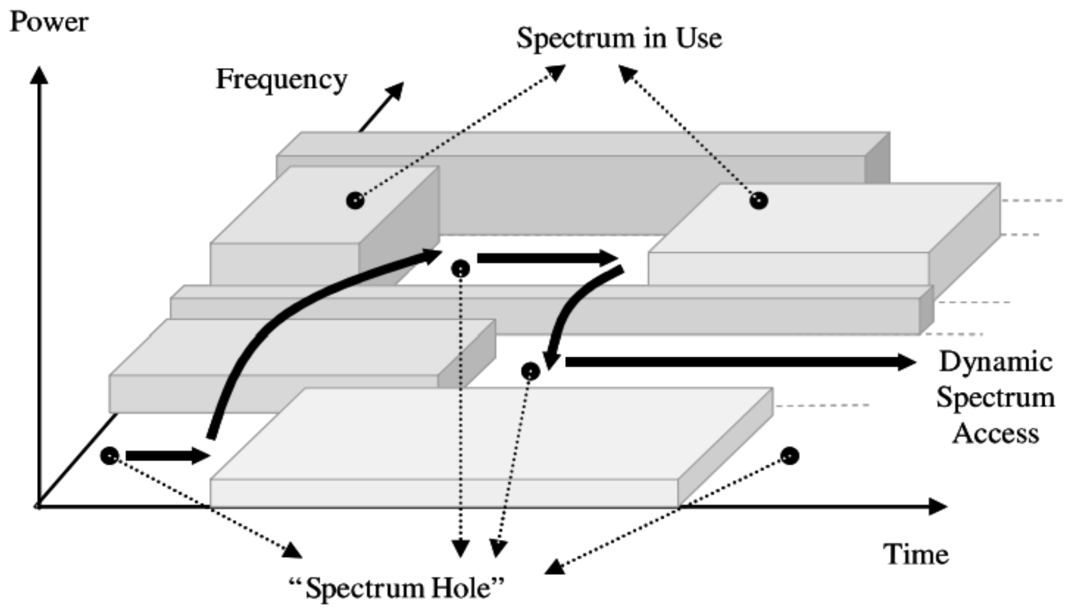


Figure 2.8: The dynamic spectrum access by Cognitive Radio.

Dynamic Spectrum Allocation (DSA) makes more efficient use of spectrum by enabling secondary users to opportunistically use frequencies that are not occupied by primary users (Fatemieh, Chandra, & Gunter, 2010). This eliminates the spectrum scarcity problem that wireless communications currently face and improves spectrum utilization through the use of whitespaces. The primary system refers to the licensed system with legacy spectrum. This system has exclusive privilege to access the assigned spectrum. The secondary system refers to the unlicensed cognitive system, which can only access the spectrum while it is not being used by the primary system. By leveraging cognitive radio technology, the proposed communications infrastructure promises to utilize potentially all available spectrum resources efficiently in the smart grid communication network (Ghosh, Das, & Chatterjee, Cognitive Radio And Dynamic Spectrum Access – A Study, 2014) (Lee, Saad, El-Saleh, & Ismail, 2015) (Zhang, et al., 2012).

2.3.2 Major Functions of Cognitive Radio

Cognitive radio enabled machines are able to sense and utilize unused frequency bands in their surroundings. Cognitive radio utilizes the potential that wireless systems have when they are context-aware and capable of reconfiguration based on their environments and their own properties (Zhang, et al., 2012) as shown in Figure 2.9.

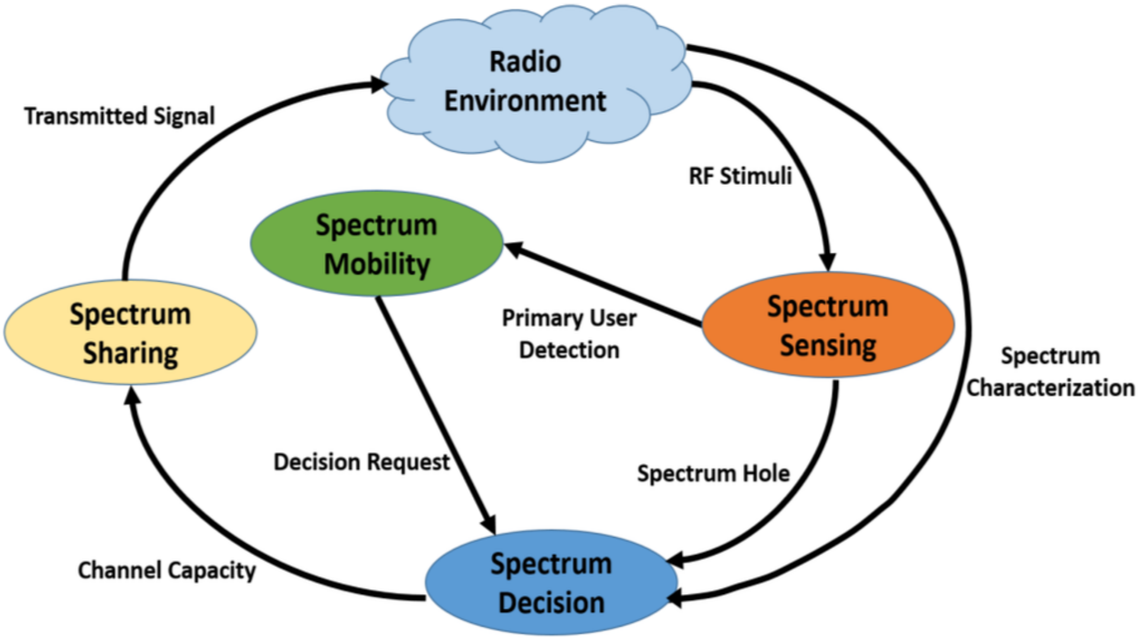


Figure 2.9: The cognitive cycle in detecting spectrum holes.

As seen in Figure 2.9, there are four major functions for cognitive radios:

2.3.2.1 Spectrum Sensing

Spectrum sensing is the most important and the very first step of the cognitive cycle. The objective of spectrum sensing is to detect the presence of transmissions from primary users. It determines if a primary user is present on a band by periodically sensing the target frequency band. In particular, a cognitive radio transceiver detects a spectrum which is unused or spectrum hole (i.e. band, location, and time) and determines the method of accessing it (i.e. transmitting power and access duration) without interfering of a licensed user's transmission (Bhattacharya, Khandelwal, Gera, & Agarwal, 2011) (Gaddam & Ghosh, 2010). Reliable spectrum sensing methods are needed to achieve efficient use of available spectrum and limit interference to PUs.

2.3.2.2 Spectrum Management

In order to meet the communication requirements of the users, the CRs should decide the best band of the spectrum to use in order to meet the Quality of Service (QoS) desires in all available frequency bands. Spectrum management is the selection of the best available channels in terms of the received signal strength, interference, energy efficiency, transmission power, number of users, QoS, and security requirements. These management functions can be classified as:

a. Spectrum analysis

   The spectrum sensing results are analyzed to estimate the best spectrum. This involves measuring the quality of spectrum accessed by a SU. The quality can be characterized by the Signal to Noise Ratio (SNR), the average correlation and the white spaces availability.

b. Spectrum Decision

   Spectrum access requires a decision model. The complexity of this model is dependent on the parameters considered in the spectrum analysis such as the data rate, the transmission mode and the transmission bandwidth. When users (both primary and secondary) are in the system, preference will influence the decision of the spectrum access (Ghosh, Das, & Chatterjee, Cognitive Radio And Dynamic Spectrum Access – A Study, 2014).

2.3.2.3 Spectrum Mobility

Spectrum mobility maintains seamless communication when migrating from one operating frequency to the next through spectrum handoff. Spectrum handoff occurs when a licensed PU is detected and the secondary user has to switch to a new unused spectrum band in order to continue the data transmission in the new spectrum band (Sarkar, 2012).

2.3.2.4 Spectrum Sharing

Spectrum sharing coordinates access to spectrum holes with other users. Since multiple secondary users want to use available spectrum holes, cognitive radio has to maintain balance between its self-goal of information transferring and selfless goal to share the available spectrum with other cognitive and non-cognitive users. This is done by policy rules determining behavior of cognitive radio users in radio environment (Ghosh, Das, & Chatterjee, Cognitive Radio And Dynamic Spectrum Access – A Study, 2014) (Yu, 2011).

2.4 Classification of Spectrum Sensing Techniques

Spectrum sensing techniques are broadly classified into three main types: transmitter detection or non-cooperative sensing, cooperative sensing and interference-based sensing. Transmitter detection technique is further classified into energy detection, matched filter detection and cyclostationary feature detection. Figure 2.10 shows the detailed classification of spectrum sensing techniques (Subhedar & Birajdar, 2011).

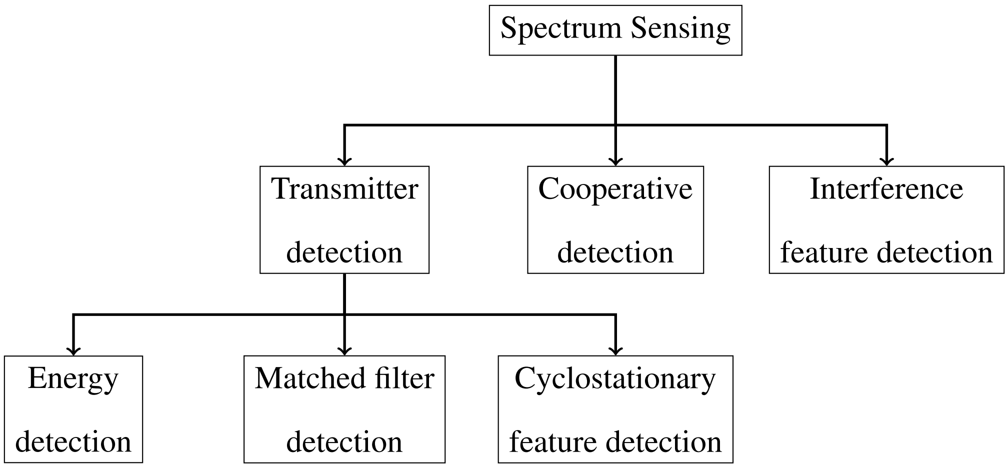


Figure 2.10: Classification of spectrum sensing techniques.

2.4.1 Primary Transmitter Detection

2.4.1.1 Matched Filter Detection

A matched filter (MF) is a linear filter designed to maximize the output signal to noise ratio for a given input signal when the input noise is white. When secondary user has a priori knowledge of primary user signal, matched filter detection can be applied. Matched filter operation is equivalent to correlation in which the unknown signal is convolved with the filter whose impulse response is the mirror and time shifted version of a reference (primary user) signal (Verma, Taluja, & Dua, 2012).

Mathematically, matched filter operation can be expressed as shown in (2.4):

$$\mathrm{Y(n)} = \sum_{k=-\infty}^{\infty} \mathrm{h(n-k)\,x(k)} \tag{2.4}$$

Detection using matched filter is applicable in cases where the information from the primary users is known to the cognitive users. Matched filter determines the presence of the PU by correlating the signal with time shifted version and comparing between the predetermined threshold and output of matched filter.

The block diagram for the matched filter detector is given in Figure 2.11.

Figure 2.11: Block Diagram for Matched Filter Detection.

Therefore, Matched filter detection needs prior knowledge about PUs, such as modulation type, and packet format, and requires the cognitive radio to be equipped with carrier synchronization and timing devices. With more types of PUs, then it requires to be equipped with carrier synchronization and timing devices for all the different types of Pus which increases the implementation complexity thus making it impractical (Pal, Indurkar, & Lakhe, 2015).

The probability of error for a coherent detector and White Gaussian noise statistics is given by (2.5):

$$P_e = Q\left(\frac{\sqrt{E_s}}{2\sigma}\right) \tag{2.5}$$

2.4.1.2 Energy Detection

This is a non-coherent detection method that detects the primary signal based on the sensed energy over an observation time window. It does not require any a priori knowledge of the primary or licensed user signal. The ED is said to be a Blind signal detector because it ignores the structure of the signal. It estimates the presence of the signal by comparing the energy received with a known threshold depending on the noise floor.

The energy detection method is based on the use of the FFT (Fast Fourier transform), which transforms a signal from a time domain to a frequency domain representation, determines the power in each frequency of the signal resulting in what is known as the PSD (Power Spectral Density). The block diagram for the energy detection technique is shown in the Figure 2.12.

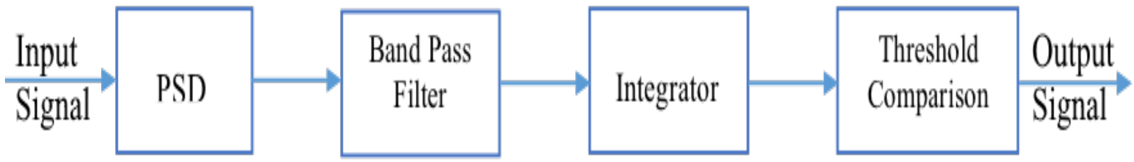


Figure 2.12: Energy detector block diagram.

In this method, the received signal x(t) is first pre-filtered by an ideal band pass filter of bandwidth W to limit the average noise power and normalize the noise variance (Hossain, Abdullah, & Hossain, 2012). Hence, noise at this stage has a band-limited flat spectral density (Nirajan, Sudeep, Suman, & Lamichhane, 2015). The band limited signal is then squared to measure the received energy and integrated over a time interval T to produce the test statistic Y. The time integrated signal is then compared with the predefined threshold λ to determine the presence or absence of a primary signal. The threshold value can be set to be either fixed or variable based on the channel conditions (Pal, Indurkar, & Lakhe, 2015) (R.Gill & A.Kansal, 2014) (Nautiyal & Kumar, 2013) (Rehman & Asif, 2012).

Analytically, energy signal detection can be reduced to a simple identification problem, formalized as a hypothesis test, as given in equations 2.6 and 2.7.

$x(n) = w(n)$……………………………….H_0 (Primary User Absent) (2.6)

$x(n) = h * s(n) + w(n)$……………………..H_1 (Primary User Present) (2.7)

where

s(n) is the signal transmitted by the primary users

x(n) is the signal received by the secondary user

w(n) is the additive white Gaussian noise(AWGN)

h is the complex channel gain between the primary signal transmitter and the detector

The estimated energy of the received signal can be expressed mathematical as given in (2.8): (Verma, Taluja, & Dua, 2012)

$$\sum_{n=0}^{N} |x(n)|^2 \tag{2.8}$$

The energy can now be compared to the threshold to check which hypothesis is true using the equations (2.9) and (2.10).

$$H_1 \text{ if } \in > \lambda \tag{2.9}$$

$$H_0 \text{ if } \in < \lambda \tag{2.10}$$

Energy Detection has low computational and implementation complexities. It is a more generic method as the receivers do not need any knowledge on the primary user's signal and is therefore ideal for ultra-wideband communication. It can therefore be applied when primary user signal is unknown or when the receiver cannot collect sufficient information about the primary signal.

2.4.1.3 Cyclostationary Feature Detection

Cyclostationary feature detection takes advantage of the introduction of periodic redundancy into a signal by sampling and modulation. Its success depends on the ability to extract those distinct modulated signals features. The periodicity is commonly embedded in sinusoidal carriers, pulse trains, spreading code, hopping sequences or cyclic prefixes of the primary signals. This periodic pattern in the transmitted signal from the primary users is known as cyclostationarity. Cyclostationary feature detection exploits the periodicity in the received primary signal to identify the presence of primary users (PU) (Chatziantoniou, 2014).

If the autocorrelation of a signal is a periodic function, then the signal is called cyclostationary signal. When the autocorrelation function is expanded in terms of Fourier series co-efficient it comes out that the function is only dependent on frequency. The spectral components of a cyclostationary process are completely uncorrelated to each other. The Fourier series expansion is called cyclic auto-correlation function (CAF) and the related frequency is called cyclic frequency. The cyclic spectral density (CSD) is calculated by taking the Fourier transform of the CAF and it represents the density of the correlation between two spectral components that are separated by a quantity equal to the cyclic frequency (Jang, 2014) (Axell, Leus, Larsson, & Poor, 2012). When the cyclic spectral density (CSD) for such signals is calculated, it helps in highlighting such periodicities.

Fourier transform of the correlated signal results in the peak at frequencies which are specific to a signal and searching for these peaks helps in determining the presence of the primary user whereas noise is random in nature and it does not exhibit such periodicities hence it doesn't get highlighted when its correlation is done.

Therefore, in this method, instead of power spectral density, cyclic correlation function is used for detecting signals present in a given spectrum (Pal, Indurkar, & Lakhe, 2015). The cyclostationary feature detection method can differentiate between the primary user signal and noise. It can therefore be used at very low SNR detection by using the information embedded in the Primary User signal which does not exist in the noise (R.Gill & A.Kansal, 2014).

A received signal x (t) is considered to be cyclostationary if it's mean and auto correlation shows periodicity as given in equations (2.11) and (2.12) (Saggar & Mehra, 2011):

$$m_x(t + T_0) = m_{x(t)} \tag{2.11}$$

$$R_x(t + T_0\,, u + T_0\ ) = R_x\,(t, u) \tag{2.12}$$

where the period of mean and auto correlation is T_0. If t and u are replaced in the autocorrelation equation with t+τ/2 and t-τ/2, then the equation becomes as shown in (2.13),

$$R_x(t + \tau/2, t - \tau/2) = \sum R_x^{\alpha}\,(\tau)e^{j2\pi\alpha t} \tag{2.13}$$

where R_x^{α} represents the Cyclic Autocorrelation Function (CAF) and α denotes the cyclic frequency. Cyclic frequency is presumed to be a known parameter to the receiver. CAF is calculated as given in (2.15):

$$R_x^{\propto}(\tau) = \lim_{T\to\infty} \frac{1}{T}\int_{-1/T}^{1/T} R_x\,(t + \tau/2\,, t - \tau/2\ )e^{-j2\pi\alpha t}dt \tag{2.14}$$

Cyclic spectral density (CSD) is obtained as shown in equation (2.15):

$$S_x^{\infty}(f) = \int_{-\alpha}^{\alpha} R_x^{\alpha}\,(\tau)e^{-\mathrm{j}2\pi\int\tau}d\tau \tag{2.15}$$

where $R_x^{\propto}(\tau)$ is the cyclic autocorrelation function (CAF).

The block diagrammatic explanation of this detector is shown in Figure 2.13.

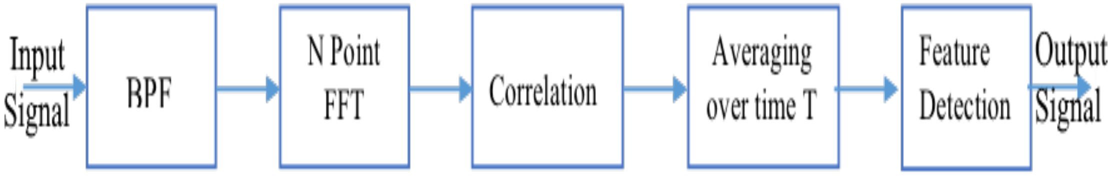


Figure 2.13: Block diagram for cyclostationary feature detection.

2.5 Machine-to-Machine (M2M) communications

Current smart grids are majorly composed of machine-to-human or human-to-human information production, exchange, and processing. However, with the the rapid penetration of embedded devices, there has been a shift to machine-to-machine communications which is characterized by low power, low cost, and low human intervention. M2M communication has features that are distinct from conventional human-to-human (H2H) communication: small amounts of data, infrequent data transmissions, delay tolerance, functions for group-based operations, massive number of M2M devices, short burst traffic, low powered, battery operated devices in most cases (Zhang, et al., 2012) (Alonso-Zarate, Matamoros, Gregoratti, & Dohler, 2012).

M2M communications are characterized by fully automatic data generation, exchange, processing and actuation among intelligent machines, without or with low intervention of humans (Tan, Sooriyabandara, & Fan, 2011) (Zanella, Bui, Castellani, Vangelista, & Zorzi, 2014). The objective of M2M communications is to increase the level of system automation in which the devices and systems can be interconnected, networked, and controlled remotely, with low-cost, scalable, and reliable technologies in order to exchange and share data. Figure 2.14 shows the architecture of M2M networks.

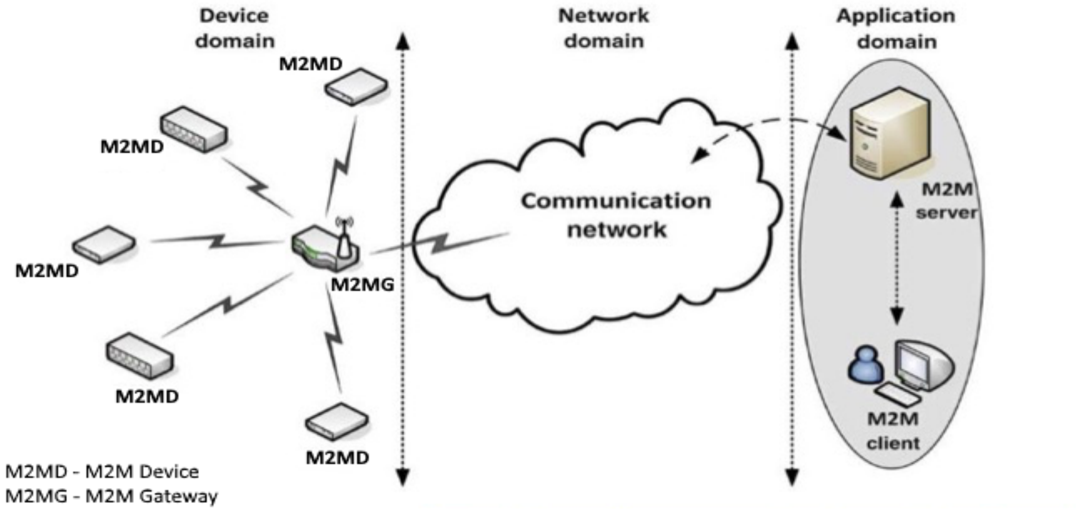


Figure 2.14: Architecture of M2M Networks.

As shown from Figure 2.14, from the data management perspective, M2M communications consists of three phases: data collection, data transmission, and data processing.

2.5.1 Requirements of the M2M communication in SG.

Several key features make M2M communications to be ideal for deployment in smart grid networks (Misic & Misic, 2014). These features include:

- Support for mass device transmissions: The support for multiple device transmissions as offered by M2M communications is very attractive for smart grids as it enables the handling of simultaneous transmission attempts from an extremely large number of M2M devices without overwhelming the network.
- Extremely low power consumption: Most M2M devices have idle and sleep modes, link power control and device collaboration which reduces power consumption and increases the life span of these devices on the grid. This is vital as some SG devices are battery operated while other devices especially in power generation are located in remote areas that experience infrequent human interaction. Due to the large number of devices in the smart grid it would be uneconomical to have to replace the battery every so often considering that the grid covers large geographical regions.
- Small bursts data transmissions: Support for transmission of small bursts of information by M2M communications resonates with the small bursts

transmissions of mostly control and monitoring data that is usually found in smart grids.

- Group control: Group control allows for easy addressing and handling of extremely large number of devices such as those in the smart grid which enables easy broadcast of changes in dynamics in the SG network such as changes in pricing information.
- Interoperability: Interoperability in M2M networks helps to cater for the highly heterogeneous traffic patterns of most SG systems and the interconnection of a potentially large number of disparate energy distribution networks, power generating sources and energy consumers.
- Scalability: The scalability of M2M devices is essential to support a steep expansion of SG devices as a SG network spans large geographical region. This ensures that the SG easily supports a large increase in number of connected devices while still maintaining acceptable Quality of Service (QoS) standards (Jermyn, Jover, Murynets, Istomin, & Stolfo, 2015).
- Delay-tolerant traffic: Time-tolerant traffic can support significant delays in data transmission and reception. This allows the SG system to give lower access priority to or defer data transmission of time-tolerant traffic.
- Extremely low latency: Extremely low latency requires that both network access latency and data transmission latency be reduced. This feature is required in many emergency situations. Changes to the bandwidth request and network entry/re-entry protocols may be required to support extremely low latency (Zhang, et al., 2011).
- Priority access mechanism: Priority access is necessary in order define a scheme of prioritizing access to resources in the smart grid communication network especially in an era of limited resources such as bandwidth (Wu, Talwar, Johnsson, Himayat, & Johnson, 2011).
- Self-organization: The self-organization, self-configuration, self-management, and self-healing properties of M2M networks enables a SG to detect faults and outages and institute corrective measures without any human intervention.
- Low cost: In many M2M communications applications, M2M devices are low cost, so that they can be easily embedded in real fields and extensively deployed on a large scale.

2.5.2 Cognitive M2M

Cognitive machine-to-machine (CM2M) communications is M2M communications that is employing cognitive radio technology (Zhang, et al., 2012) (Lee, Kim, Hwang, Yu, & Kim, 2013) (Mukherjee & Nath, 2015). By adding a new cognition dimension, CM2M becomes intelligent and adaptable and has much more potential than conventional M2M thereby opening up new application areas for M2M communications. A large number of connected devices in the SG create a major challenge in terms of spectrum scarcity. CM2M can exploit unlicensed radio resources such that spectrum congestion problems in traditional M2M can largely be eliminated (Zhang, et al., 2012). Some of the challenges of M2M networks that are addressed through cognitive M2M are:

- ✓ Spectrum scarcity: The biggest challenge in M2M communications is the ever-increasing number of M2M devices. This together with the massive number of sensors in smart grids creates a major challenge for existing wireless communication networks due to spectrum congestion. With dynamic spectrum access capabilities of cognitive radio, existing spectrum can be utilized more efficiently in order to avoid the potential shortage of spectrum and to support large-scale data transmissions of the smart grid (Huang, Wang, Qian, & Wang, 2013) (Kaabouch & Naima, 2014).
- ✓ Interference: With a multitude of connected devices operating in wireless networks, significant interference issues arise between self-existing and co-existing M2M networks. An example is the ISM band which is occupied by many devices. Hence, data communications is hampered by interference. The crowded heterogeneous spectrum characteristics degrade performance and result in high latency and packet losses, which undermines reliability and security. This not only deteriorate the performance of M2M network, but also adversely affects the other services operating in the same bands. However, by exploiting the dynamic spectrum access and leveraging the software-reconfigurability of cognitive radios, M2M devices are able to rapidly switch between different wireless modes, and hence reducing or even avoiding the interference devices coexisting within the same environment. Furthermore,

CM2M devices have the capability to vary their transmission power hence reducing possibility of interference occurring (Beale & Morioka, 2011).

- ✓ Coverage issues: A critical issue in some M2M applications such as smart grid is the huge variation in device locations. Some devices might be deployed in areas where wireless propagation is not always guaranteed, especially if operating in the industrial, scientific and medical (ISM) band. Cognitive radio-equipped M2M networks can effectively overcome this issue as it rides on TVWS frequencies which have better propagation, reach and performance than most wireless networks (Subhani, Shi, & Cobben, 2015).
- ✓ Green requirement: An M2M device is a low-cost and low-power device, which is designed to work for several years without battery replacement. It is capable of adaptively adjusting their transmission power levels based on the operating environments, without interfering with the primary network and at the same time not causing spectrum pollution resulting in environment-friendly radio systems.
- ✓ Device heterogeneity: An M2M network comprises a diverse array of different devices with varying network protocols and data formats. The cognition ability enables M2M communications to deal device and protocol heterogeneity that makes M2M networks to be more efficient and flexible in integrating with different applications and services.
- ✓ Energy-efficiency: Majority of M2M devices are battery-operated and do not have the ability to draw power from the mains. Moreover, they are often deployed in areas where frequent human access is not tenable, and hence battery replacement is not always feasible. With CM2M devices, they can control transmission power and can sleep when not communicating to ensure that they have a longer life span before requiring their batteries to be replaced (Aijaz & Aghvami, 2015).

2.5.3 CM2M network architecture for the smart grid

The M2M communication architecture for the SG must meet the needs of current and future applications in a cost-effective, scalable, reliable, and secure way. The smart grids communication architecture is organized into three-layered hierarchical structure consisting of Home Area Networks (HANs), Neighborhood Area Networks (NANs), and Wide Area Network (WANs) (Zhang, et al., 2012) (Niyato, Xiao, & Wang, 2011) spanning across the SG functional domains of power generation, transmission, distribution and consumption as shown in Figure 2.15.

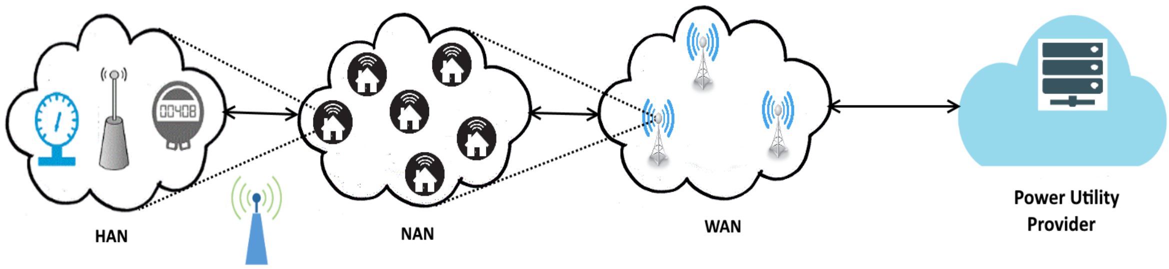


Figure 2.15: Hierarchical structure of CM2M architecture.

2.5.3.1 Wide Area Networks (WANs)

The WAN is the upper layer of the SG communication architecture and serves as the backbone for communication between network gateways or aggregation points, NANs, SG substations, distributed grid devices, and the core utility systems.

2.5.3.2 Home Area Networks

The Home area network (HAN) is a subsystem in the bottom layer of the hierarchical spectrum within the SG dedicated to effectively manage the on-demand power requirements and consumption levels of the end-users. HAN is therefore located in the customer domain and creates a communication path between home appliances, in-home displays, energy management systems, and energy dashboards. Every home device will send their power readings over this network to the home meter or gateway for communication with the outside world.

2.5.3.3 Neighborhood Area Networks

The NAN is the intermediate layer of the SG communications architecture that connects multiple HANs to the WAN of the utility company. A smart grid neighborhood area network communicates and manages several HANs within its coverage area and transfers the data to the WAN. A NAN represents a locality or a particular region (e.g., a ward within a city).

2.6 Review of Existing Systems in Smart Grid

2.6.1 Review of Existing Communication Technologies

2.6.1.1 Wired Communication

Wired communication networks require expensive cables to be installed and maintained on a regular basis. This might therefore not be a cost-effective solution that would enhance the management process of the smart power grid systems. The costs associated with setting up a wired infrastructure network for a utility provider are prohibitive due to cable/fiber infrastructure costs. Among wired communication technologies, the most prominent wired communication technology that could be deployed for interconnecting smart grid networks is Power line communications (PLC). PLC seems like an obvious choice given its ubiquity since every customer has a power line in their premises. It is a mature and field-tested technology that is currently being used by the utility providers for substation monitoring. However, PLC has some major limitations that hinder the large-scale deployment of AMI networks. It is not a suitable candidate for smart meter-concentrator interconnection due to high attenuation induced by the transformers on the power lines. The power line channel performance is severely affected by the harsh and noisy transmission medium while Mobile Broadband Wireless Access, Digital Microwave Technology, and Cellular Communication provide reasonable coverage ranges but support only licensed users. Wired communication networks therefore do not offer the scalability provided by wireless communication networks (Vo, Choi, Chang, & Lee, 2010). Their larger coverage and minimal cost, has made wireless communication standards to become more promising technologies for smart grid systems (Vo, Choi, Chang, & Lee, 2010).

2.6.1.2 Wireless Communication

The first option is to use existing technologies like cellular, especially given the widespread adoption of cellular technologies and their countrywide coverage. In such a scenario, a smart meter augmented with a subscriber identity module (SIM) card could send the meter readings over a cellular link to the utility provider. Devices augmented with a cellular modem (using any of general packet radio service [GPRS]/3G/4G technologies) would then transmit these over a cellular link to the utility provider. The advantage of this approach is that it leverages a time-tested technology. However, coverage could be limited by radio signal penetration. Another issue to consider is availability, particularly in some of the developing countries where mobile phones/cellular coverage is not as ubiquitous as that in the developed countries. However, from a utility provider's perspective, they will have to pay the cellular operator to use their infrastructure for transporting metering data. While utility providers might opt to set up and maintain their own cellular networks, this might help mitigate some of the operational weaknesses associated with employing of a third party cellular based infrastructure solution but the costs associated with setting up and running the network would be very huge (Kulkarni, Gormus, Fan, & Motz, 2012).

Another alternative that follows intuitively is the use of the broadband link in the customer's premises. This is particularly attractive as the customer is already paying for broadband service. The utility provider could use the broadband link as a bit pipe to securely tunnel the metering data over the public Internet. However, the level of broadband penetration could be a major deterrent to deploying such a solution, especially in developing countries.

The other alternative is Zigbee and Bluetooth technology. Zigbee is characterized by low rate, low power, and short-range transmission. Zigbee operates on the IEEE 802.15.4 radio specification while Bluetooth is suitable for short-range and low-data-rate peer-to-peer communications. IEEE 802.11 (Wi-Fi) could also be deployed. Wi-Fi is however not appropriate for wide area networks due to its limited radio coverage; it is, however, a cost-effective option for home area networks and neighborhood area networks. Wi-Fi hardware tends also to be more expensive and consumes more power as compared to Bluetooth and Zigbee but is well suited for higher data rate applications. Worldwide Interoperability for Microwave Access (WiMAX) has a disadvantage is high infrastructure and spectrum costs involved.

2.6.1.3 Comparison Between Various Communication Technologies

Table 2.1 provides a summary comparison of various communication technologies that can potentially be employed in the SG (Kulkarni, Gormus, Fan, & Motz, 2012) (Gungor, et al., 2011) (Khan, Rehmani, & Reisslein, 2016) (Rahman, Hossain, Sayeed, & Palash, 2013).

Table 2.1: Comparison between different potential communication technologies for the smart grid.

Technology	Media	Operation	Merits	Demerits
Zigbee	Wireless	Unlicensed	Low power usage; Short range; Low complexity; Low deployment cost;	Short range; Low data rate; Low processing capabilities; Interference from WiFi, Bluetooth and microwave.
Bluetooth	Wireless	Unlicensed	Low power usage;	Short range; Low data rate; Prone to interference from IEEE 802.11
Wi-Fi	Wireless	Unlicensed	High power usage;	Short range;
Wimax	Wireless	Licensed	High data rate; Long range;	Network speeds degrades with increasing distance; High licensing costs; High frequencies do not penetrate through obstacles;
Cellular Communications	Wireless	Licensed	High data rate; High mobility; Low latency;	High deployment cost; Scarcity of spectrum;
Power Line Communications	Power line		High Speed; Low cost due to already available infrastructure; Low latency; Widespread availability;	Harsh and noisy medium; Low bandwidth; Signal quality affected by network topology;
Optical Networks	Wired	Licensed	High speed; Large bandwidth; High degree of reliability; Long range;	High deployment cost;
TV White Space	Wireless	Unlicensed	High Data rate; Long range; Adaptive power levels;	Susceptible to disruptions due to reappearance of PU;

From the Table 2.1 we conclude that CR communication through the IEEE 802.22 WRAN standard, has several appealing features for SG applications compared to other wired and wireless communication technologies that make it an ideal candidate for deployment of a communications network. The benefits of using TVWS for smart grid communications, are in terms of bandwidth, deployment cost, the self-X (X= organization, management and configuration) capabilities of cognitive radio technology and the integration of CM2M communications for smart grid applications provides a communication architecture that is much better than current wireless smart metering technologies. This is especially ideal for rural communication where TVWS are in plenty. However, CR communication has also a few shortcomings, such as susceptibility to disruptions due to extensive PU activity. However, CRs can flexibly support a wide range of SG applications and is therefore a promising communication technology for the SG (Khan, Rehmani, & Reisslein, 2016) (Kawade & Nekovee, 2009).

2.6.2 Gaps in Existing Grid Networks

Most of the current grid networks that we have today are not intelligent and they are prone to constant outages, overloading during peak hours, service disruptions that are never reported in time, human inefficiencies such as in meter transactions (meter reading in analogue meters and prepaid code generation and inputting in digital meters). These problems are mainly due to lack of a communication infrastructure between the network devices, the providers and the customers. In many instances power blackouts and water outages do occur but since the utility providers do not have a reliable mechanism to communicate of these grid failures in time, they have to wait for customer complaints to alert them. This results in great losses (depending on the time taken to rectify the situations) and also inconveniences their customers.

Limited availability of (and high cost of acquiring) radio spectrum is a key disadvantage of deploying wireless backhaul in smart grid applications. This is especially so for LTE and WiMAX based smart grid systems where the utility companies have to acquire licensed spectrum as suggested in (Aguirre & Magnago, 2013) (Khan, et al., 2012) (Al-Omar, Landolsi, & Al-Ali, 2015) (Aloul, Al-Ali, Al-Dalky, Al-Mardini, & El-Hajj, 2012). In current grid networks, smart meters are deployed by using the 2G/3G cellular technology as communication infrastructure. These smart meters are equipped with embedded SIM cards and have the ability of communicating autonomously with the cellular network like a normal user equipment. Traffic is delivered to other grid devices or to utility servers via the 2G, 3G or 4G cellular core network. Although cellular networks can guarantee better communication performance, because of exclusive rights to the use of the cellular bands and elaborate management by the cellular network, an excessive number of M2M devices can cause a significant congestion/overload problem in cellular networks. To support a massive number of grid devices in cellular networks, the utility provider needs to invest in its communication infrastructure and/or bandwidth (Lee, Kim, Hwang, Yu, & Kim, 2013) (Chen, Wan, Gonzalez, Liao, & Leung, 2014). However, this solution presents some drawbacks, like the low coverage in certain areas, given the fact that smart meters are typically located underground, with heavy shadowing effects caused by walls and other buildings. In addition, cellular bands already experience a heavy utilization over dense areas, so they might not be suitable to support a large-scale deployment of scalable grid networks.

Cognitive radio concept provides a solution for scarcity of spectrum by providing opportunistic usage of frequency bands that are not densely occupied by licensed primary users (Hossain, Han, & Poor, Smart Grid Communications and Networking, 2012). Cognitive radio gives the opportunity for unlicensed shared access of the spectrum where the utility companies do not actually have to buy the spectrum as long as they do not cause interference to the licensed primary users.

The application of TV white space in a smart grid communication network is very advantageous especially for those parts of the geographical area which are very difficult to reach and expensive to reach by optical fiber techniques and other types of technologies. It’s also very applicable to developing countries where the telecommunications infrastructure isn’t in place and white spaces can potentially be a cost-effective way of bridging this gap easily (Ko, Lee, Lin, Chung, & Chu, 2014). In the USA, the FCC has allowed cognitive users to exploit occupied digital television (DTV) spectrum or TV white space. TV channels are highly desirable in long range coverage and difficult terrain for their ability to provide NLOS coverage and penetrate foliage (Hossain, Han, & Poor, Smart Grid Communications and Networking, 2012). The long-distance coverage of TV channels resonates well with the wide regions covered by current grid networks spanning several counties, whole countries and even multiple countries.

Another problem that has plagued current grids is that due to human inefficiencies. In most places especially in the rural areas, there still exist analogue utility meters where the utility companies have to send manpower to go and physically collect the meters' readings. Even in places where the digital utility meters are said to exist, they still do not communicate with the utility providers' data servers and one has to buy the prepaid tokens and then manually key in the 20-digit code into the meter. This has resulted in constant complaints by the customers most of whom have either overlooked one of the digits or have keyed in the wrong digits. This lack of a communication infrastructure has also denied the utility providers of valuable information about their customers' usage patterns that is very vital in planning the network and also in carrying out maintenance of the grid. In (Mitola, 1993) (Alonso-Zarate, Matamoros, Gregoratti, & Dohler, 2012) various short-range wireless technologies are used to support various M2M applications and in particular how wireless sensor and actuator networks (WSAN) can play a key part in delivering M2M applications in an SG context. It identifies optimal network design while minimizing the cost of M2M communications and data processing due to large amount of information collected as some of the challenges hindering the full integration of M2M devices in the smart grid. In this research, we apply a centralized processing scheme where a fusion center is responsible for decision making in the smart grid to optimize and reduce the power consumption of the low powered M2M devices. The integration of machine to machine communications in the grid network is envisioned to eliminate these human related problems by automating the processes of reading and reloading of utility meters, collecting information on customer usage patterns and instantaneously informing the utility companies in case of any faults and/or outages in the network.

The implementation of a two-way communication system in the smart grid network also paves the way for effecting of dynamic pricing structures whereby customers will be charged higher rates during peak hours to discourage much consumption (consumption by critical uses) and charge lower rates during off-peak hours to encourage consumption. This can then be used as one of the mechanisms of effecting load balancing which is still a very big problem in existing grid networks.

In flat-tariff power pricing structures, all the consumers are charged the same price per unit of power throughout the day. However, this approach fails to take into account the instability on the grid network brought about due to load shifting during peak hours and off-peak hours. Dynamic pricing where consumers are charged varying prices depending upon the demand response curve can help remedy this problem. Dynamic pricing induces consumers to alter their demand in response to the time-varying prices by delaying or switching off some of the non-urgent, non-critical loads. Consumers can hence take advantage of household appliances that have a timer for a delayed start option. Such appliances include dish washers which can be set to automatically run late at night during off-peak hours thereby taking advantage of the lower off-peak prices.

The biggest hindrance in implementing dynamic pricing in current grid networks has been identified to be the lack of a two-way communication system in the smart grid network. In the proposed smart grid communication network, the bi-directional flow of information between service providers and consumers enables the realization of an intelligent SG network and allows the effecting of SG applications like SCADA, AMI, outage management, self-healing and recovery from faults, dynamic pricing, electricity theft detection, load controlling and incorporation of distributed power generation.

2.6.3 Load Balancing

Kenya Power (Kenya's main power distribution utility company) has an estimated five million customers as of December 2016. Based on statistics from Kenya Power, the peak electrical load is 1228 MW while the total yearly electrical demand is 7.53 TWh, corresponding to an average demand of 860 MW. This shows that load balancing is a big issue for the utility provider. Figures 2.16 and 2.17 show the average daily load profile and the average weekly load profile respectively for Kenya Power company.

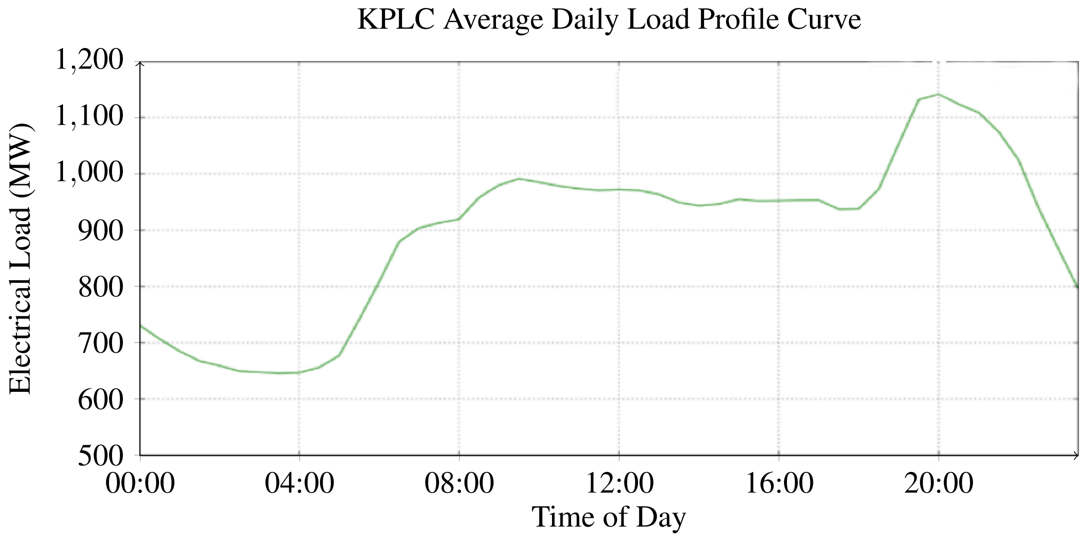


Figure 2.16: Average daily load profile curve.

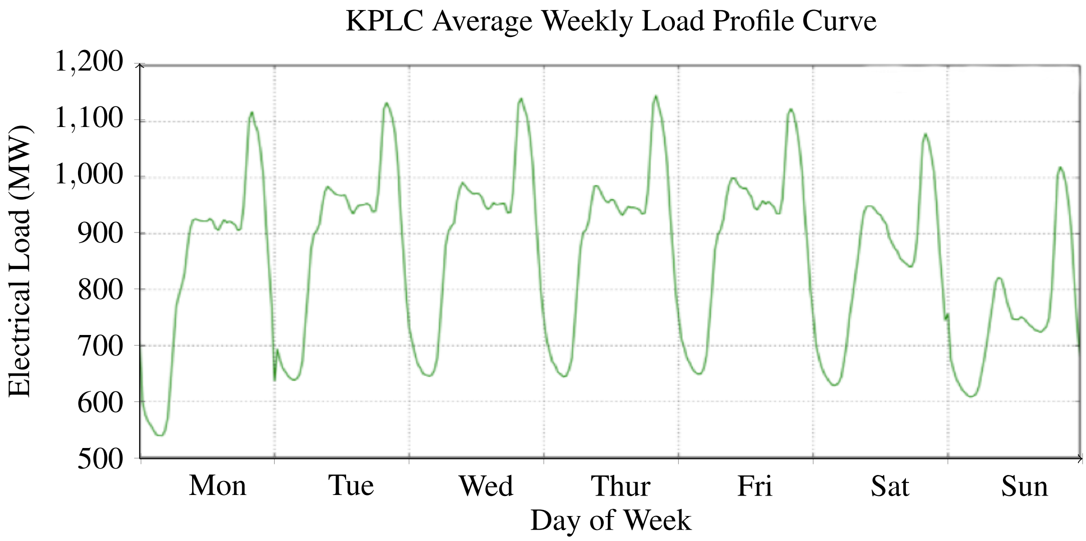


Figure 2.17: Average weekly load profile curve.

The load profile curves show the peak time to be from 6 pm to 10 pm with the highest peak at 1140 MW at 8 pm compared to the off-peak period of between 12 am to 6 am with the lowest at 650 MW at 3am. If the estimated demand is actually larger than actual demand, the supplied power is wasted due to over-supply. On the other hand, if actual demand is larger than the estimated demand, additional power supply is required due to under- supply. Therefore, to cover for the huge difference in demand and supply, utility companies will require to effect dynamic pricing structures where they will have different prices such as higher prices for peak demand time to discourage much consumption and lower prices for off-peak demand times to encourage more consumption. This can be used as one of the measures to try and effect load balancing. This is only possible if there is a smart power grid communication network to facilitate communication between the grid components without the need for human intervention. Thus, using the designed communication network, real-time transmission of power data and load information of smart meters is easily transmitted from the user side to the utility center. At the same time, dynamic electricity pricing information is easily communicated from the utility center to consumers (Huang, Wang, Qian, & Wang, 2013) (Kethsiyal, Pugazhendi, Kumar, & Nerenjana, 2014).

2.7 Channel Propagation Model for TVWS Devices

The fundamental aim of a radio link is to deliver sufficient signal power to the receiver at the far end of the link to achieve some performance objective. For a data transmission system, this objective is usually specified as a minimum bit error rate (BER). In the receiver demodulator, the BER is a function of the signal to noise ratio (SNR) measured in decibels (dB). In designing a spectrally efficient wireless communication system like TVWS, it is important to understand the radio propagation channel. The characteristics of the radio channel will change mainly due to the operating frequency and the propagation environment. To help predict the performance of the system, certain analytical tools can be used.

2.7.1 Path-Loss models

Path loss models are used to estimate the average received signal power as a function of distance, carrier frequency, and other transmission parameters. Path-loss models are classified into theoretical and empirical models. The theoretical models predict transmission losses by mathematical analysis of the path geometry of the terrain between the transmitter and the receiver and the refractivity of the troposphere Empirical models are based on measurement data and thus add environmental-dependent loss variables to the free-space loss to compute the net path loss in the corresponding environment (Faruk, Ayeni, & Adediran, On the study of empirical path loss models for accurate prediction of TV signal for secondary users, 2013). These models require measurements and so considered more accurate in view of its environmental compatibility. The most common empirical models in use in TVWS studies are the Friis Free Space Path Loss (FSPL), ITU Radio Communications Sector

(ITU-R) P.1546-2, Egli, Okumura and Hata models for predicting the TV coverage (Faruk, Ayeni, & Adediran, Impact of Path loss models on Spatial TV white space, 2013) (Mauwa, Bagula, Zennaro, & Lusilao-Zodi, 2015). We will explore two main propagation models: - The Free space propagation model and the Okumura-Hata propagation model.

2.7.1.1 Free Space Path Loss Model

In a line-of-sight radio system, losses are mainly due to free-space path loss (FSPL). FSPL is proportional to the square of the distance between the transmitter and receiver as well as the square of the frequency of the radio signal. Developed from the Friis free space equation, the Free Space Path Loss model is the basic path loss equation. It accounts only for the reduction in power due to the distance between the transmitter and receiver, and the frequency of operation. Free-space path loss increases significantly over distance and frequency. It is the simplest model to study white space availability.

The equation for FSPL is given in (2.16)

$$PL_{FreeSpace} = \left(\frac{4\pi d}{\lambda}\right)^2 = \left(\frac{4\pi df}{c}\right)^2 \tag{2.16}$$

where:

λ is the signal wavelength (in metres), c is the speed of light in a vacuum,
f is the signal frequency (in hertz), λ = c/f where c = speed of light,
d is the distance from the transmitter (in metres)

FSPL is in terms of dB is given by equation (2.17):

$$PL_{Free\ Space}(dB) = 20\ \log_{10}(d) + 20\ \log_{10}(f) + 32 \tag{2.17}$$

If we consider a signal transmitted though free space to a TV receiver located at distance d from the CR transmitter. Given that there are no obstructions in between and the signal propagates along a straight line, we have equation (2.18) (Mikeka, et al., 2014)

$$\frac{P_r}{P_t} = \left(\frac{\sqrt{G_t G_r}\,\lambda}{4\pi d}\right)^2 \tag{2.18}$$

where P_t is the transmit power and P_r is the receive power. Such a model is called as line-of-sight (LOS) channel. Furthermore, G_t and G_r denote the antenna gains of the transmitter and the receiver, respectively, and λ is the wavelength.

The actual received power Pr at each TVWS station was calculated using (2.19) which takes into account; system losses and antenna gain for the transmitter and the receiver.

$$P_r = P_t + G_t + G_r - L_{sys} - 10 \log\left(\frac{4\pi}{\lambda}\right)^2 - 20 \log(d) \tag{2.19}$$

Where

P_r = Receive power in dB	G_r = Antenna gain for receiver
P_t = Transmit power in dB	L_{sys} =System losses
G_t = Antenna gain for transmitter	d = Distance
λ = c/f where c = speed of light.	

2.7.1.2 Okumura-Hata Path Loss Model

A common propagation model used for TVWS is the Okumura-Hata model. The model incorporates the graphical information from Okumura model and develops the information further to realize the effects of diffraction, reflection and scattering caused by city structures. It is suited for both point-to-point and broadcast transmissions. The Okumura-Hata propagation model is widely used throughout different applications to predict propagation in different environments.

The Hata model path loss calculations for urban environments is given by equation (2.20):

$$PL_U = 69.55 + 26.16 log_{10} f - 13.82 log_{10} h_t - a(h_r) + [44.9 - 6.55 log_{10} h_t] log_{10} d \tag{2.20}$$

The Hata model path loss calculations for suburban environments is given by (2.21):

$$PL_S = PL_U - 2\left(log_{10} \frac{f}{28}\right)^2 - 5.4 \tag{2.21}$$

The Hata model path loss calculations for rural environments is given by (2.22):

$$PL_R = PL_U - 4.78 \,(log_{10} f)^2 + 18.33 \, log_{10} f - 40.94 \tag{2.22}$$

Where:

PL_U = Path loss in urban areas (dB)	h_t = Height of base station antenna (m)
PL_S = Path loss in suburban areas (dB)	h_r = Height of receiving station antenna (m)
PL_R = Path loss in open areas (Rural) (dB)	f = Frequency of transmission (MHz).

d = Distance between the base and receiver stations in Kilometers (km)

$a(h_r)$ is an antenna height-gain correction factor that depends on the environment. It is equal to zero for $h_r = 0$ otherwise it is equal to;
Equation (2.23) for small or medium-sized city;

$$a(h_r) = (1.1 \log_{10}(f) - 0.7)\, h_r - (1.56 \log_{10}(f) - 0.8) \tag{2.23}$$

Equations (2.24) and (2.25) for large cities;

$$a(h_r) = \begin{cases} 8.29 \left(\log_{10} (1.54\, h_r)\right)^2 - 1.1 & for\ f \le 300\ MHz \quad (2.24) \\ 3.2 \left(\log_{10} (11.75 h_r)\right)^2 - 4.97 & for\ f > 300\ MHz \quad (2.25) \end{cases}$$

Okumura-Hata model is one of the most widely used models for signal coverage prediction (Faruk N. , Ayeni, Adediran, & Surajudeen-Bakinde, 2014). In (Phong, Bao, & Tue, 2013) a comparison was done between Okumura-Hata, the free space model and the two ray ground reflection model while in (Kasampalis, et al., 2014) the Okumura-Hata was compared against the ITU-R P.1546. In both instances, it was shown that the Okumura-Hata model is better at predicting the channel model between fixed CR devices. This model is applicable for distances of 1-20 km and for frequencies in the range of 150-1500 MHz. Base station antenna heights, which are valid for the model, are from 30 to 200 m (Australian Communications Authority, 2001).

2.7.1.3 Hata-Okumura Extended Model (ECC-33 Model)

Although the Hata-Okumura model is a well-established model for the Ultra High Frequency (UHF) band, it is limited to the lower frequency bands and can only predict the propagation loss in the range of 150-1500 MHz (Abhayawardhana, Wassell, Crosby, Sellars, & Brown, 2005). The COST-231 model extended its use up to 2 GHz. Recently, through the ITU-R Recommendation P.529, the International Telecommunication Union (ITU) encouraged further extension of the Hata-Okumura model up to 3.5 GHz (Mahesh & Rao, 2014). This model is referred to as ECC-33 model or simply as the Hata-Okumura extended model. In this model path loss is given by equation (2.26) (Miah, Rahman, Singh, & Islam, 2012).

$$PL = A_{fs} + A_{bm} - G_b - G_r \tag{2.26}$$

Where:

A_{fs} = Free space attenuation (dB) given in equation (2.27),

A_{bm} = Basic median path loss (dB) given in equation (2.28),

G_b = Transmitter antenna gain factor given in equation (2.29),

G_r = Receiver antenna height gain factor.

$$A_{fs} = 92.4 + 20 \log_{10}(d) + 20 \log_{10}(f) \tag{2.27}$$

$$A_{bm} = 20.41 + 9.83 \log_{10}(d) + 7.894 \log_{10}(f) + 9.56 [\log_{10}(f)]^2 \tag{2.28}$$

$$G_b = \log_{10}(h_b) \{13.958 + 5.8 [\log_{10}(d)]^2\} \tag{2.29}$$

For small or medium-sized city G_r is given by (2.30);

$$G_r = [42.57 + 13.7 \log_{10}(f)][\log_{10}(h_r) - 0.585] \tag{2.30}$$

For large cities G_r is given by (2.31);

$$G_r = 0.759h_r - 1.862 \tag{2.31}$$

Where

h_b = Transmitter antenna height [m]

d = transmitter to receiver antenna distance (km)

h_r = Receiver Antenna height [m]

f = frequency (GHz)

The Okumura-Hata extended propagation model will be used to calculate the path loss in between the base station and the modelled communication network devices utilizing TVWS.

CHAPTER THREE

DYNAMIC SPECTRUM ACCESS FOR PROPOSED COMMUNICATION NETWORK

3.1 Interference analysis for coexistence

As discussed in section 2.1, it has been shown that a large number of TV channels are not effectively utilized. Cognitive radio enables the dynamic spectrum access of idle spectrum in order to enhance the utilization of the spectrum. However, the main fear arising from utilizing TVWS arises due to the possibility that it might cause harmful interference to the primary users by the secondary users. In this section, the aspect of interference in TV White spaces is investigated to determine the possibility of mutual coexistence between primary users and secondary users operating in TV White spaces.

3.1.1 Interference Modelling

SEAMCAT (Spectrum Engineering Advanced Monte Carlo Analysis Tool) is a statistical simulation software tool based on Monte-Carlo analysis (European Communications Office (ECO), 2016). SEAMCAT is developed within CEPT since the year 2000 and is used for addressing compatibility studies between different radio technologies by assessing the potential interference between different radio communication systems (Lyubchenko, Kermoal, & Devendec, Implementation of Cognitive Radio in SEAMCAT, 2010). In this section, various SEAMCAT aspects are taken to account in modelling the interference between primary and secondary users.

In SEAMCAT, the interference scenario considers 3 different received signals. These signals are illustrated in Figure 3.1 and defined as follows:

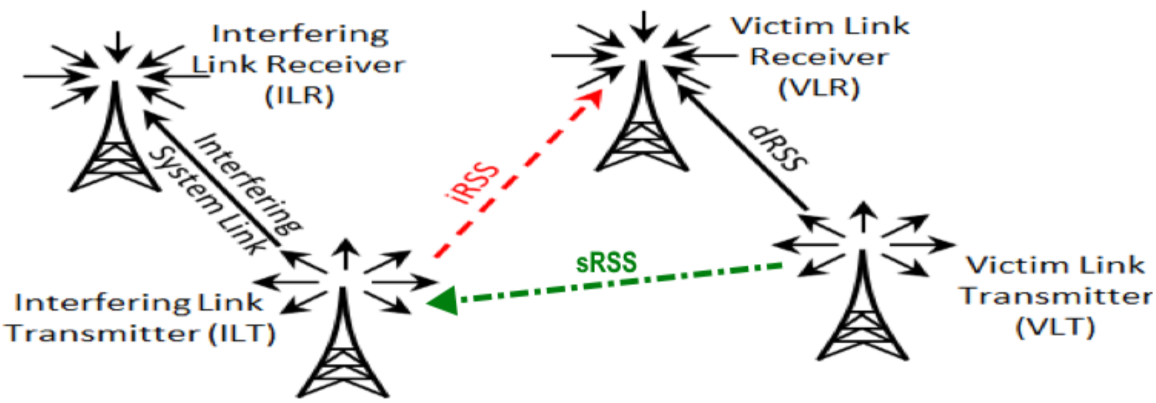


Figure 3.1: Overview of interference scenario in SEAMCAT.

- dRSS (desired Received Signal Strength) refers to the signal broadcasted to the Victim Receiver (\textit{Vr}) by the Wanted Transmitter (\textit{Wt}). This is the signal that experiences attenuation due to the interferer. In this case, the dRSS is a DTT (Digital Terrestrial Television) system.
- iRSS (interfering Received Signal Strength) refers to the signal received by the Victim Receiver (Vr) and broadcasted by the Interfering Transmitter (It). This is the signal that impairs the dRSS. In this case, the It is the transmitting TVWS device.
- sRSS (sensing Received Signal Strength) refers to the signal that is broadcasted by the Wt and is sensed by the It. In this case, It acts as a transceiver.

The sRSS (taking into account the unwanted mask of the DTT) at the channel m can be calculated as shown in equation (3.1):

$$sRSS(f_m) = P_{Wt}(f_m) + G_{Wt \to It} + G_{It \to Wt} + L \tag{3.1}$$

where:

- P_{Wt}: is the transmit power in dBm from the Wt.
- f_m : is the frequency of the WSD.
- $G_{Wt \to It}$: is the gain of the antenna in dBi of the Wt, in the Wt to It direction
- $G_{It \to Wt}$: is the gain of the antenna in dBi of the It in the It to Wt direction
- L: is the path loss in dB between the It and the Wt.

If the sRSS is below the Detection threshold then there is no interference but if the sRSS is greater the Detection threshold then there is interference that has occurred (Lyubchenko, Kermoal, & Devendec, Spectrum sensing capabilities in SEAMCAT, 2011) (Huynh & Lee, 2012). The simulation parameters used are tabulated in Table 3.1.

Table 3.1: Simulation modelling parameters

Simulation Parameters	DVB-T/T2	Cognitive Radio
Channel Width	8 MHz	8MHz
Transmit Power	72.15 dBm	36.02 dBm
Receiver Bandwidth	7.71MHz	7.71MHz
Antenna Height Tx	100m	30m
Antenna Height Rx	10m	1.5m
Antenna Gain	6dBi	6dBi
Receiver Sensitivity	-98dBm	-98dBm
Receiver Noise Floor	-114dB	-114dBm
Propagation Model	Extended Hata	Extended Hata
Receiver Noise Figure	7dB	5dB
Modulation	64 QAM	64 QAM
Frequency Band	498 MHz	470~698 MHz

The spectrum from 470 MHz through channel 698 MHz is the most preferred as at these higher UHF frequencies, the antennas are shorter and much more manageable as compared to antennas for VHF frequencies 54 MHz through channel 216 MHz (Lyubchenko, Kermoal, & Devendec, Spectrum sensing capabilities in SEAMCAT, 2011). According to guidelines provided by the ITU in (International Telecommunication Union, 2009), it restricts power levels to 1 W for base stations or 4 W effective isotropic radiated power (EIRP) with a gain antenna. Antenna height is restricted to 30 meters above ground. For mobile units, the maximum power is 40 mW or 100 mW EIRP. To avoid interference on the adjacent channel, operation of a fixed station may not occur in a channel directly adjacent to an active TV channel. In most instances, a WSD transmission usually occupies most, but not all, of an 8 MHz TV channel. However, WSDs with wider and narrower bandwidths are also possible. A radio microphone transmitter generally occupies a bandwidth of 200 kHz. In deriving the protection ratio, the wanted PMSE signal power is measured in 200 kHz and the unwanted WSD signal power is measured in 8 MHz (Popescu, Fadda, Murroni, Morgade, & Angueira, 2014).

For the purpose of this paper, the transmission technology will be assumed to be OFDM since the OFDM family of technologies currently represents the most efficient and reliable transmission.

3.1.2 Interference Simulation

Radio frequency signal-to-interference ratio (C/I) is the power ratio of the total power from the wanted signal to that of the combined interfering signals and noise, as detected at the receiver input. Radio frequency protection ratio (PR) is the minimum value of the signal-to-interference ratio required to obtain a specific reception quality, at the receiver input, under specified conditions. PR is usually specified as a function of the frequency offset between the interfering and the wanted signals over a wide frequency range.

In this research, a case where the victim receiver (VR) bandwidth and the interfering transmitter (IT) reference bandwidth have the same value (i.e. 8 MHz) was considered hence no bandwidth correction factor was to be applied. The possibility of interference to incumbent primary systems from nearby secondary devices severely limits the number of available TV channels accessible for secondary devices. The effect of adjacent channel interference is most significant on the first two adjacent channels, so a greater emphasis was concentrated on simulating interference on the two channels as well as the co-channel interference. SEAMCAT is used to address all radio interference scenarios on terrestrial paths in both adjacent and co-channel frequency interference scenarios.

3.1.2.1 Simulation Scenario 1:

In this case the effects of a secondary user transmitting at the same frequency as the primary user were considered. The secondary user is transmitting at 498 MHz. There is a high probability of interference at 37.30% as shown in Table 3.2. Figure 3.2 compares the dRSS and iRSS values of the secondary user and DVB-T signals while Figure 3.3 shows the probability of interference for co-channel coexistence.

Table 3.2: Simulation parameters (Same Channel)

Parameter	Value
dRSS mean value	-44.21 dBm
iRSS unwanted value	-70.56 dBm
iRSS blocking value	-100.05 dBm
C/I	19.0
Probability of interference	37.30%

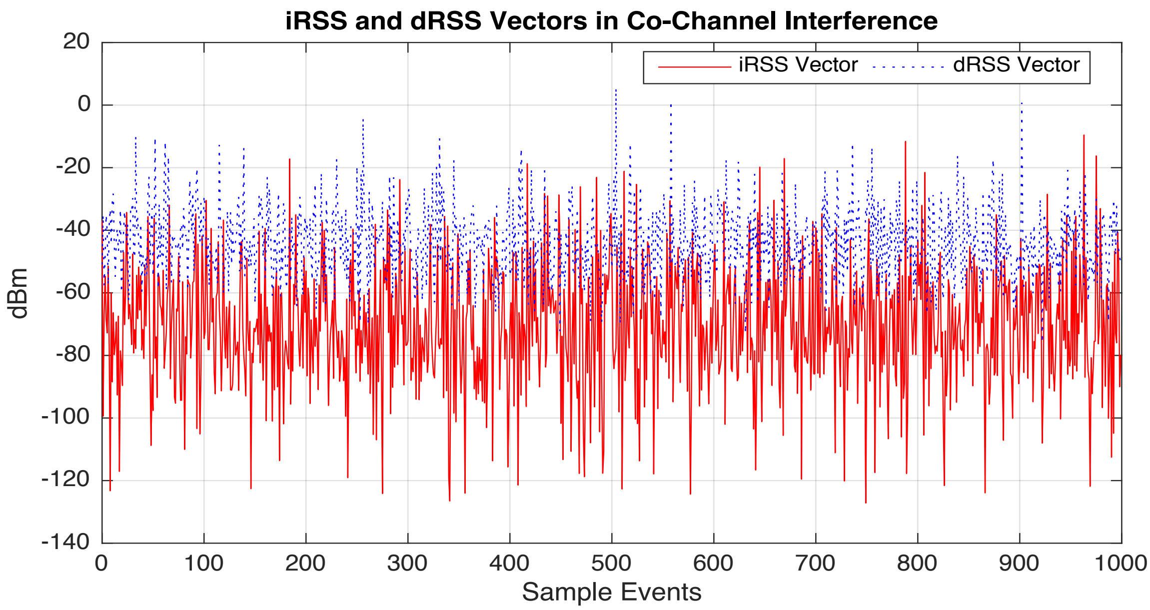


Figure 3.2: dRSS and iRSS values of co-channel SU

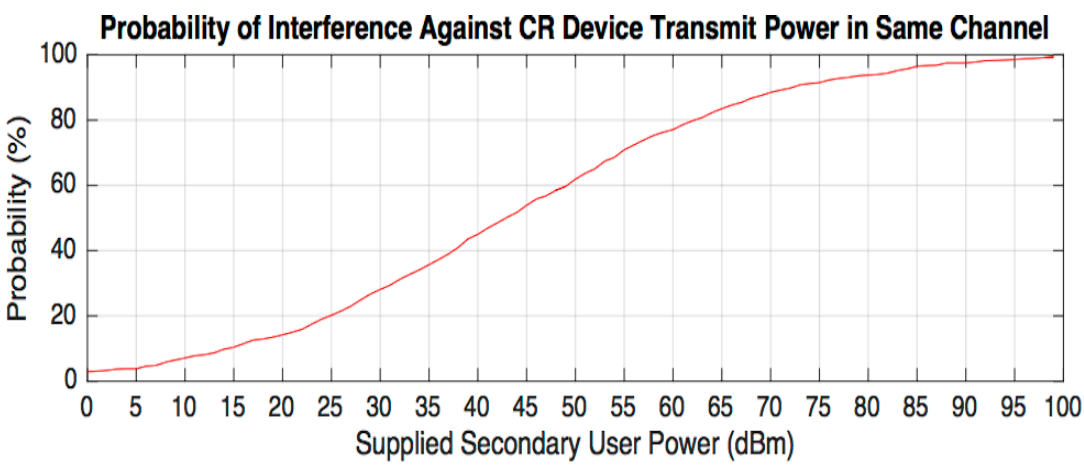


Figure 3.3: Probability of interference against transmit power of co-channel SU.

3.1.2.2 Simulation Scenario 2:

In this case we consider the effects of a secondary user transmitting in an adjacent channel (490 MHz Channel) to the one in use by the primary user (at 498 MHz Channel). There is a high probability of interference at 23.60% as shown in the Table 3.3. Figure 3.4 compares the dRSS and iRSS values of the secondary user and DVB-T signals while Figure 3.5 shows the probability of interference for 1st adjacent channel coexistence.

Table 3.3: Simulation parameters (Adjacent Channel)

Parameter	Value
dRSS mean value	-43.92 dBm
iRSS unwanted value	-79.42 dBm
iRSS blocking value	-99.97 dBm
C/I	19.0
Probability of interference	23.60%

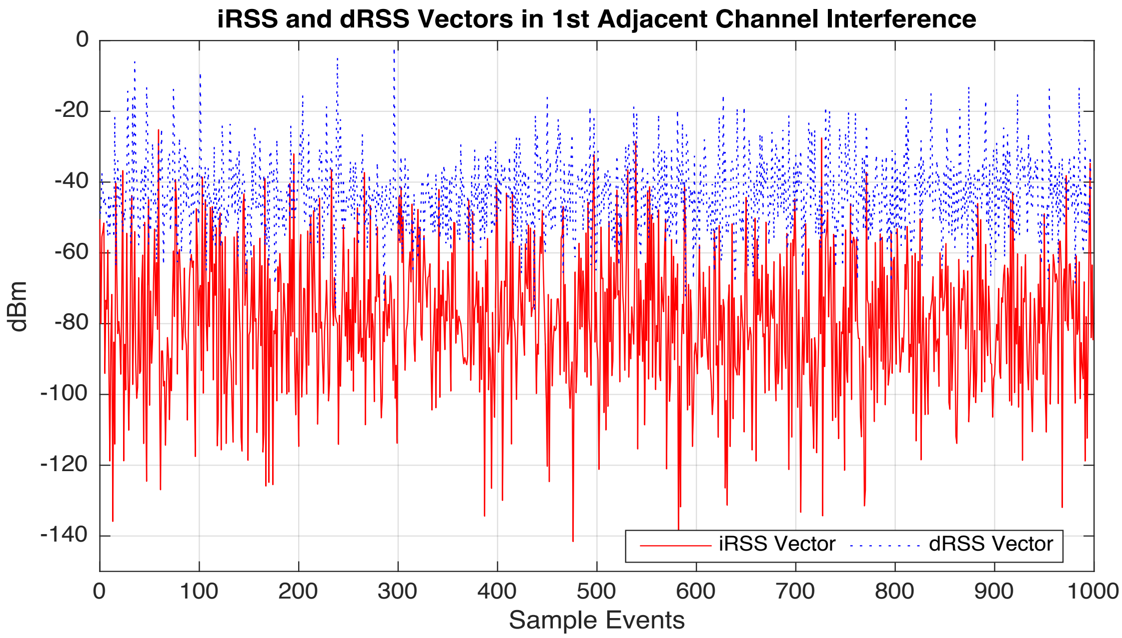


Figure 3.4: dRSS and iRSS values of 1st adjacent SU.

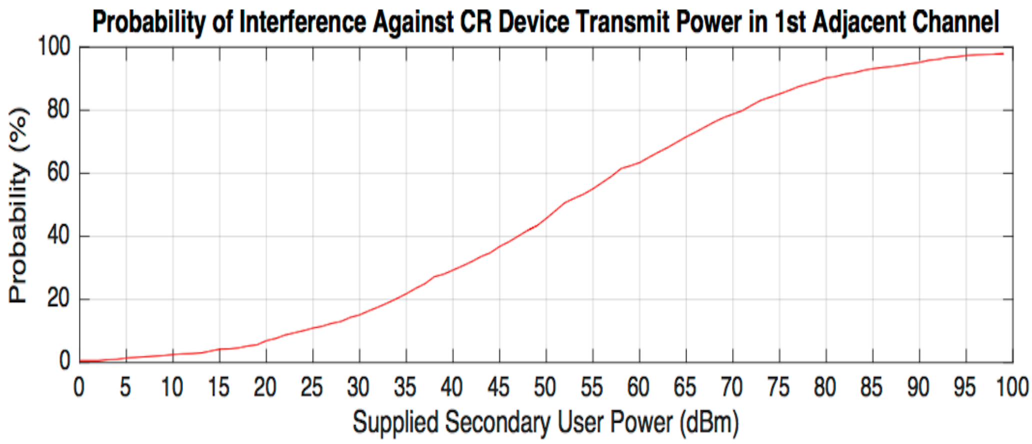


Figure 3.5: Probability of interference against transmit power of 1st Adjacent SU.

3.1.2.3 Simulation Scenario 3:

In this case we consider the effects of a secondary user transmitting in a second adjacent channel (514 MHz Channel) to the one in use by the primary user (at 498 MHz Channel). There is a low probability of interference at 3.50% as shown in the Table 3.4. According to recent research carried out in [89] [90], a probability of interference of 5% was considered to be acceptable for DTV transmissions. Figure 3.6 compares the dRSS and iRSS values of the secondary user and DVB-T signals while Figure 3.7 shows the probability of interference for 2nd adjacent channel coexistence.

Table 3.4: Simulation parameters (2nd Adjacent Channel)

Parameter	Value
dRSS mean value	-44.36 dBm
iRSS unwanted value	-107.70 dBm
iRSS blocking value	-101.19 dBm
C/I	19.0
Probability of interference	3.50%

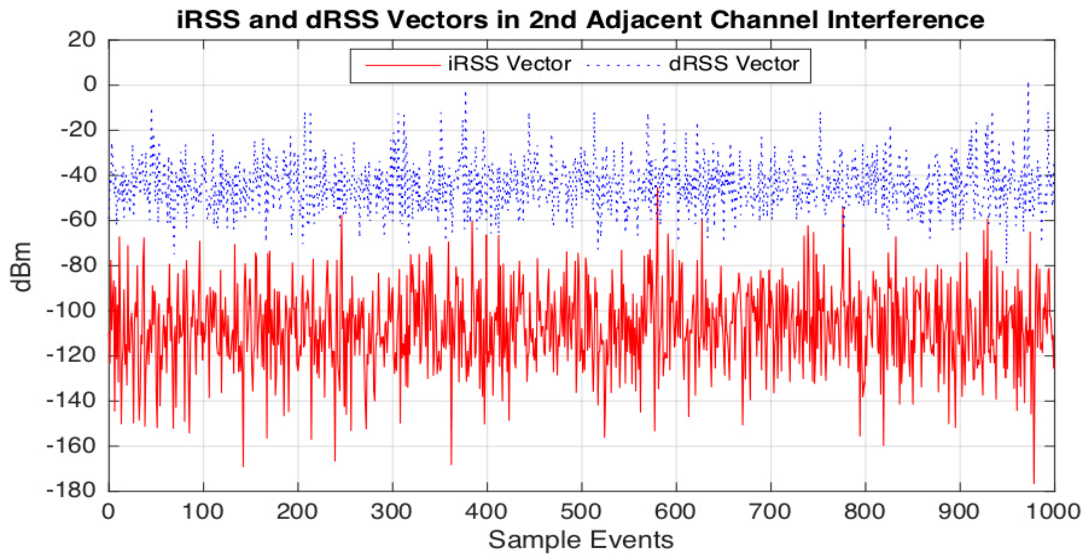


Figure 3.6: dRSS and iRSS values of 2nd adjacent SU.

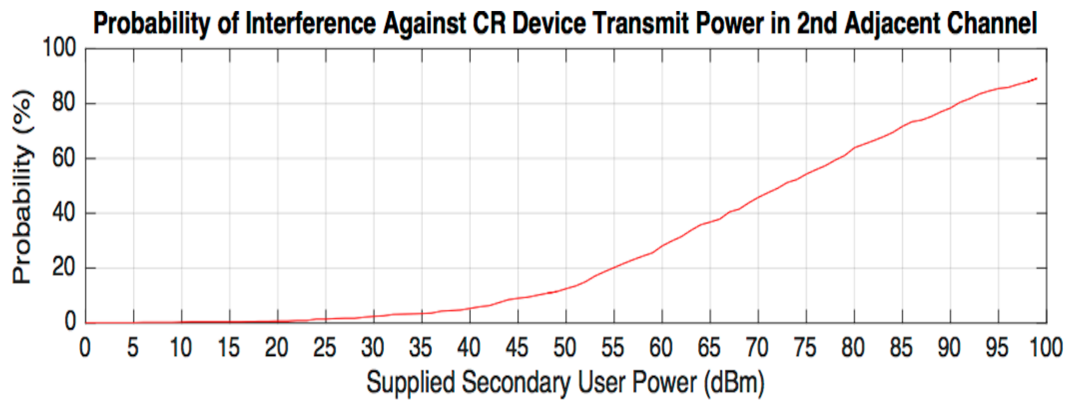


Figure 3.7: Probability of interference against transmit power of 2nd Adjacent SU.

One of the most challenging problems and concerns in using cognitive radio systems is interference, which occurs when the SU accesses the spectrum but fails to become aware of the presence of a transmitting primary user in the channel. The interference is thus highest when both the primary user and the secondary user are transmitting on the same channel as can be seen in scenario 1 where the probability of interference is 32.6% at 4W secondary power. Interference in the same channel may also occur when multiple secondary users select the same TV channel for transmission due to an uncoordinated selection process or limited availability or if the spectrum-sensing period is very long such that the secondary user is not able to detect the reappearance of the primary user fast enough in a previously unoccupied channel that it continues to transmit instead of vacating the channel.

It is therefore important for the secondary users to sense not just the primary users but also sense for other secondary users that might be transmitting at the same instance to avoid interference between the secondary users as they try to transmit at the same time. Secondary users transmitting at the adjacent channel to a currently occupied channel also causes interference though not nearly as high as in the same channel interference. This is as demonstrated in scenario 2.

Secondary users transmit power control is therefore a very important factor to consider as it is a major factor affecting the interference of primary users by the secondary users. The higher the transmit power supplied to the secondary user, the larger the coverage radius of the secondary cognitive user network, but also the higher the interference on the primary users as can be seen in Figure 3.3, 3.5 & 3.7. Tradeoff is therefore required when setting up the secondary network to ensure maximum coverage radius at minimum interference to the primary users. The probability of interference results obtained between the radio systems is able to help determining specific limits for the transmitter/receiver performance. Interference avoidance techniques provide unique ways of minimizing and mitigating interference between the various systems exploiting spatial reuse opportunities.

3.2 Comparison Between the Various Spectrum Sensing Techniques

In order to analyze the comparative performance of all three transmitter detection techniques, described in section 2.4.1, an extensive simulation was performed in Matlab using Receiver Operating Characteristic (ROC) Curves.

3.2.1 Receiver operating characteristics (ROC) curves

Receiver Operating Characteristic curve (ROC curve) is a plot of the true positive rate against the false positive rate for the different possible cut points. In spectrum sensing, the true positive value is called the probability of detection (P_D) and is the probability that the sensing device decides that a primary signal is present in a given channel when in fact the primary system does occupy that channel. The false positive value is called the probability of false alarm (P_{FA}) and is the probability that the sensing device decides that a primary signal is present in a given channel when in fact it is vacant, i.e. the decision that is based on some statistics transcends the threshold when only noise is present. Also, the probability of misdetection (P_{MD}) which is defined as the probability that the sensing device decides that a primary signal is not present in a given channel when in fact the primary system does occupy that channel. The value of the probability of misdetection is usually one minus the value of the probability of detection (Pal, Indurkar, & Lakhe, 2015).

The sensing performance of each detection scheme can thus be illustrated by using the receiver operating characteristic (ROC) curves. ROC curves are used to plot the probability of detection vs. the probability of false alarm. The probability of detection varies based on SNR, false alarm probability and various time bandwidth factors (Kumar, 2014). ROC has been widely used in the signal detection theory due to the fact that it is an ideal technique to quantify the tradeoff between the probability of detection (P_D) and the probability of false alarm (P_{FA}) (Pal, Indurkar, & Lakhe, 2015) (Nirajan, Sudeep, Suman, & Lamichhane, 2015) (Kaur & Singh, 2015). Plots of the receiver operating characteristics (ROC) curves are used to study the detection performance of primary signal under Additive White Gaussian Noise (AWGN) for simple energy detection, matched filter detection and cyclostationary detection. The simulations are carried out in Matlab environment.

In the Figure 3.8, the performance of energy detector method is investigated for varying levels of probability of false alarm. It shows that for a given SNR value, the detector can tolerate a higher probability of false alarm value with increasing probability of detection. Therefore, with increasing probability of detection, the detector can tolerate a higher false alarm probability and vice versa. This is especially the case at low levels of SNR since the energy detector method cannot easily differentiate between the primary signal and noise.

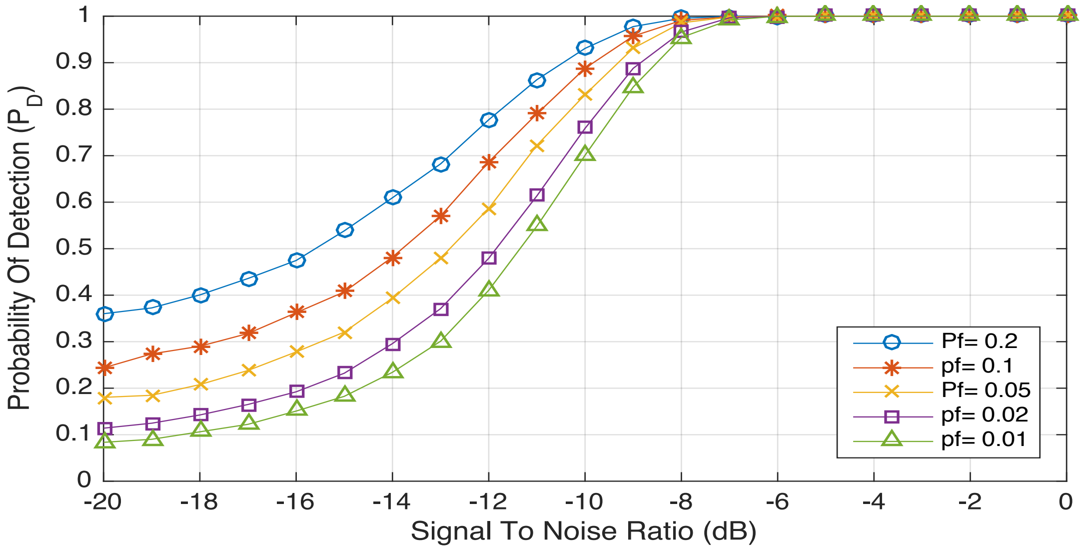


Figure 3.8: Energy Detection ROC curve for P_D vs SNR with varying P_{FA}.

In the Figure 3.9, the impact of SNR on the performance of Energy Detector method is investigated. It shows that the probability of detection is increased when SNR increases and probability of detection is decreased when SNR decreases. This shows that energy detection generally performs poorly in low-SNR environments and hence might be unable to distinguish between signal power and noise power at low SNR.

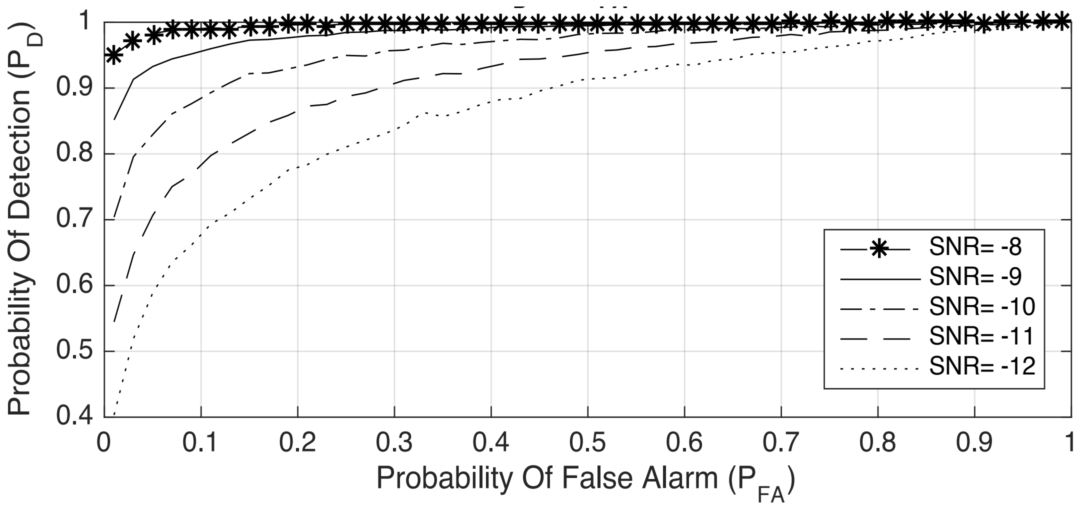


Figure 3.9: Energy Detection ROC curve for P_D vs P_{FA} with varying SNR.

In the Figure 3.10, the impact of SNR on the performance of Energy Detector method is investigated. It shows that at low SNR values, the energy detector has high probability of either missed detection or probability of false alarm while at higher SNR values a higher probability of misdetection implies there is a low probability of false alarm.

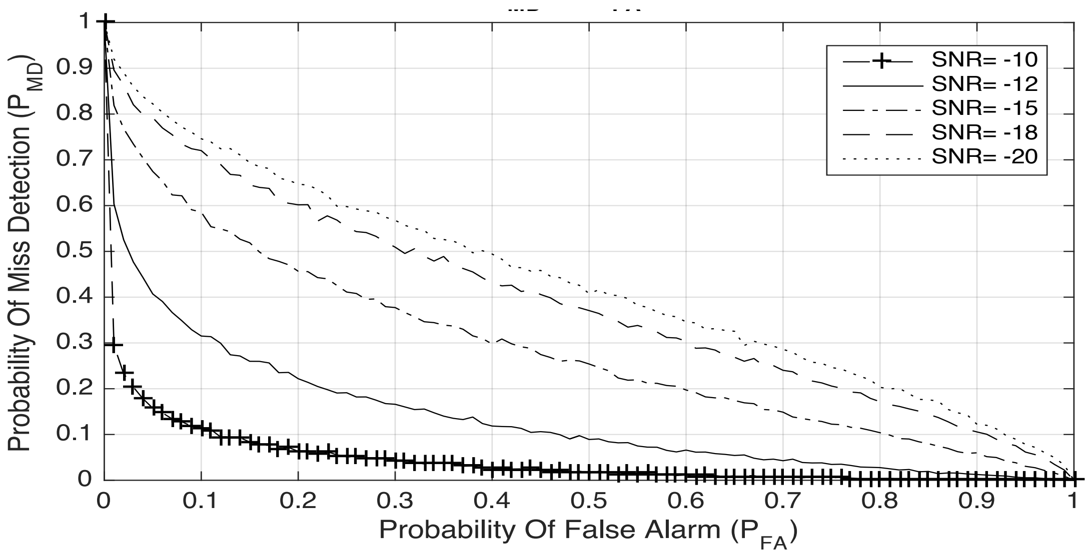


Figure 3.10: Energy Detection ROC curve for P_{MD} vs P_{FA} with varying SNR.

In the Figure 3.11, the performance of matched filter detector method is investigated for different probability of false alarm. It is observed that, as the probability of detection increases, so does the maximum tolerable probability of false alarm.

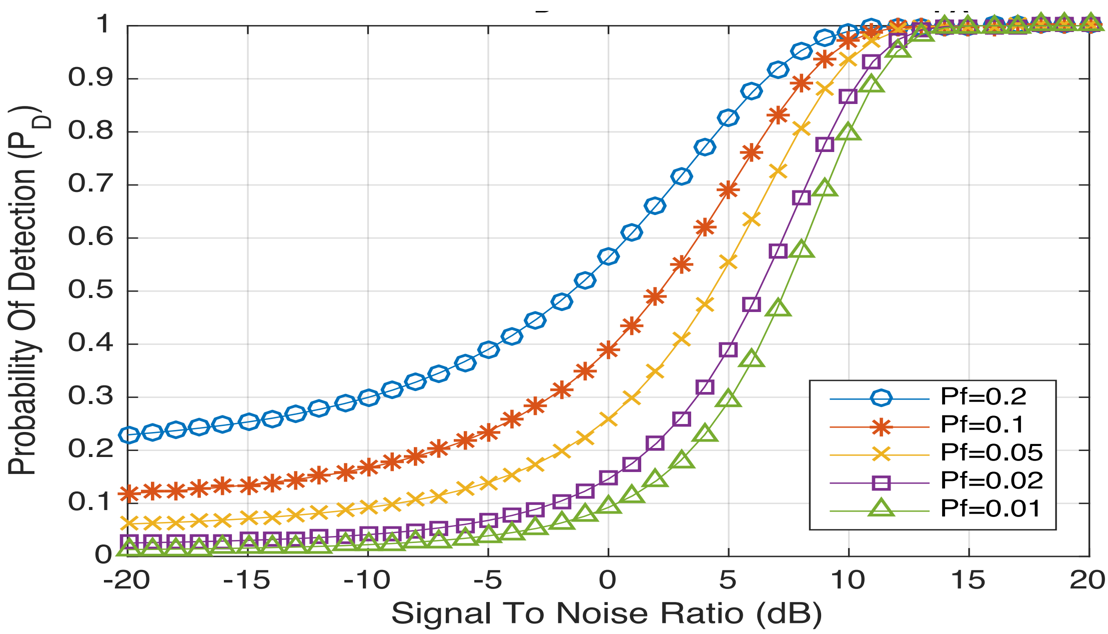


Figure 3.11: Matched Filter Detection ROC curve for P_D vs SNR.

In the Figure 3.12, the impact of SNR on the performance of Matched Filter Detector method is investigated. It shows that the probability of detection is increased when SNR increases and probability of detection is decreased when SNR decreases.

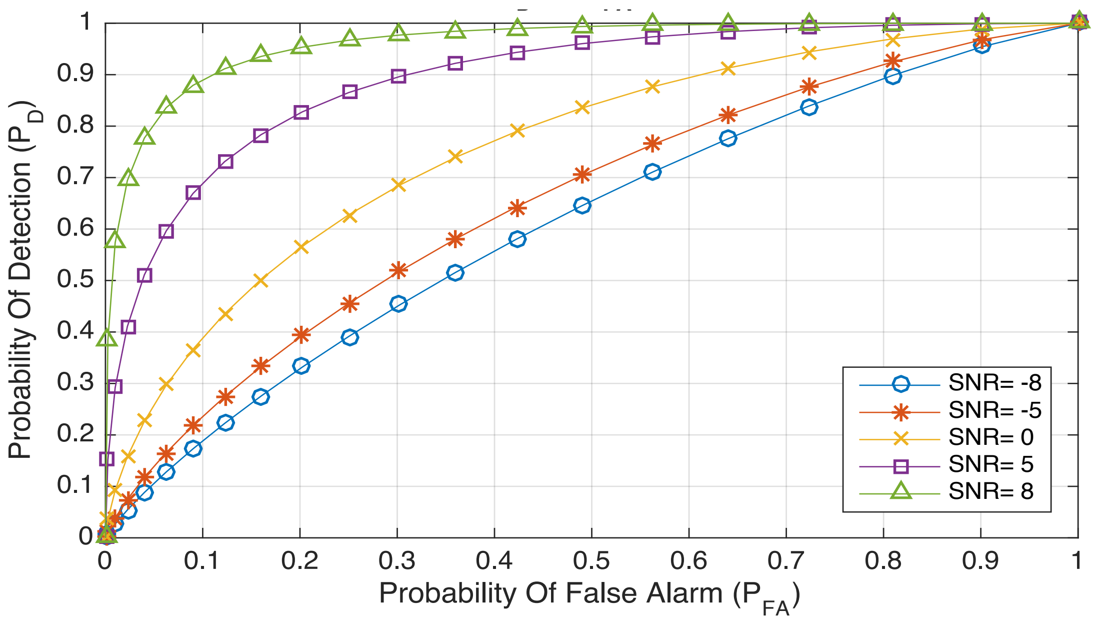


Figure 3.12: Matched Filter Detection ROC curve for P_D vs P_{FA}.

Figure 3.13 shows the probability of missed detection as a function of SNR. Here we can observe that the probability of either false alarm or missed detection for matched filter detector increases with the decrease in SNR. However, at higher values of SNR, a low probability of missed detection results in a higher probability of false alarm.

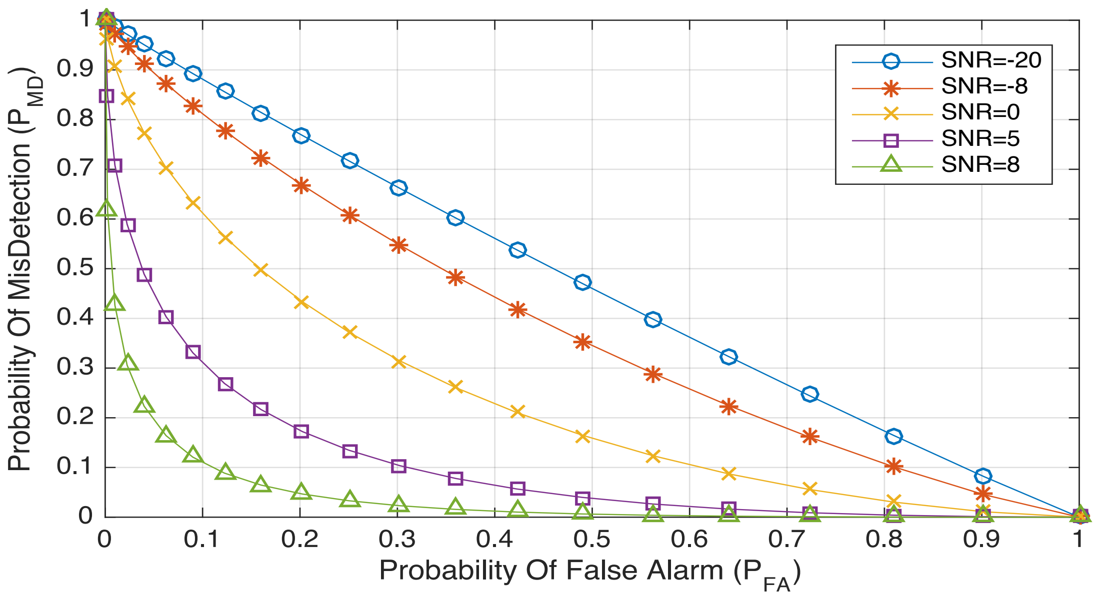


Figure 3.13: Matched Filter Detection ROC curve for P_{MD} vs P_{FA}.

In the Figure 3.14, the impact of SNR on the performance of cyclostationary feature detector method is investigated. The cyclostationary detector is observed to have probability of missed detection of almost zero i.e. negligible. Also, the probability of tolerable false alarm values increases with increasing probability of detection. The cyclostationary detector shows better performance at lower SNR with negligible false alarm probability.

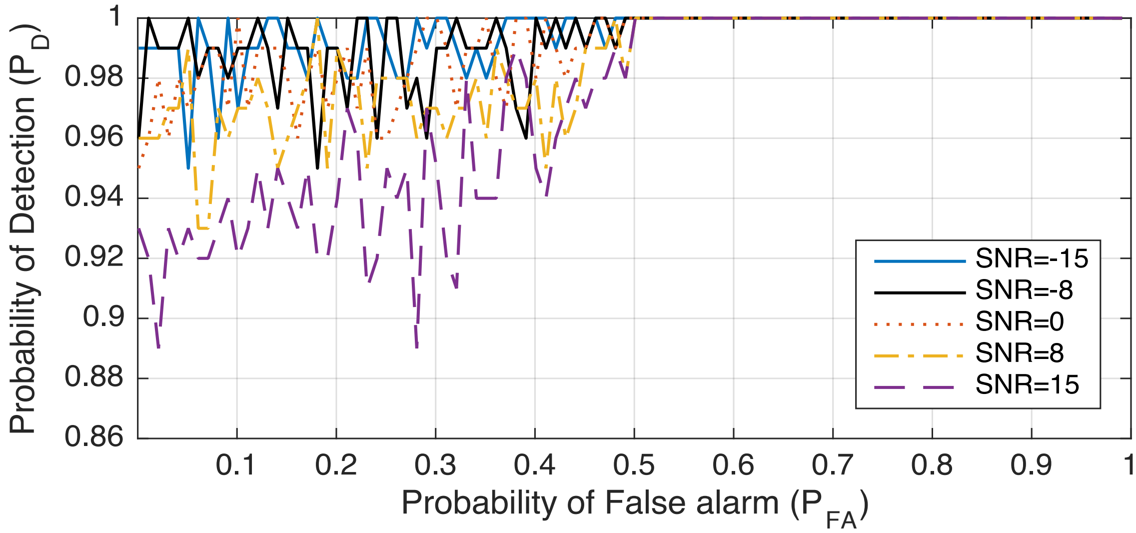


Figure 3.14: Cyclostationary Detection ROC curve for P_D vs P_{FA}.

The three major transmitter detection techniques for spectrum sensing were compared for their performance on detection of spectrum opportunities with the receiver operating characteristics as the performance metrics as shown in Figure 3.15.

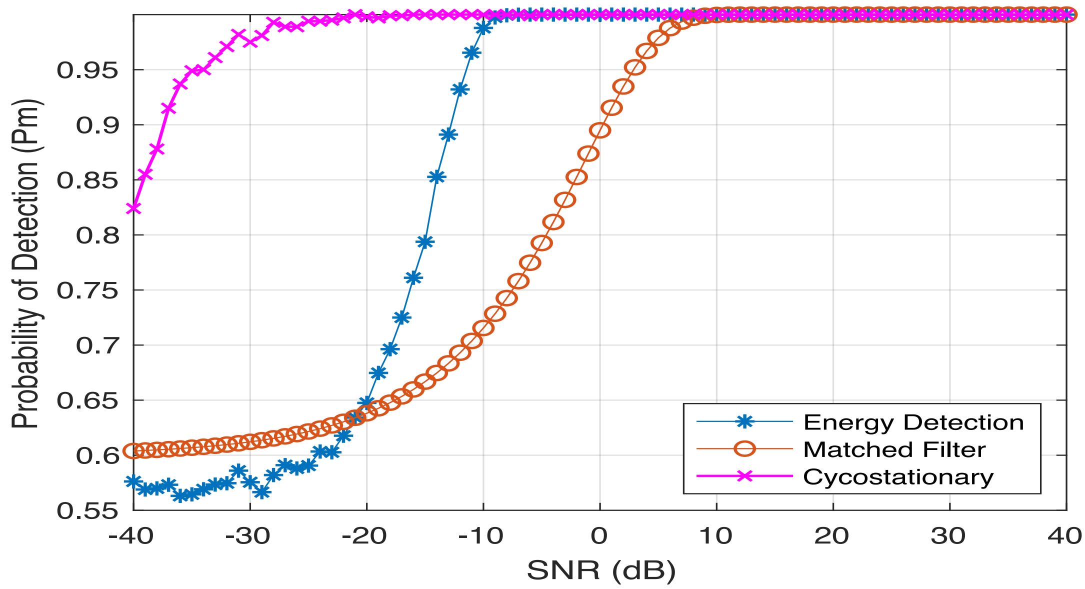


Figure 3.15: Performance Comparison of Transmitter Detection Techniques.

From the Figure 3.15 we can observe that the performance of all three techniques is 100% at higher SNR values of above 10dB. At low SNR values, the performance of the cyclostationary feature detection technique is best as compared with the others two techniques. It shows very good results over the range of 30dB to -30dB and its performance is not affected by the SNR values as it relies on the periodic signal features for detection.

3.2.2 Choice of detection method.

Cyclostationary detector can achieve very high detection at the range above -30dB SNR whereas to achieve such detection, energy detector needs to have above -9 dB of SNR and matched filter detector can achieve the same detection performance at SNR of above 8dB. The performance of the ED over the MFD is better over the range of -20dB to 10dB. But the MFD results are reliable because the ED cannot differentiate between the actual signal and the noise signal at weaker SNR values. Also matched filter detection has better detection performance at low SNR than energy detection as seen in the Figure 3.15. We can therefore conclude that cyclostationary detector performs better than the other two major detectors by a large margin as it performs extremely well at low SNR upto about -30dB SNR. Therefore, if the mathematical complexity can be compromised then the cyclostationary feature detector is the best sensing detection technique for cognitive radio based smart grid applications. This is especially so considering the fact that most applications of the smart grid do not require real time bandwidth. Most of the applications are delay tolerant especially where the smart grid devices have been equipped with data storage mechanisms to store the data and only transmit it when the spectrum is free from use by the primary users. Another disadvantage of cyclostationary detection is its long sensing time. This can be improved by using both cooperative sensing among the various nodes and storing the sensing data in the fusion center database and using it as a reference for faster future sensing of idle spectrum.

CHAPTER FOUR

THE DESIGNED COMMUNICATION NETWORK

4.1 CM2M Communication in Smart Power Grid

Due to a rapid increase in world population and power demand, the current power grid has encountered many challenges. Key among them is the ever growing energy demands, unreliable communication and monitoring, unidirectional flow of power, emerging renewable energy sources, aging infrastructure, as well as reliability and security problems. As a result, current infrastructures and standards are incapable of supporting the ever-changing demands caused by the overwhelming increase in bandwidth, transport of IP traffic, and the need for more flexible connectivity, higher resiliency, and network automation. Due to large geographical spread of grid networks coupled with changing network conditions, SG communication has potentially large numbers of devices and appliances resulting in large amounts of data. Scalability and fast communication are therefore crucial for practical deployment of SG. To overcome these challenges, a smart power grid communication network is envisioned.

However, there are some challenges in the SG environment that hinder the setting up an efficient smart power grid communication network. These include harsh wireless signal propagation conditions, heterogeneous SG network structure and traffic as the power grid delivers electricity to a wide landscape of varying topology ranging from sparsely populated rural areas to densely populated urban areas, lack of spectrum for deploying a wide area network as all available spectrum has already been allocated and where available, high cost of buying spectrum for setting up a wireless network architecture (Kouhdaragh, Tarchi, Coralli, & Corazza, 2013) (Khan, Sohail, Ghauri, & Aqdas, 2017).. Since most SG applications e.g. demand response applications require highly reliable communication network, application of M2M communications in the smart grid is suggested in this research to provide the infrastructure through which millions of SG devices can communicate. The CM2M communication network is designed considering the scalability, energy efficiency requirements, periodic traffic patterns, and large-scale deployments requirements of the current grid networks.

4.2 Designed Network Layout

Different SG services, and applications have different requirements in terms of bandwidth, capacity, latency, and security, which makes it difficult to design an appropriate system for the overall power grid. Most of the existing communication technologies, either lack of bandwidth, latency, security, full coverage, and reliability capabilities or the cost for investment, maintenance, and operation, are high as discussed in section 2.7. In order to meet the complex communication needs of the smart grid, innovative approaches to communicate various data over a range of environments, spanning from individual homes and neighborhoods to wide area networks covering electrical interconnections is required. SG communications needs to be designed to accommodate the current energy management requirements as well as the potential demand of future applications (Wu, Talwar, Johnsson, Himayat, & Johnson, 2011).

The design of different area networks that supports the needs of smart grids has its own technical challenges. One of the most significant requirements in fulfilling the data traffic requirements is to connect all the sensors and actors as well as other communication devices across every corner of the smart grid, either in rural areas or in dense urban centres. A TVWS communication network provides connectivity for large-coverage areas with a required bandwidth capacity and QoS maintenance including for low latency connections. The main advantage of utilizing wireless communications is the cheap deployment cost of wireless infrastructure, to cover WANs as compared to wired channels. Wireless networks provide scalability and easy upgrading feature without the need of changing the whole architecture. A wireless network is the best way to support the last mile access for the distribution domain and for supporting applications in the transmission and distribution domains as discussed in section 2.7 since smart grid data traffic requirements are low when compared to multimedia applications.

The designed network layout incorporating the main functional domains of a SG network is as shown in Figure 4.1.

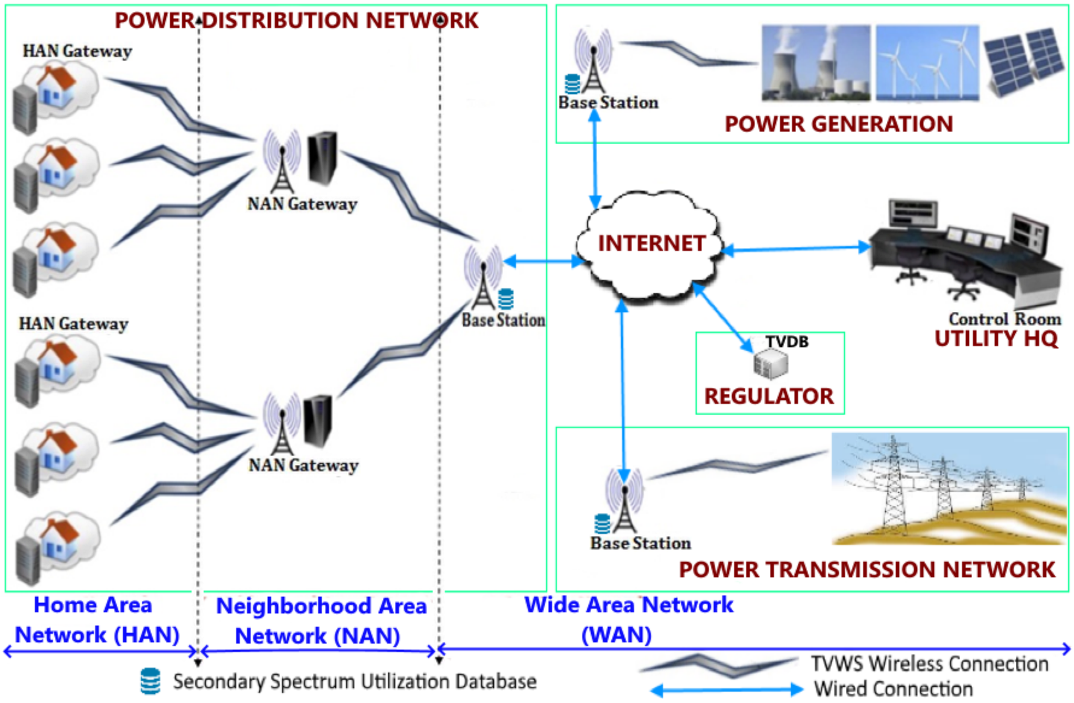


Figure 4.1: Proposed Network Layout.

In the designed architecture, the communication network comprises of a HAN, NAN and WAN with communication up to the WAN base station based on TVWS. The HAN comprises of a CR home gateway (HGW), smart meters, and other smart devices around the home environment. Energy consumption data collected by smart meters is sent via HGWs to the NAN. In the NAN, each NGW serves as an access point allowing the different NAN devices to communicate with Fusion Center (FC) at the base station through TVWS. The control center at the utility offices is connected to the CR base stations, which manage the communications of the NGW and are spread over a large geographic area spanning the different functional domains of a SG network. The use of Cognitive radio allows for dynamic resource allocation (different latency requirements and sporadic bandwidth requests) for the diverse applications in the smart grid. In this research, Cognitive Radio and M2M communications over TVWS are deployed to design a SG communication network.

4.3 Designed Detection Mechanism

The spectrum sensing technique employed in the designed detection mechanism is cyclostationary feature detection for the individual node sensing as seen in section

3.2.1. Although cyclostationary feature detection has a drawback in its dependence on the specific features and that it may have difficulties to adapt to any new radio system introduced by the incumbent in the band later, these weaknesses are eliminated by access of the regulator database which is regularly updated with any changes in spectrum allocation. Since DVB-T has a set of standardized wave forms, the detection method can take advantage of the embedded signal features in order to improve performance (Choi, Chang, Choi, & Lee, 2012) (Foo & Takada, 2016) (Waddell & Harrold, 2012). From Figure 3.15 we observed that cyclostationary feature detection is robust to noise uncertainties and performs better in low SNR regions when compared to other detection mechanisms. Although CFD requires prior knowledge of the signal characteristics, this enables it to differentiate between CR transmissions and PU transmissions. This in turn eliminates the need for synchronization during cooperative sensing. CR users can also transmit while sensing during cooperative sensing thus improving the overall CR throughput (Verma, Taluja, & Dua, 2012).

4.3.1 Operational Design

The designed operational design of the smart power grid network is as shown in Figure 4.2. The designed secondary network operates in the UHF/VHF spectrum bands allocated for digital terrestrial Television broadcasting channels 21-48 (470-694 MHz) (Electronic Communications Committee , 2011). The secondary communication system transmits and receives data as long as the primary system is not using its assigned frequency and on condition that it does not cause interference to the primary users. The operational design is based on the IEEE 802.22 WRAN standard.

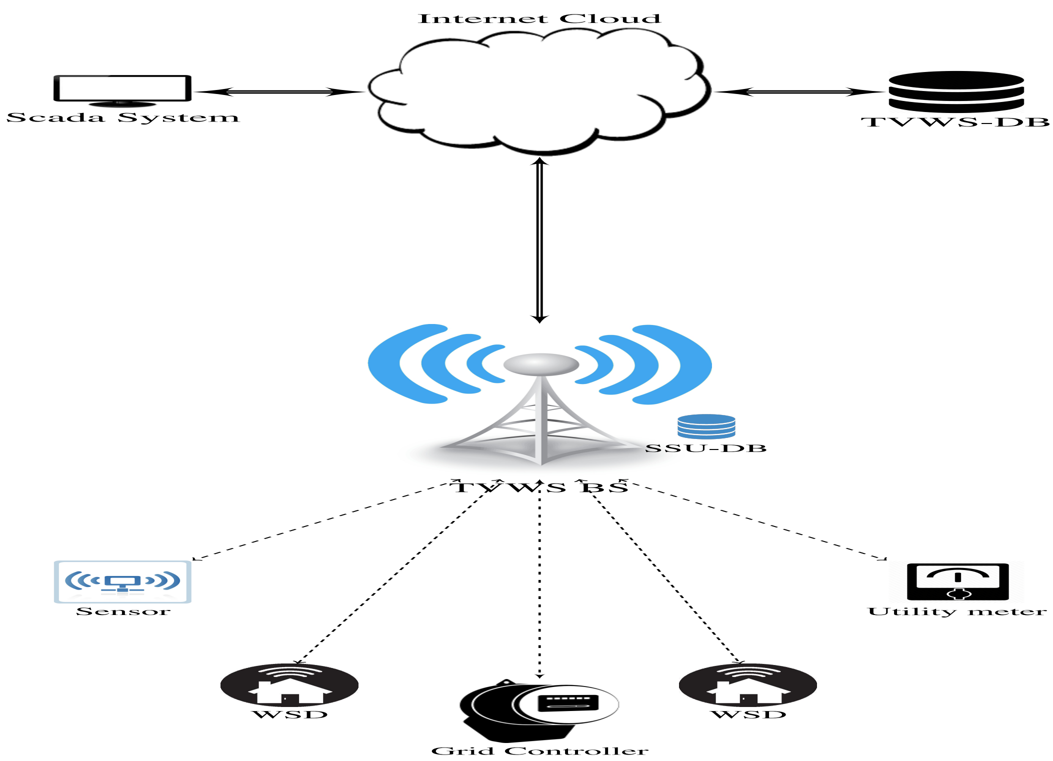
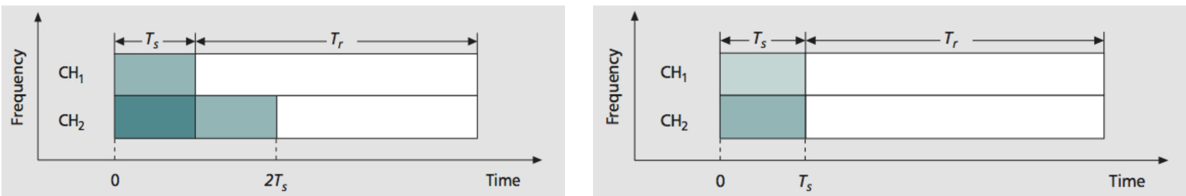


Figure 4.2: Proposed network design

Each of the individual nodes has geolocation capability and is able to sense the unused spectrum on their own but have to share their sensing information with a Fusion Centre (FC) or a Base Station (BS) which is responsible for decision making to decide which is the best frequency to use for transmission. The fusion center combines the sensed information together with information obtained from the regulator-maintained TV white space database (TVWS-DB) and maintains its own database known as the Secondary Spectrum Utilization Database (SSU-DB) which it uses for future prediction of vacant bands and also in decision making to decide which vacant bands to utilize in accordance with past historical utilization patterns that are already stored in the database. The fusion center acts as the master CR device while the individual nodes act as slave CR devices. The master CR device ensures that the slave CRs operate according to the rules returned by the database.

4.3.2 Cooperative Transmitter Sensing

In transmitter detection, only one channel is sensed at a time, by a single node. Therefore, in order for a single node to obtain the activity of two channels, it would require two timeslots with the total sensing time amounting 2Ts. In wideband sensing two or more nodes are employed to sense multiple channels simultaneously. After sensing, all nodes send the sensing results to the smart grid fusion center to make the final decision (Zhang, et al., 2012) (Liu, Xie, Zhang, Yu, & Leung, 2012). The fusion center can know the activity of the n channels after Ts which can then be shared with the other nodes via the smart grid fusion center as shown in Figure 4.3. The cooperative sensing scheme employed utilizes wideband sensing. Multiple devices therefore cooperate by sending their sensing data to the fusion center, thereby reducing energy consumption during spectrum sensing. Therefore, even though cooperative sensing deals with a communication and processing overhead, the accuracy of spectrum sensing is improved while the energy consumption during the spectrum sensing phase is reduced (Ghosh, Das, & Chatterjee, Cognitive Radio And Dynamic Spectrum Access – A Study, 2014).



(a): Uncooperative Sensing **(b): Cooperative Sensing**

Figure 4.3: Effect of Cooperative Sensing on time factor.

The sensing results are then sent to the fusion center which employs a centralized cooperative detection mechanism in the smart grid communication network. In centralized cooperative sensing a Base Station (BS) or a Fusion Centre (FC) coordinates the process of decision making in the cooperative spectrum sensing. All CR devices send their sensing results to the FC, and the FC combines the received signals to determine the presence or absence of a PU. Once a determination has been made, it sends the decision back to the cooperating CRs.

4.3.3 Using history for prediction

In order to minimize interference to primary users while ensuring fast decision-making during spectrum sensing, the cognitive radio sensing nodes keep track of changes in spectrum availability and make predictions based on past experiences. Since spectrum sensing is a continuous process and the cognitive radio are intelligent enough to learn and make decisions based on the surrounding environment, the spectrum usage historical data is very vital for predicting the future profile of the spectrum channels. Channel usage patterns of PUs are identified from the historical data and then utilized for predicting future spectrum occupancy. These patterns are then used to forecast the channel idle probability for a given channel and predict the future occupancy even before spectrum sensing is used to identify the range of frequencies that can be used for transmission. Channels with frequent and heavy appearance of primary users are filtered out and the channels most likely to be free are scanned first. Therefore, when observation history is used, the cognitive radio can predict transmission opportunities and then first scan these channels during selection of a channel for transmission during which the throughput of the secondary user is increased. Most primary systems have predictable usage patterns in time and/or space which makes it easier to predict the presence of the primary user even before spectrum sensing starts. Figure 4.4 shows a modified spectrum sensing model derived from the cognitive cycle reviewed earlier in section 2.3.2. It combines a prediction and sensing mechanism that is used to determine the presence primary users for faster sensing in the designed detection mechanism.

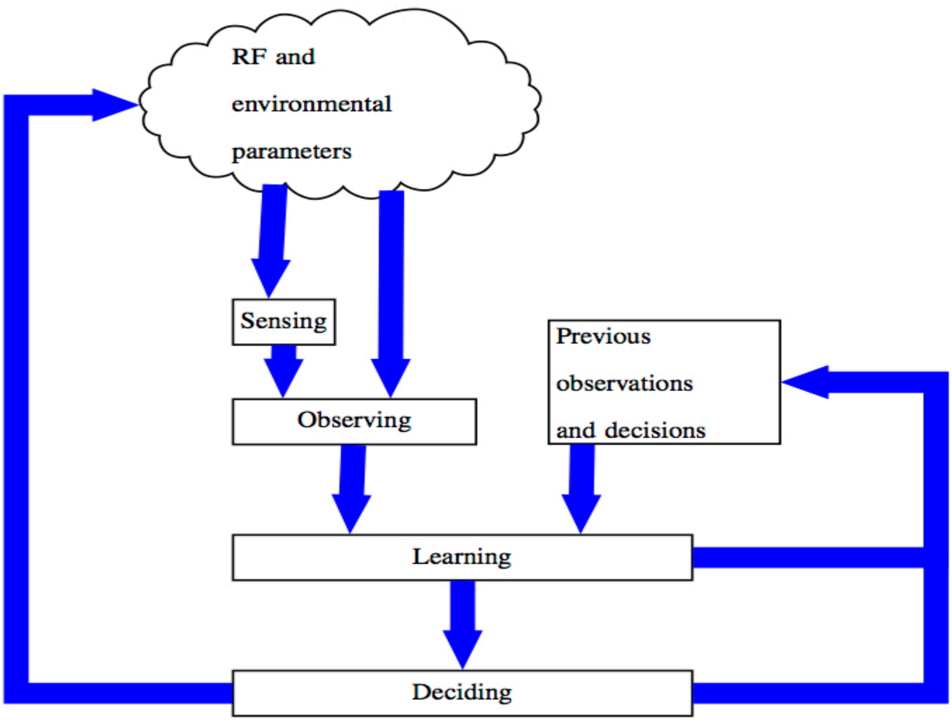


Figure 4.4: Learning process utilized by the system.

4.3.4 Frame Structure for SG Communications

Figure 4.5 shows the communication frame structure of a secondary system adopted in this research. Unlike the normal frame structure for wireless communications, it consists of a sensing time slot and a data transmission slot. During each frame duration, secondary users sense the channel for a given duration TS. If none of the PU signals is detected in the targeted channel, the SU uses the rest of the frame for data transmission. The sensing duration is further divided into two. The individual node sensing takes place during the period TLS while the secondary users transmit their sensing data to the fusion center for a duration of TC. TC is known as the cooperating overhead. If an active PU is detected, however, the secondary user will not transmit but will migrate to another channel or wait until the next frame where channel sensing is repeated.

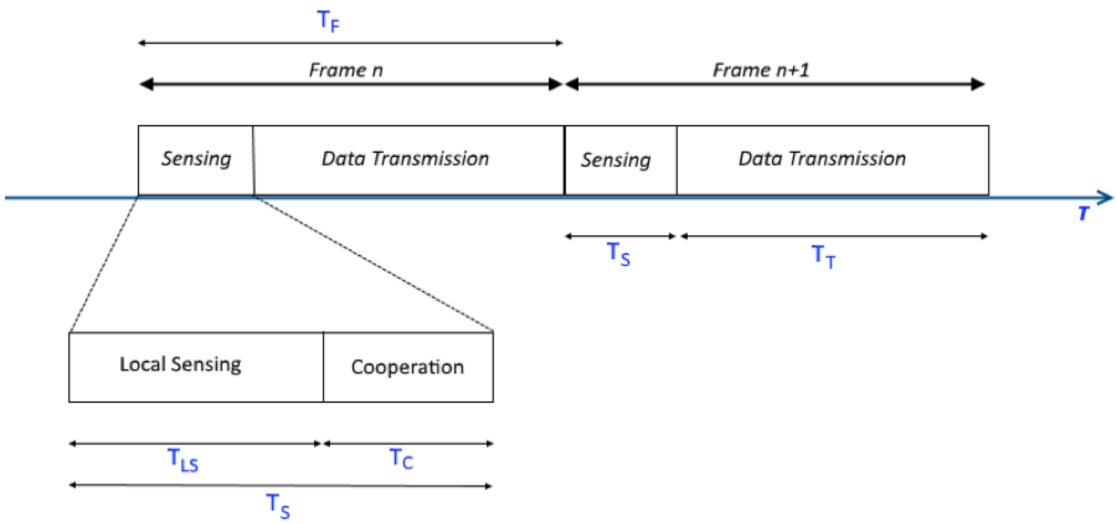


Figure 4.5: Communication frame for secondary cognitive radio networks.

The cooperation overhead increases with the number of cooperating users due to the increased volume of sensing data that needs to be forwarded to the FC. Therefore, there exists a trade-off between the local processing overhead and the cooperation overhead as they both add to the total sensing time T_S. In this research, the total sensing time T_F is evaluated by equation 4.1:

$$T_F = T_s + T_T \quad where \quad T_S = T_{LS} + T_C \tag{4.1}$$

4.3.5 Principle of Operation of the Detection Mechanism

The operational design combines both Geolocation based database approach and spectrum sensing for better accuracy. The CR devices query a remote TV band database in order to determine the list of available channels in the area together with the allowed set of operating rules. This CR the performs spectrum sensing to confirm the emptiness of these channels. A flowchart of the designed detection model is shown in Figure 4.6.

Spectrum sensing is followed by Secondary user sensing in order to prevent secondary to secondary interference. Secondary to Secondary Interference is interference that is experienced by a white space receiver from other TVBD users that it causes severe impacts on its performance. Secondary user sensing also enables in enforcing a priority check mechanism which enables preference to be given to higher priority messages to be transmitted first. Once a transmission has been successful, the FC updates its internal database with the frequency of the utilized channel. The flowchart is based on the cognitive cycle of detecting spectrum holes described earlier on Figure 2.9. in section 2.3.2. For the designed communication model, different priorities are assigned to each different application.

All the users in the CR network system are categorized into priority levels. The base station makes spectrum allocation decisions subject to available spectrum resources and informs each SU according to their priority. Each SU has an information queue to buffer source packets according to the packet priority. Each SU is also capable of relinquishing the channel in case of PU reappearance or the appearance of a secondary user message with higher priority (Huang, Wang, Qian, & Wang, 2013) (Kaabouch & Naima, 2014). Based on QoS requirements for each of the smart grid applications, the FC makes intelligent decisions on the spectrum to use.

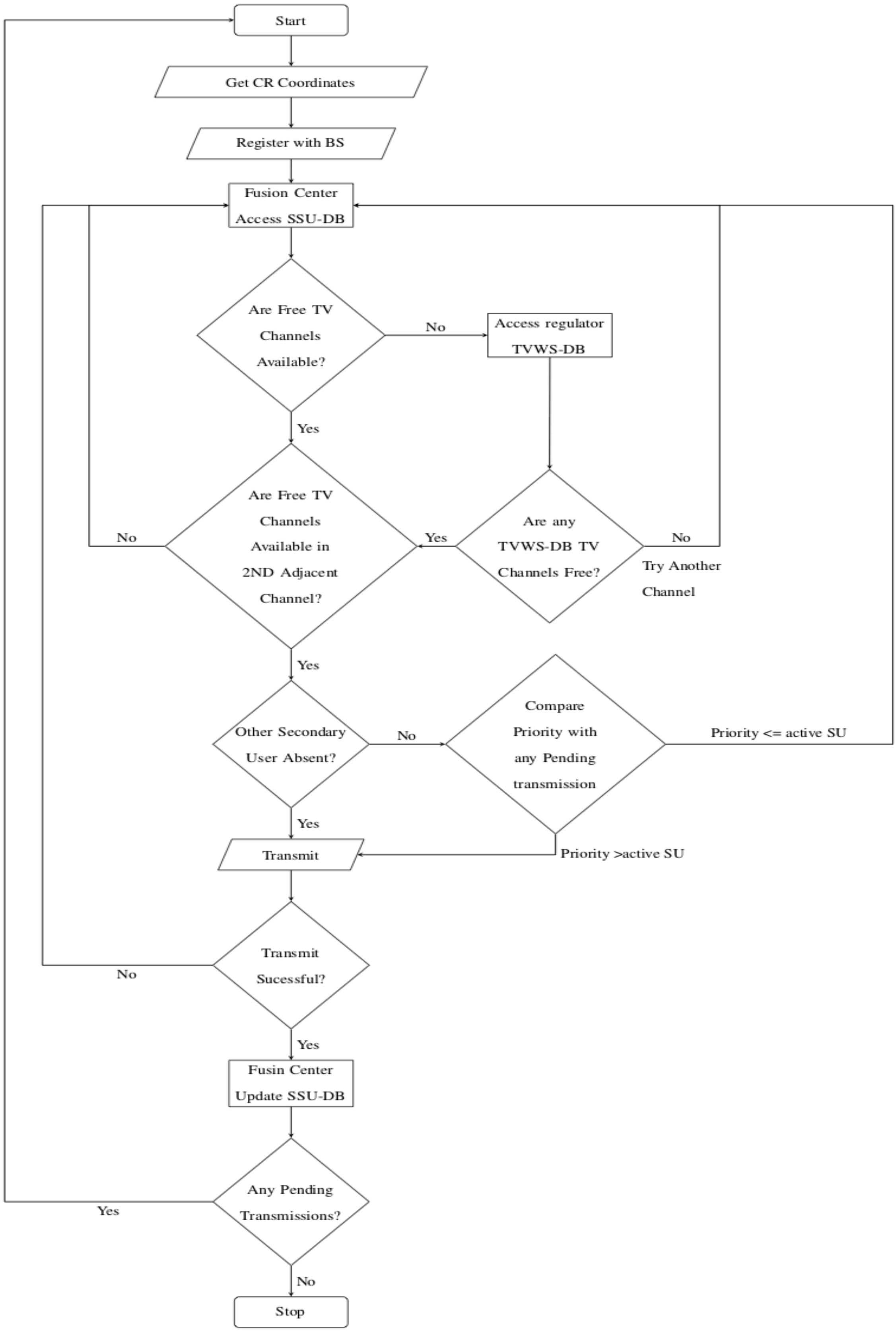


Figure 4.6: Flowchart of the proposed detection model.

Although smart metering data has low volume with very minimal spectrum usage time, the massive number of smart meters, results in a combined huge volume and the FC has to coordinate access to the limited wireless resources by the massive number of devices. The FS uses a scheduling algorithm that prioritizes data traffic into different classes. SG critical messages are transmitted first according to the priority scheme while those with less stringent requirements are transmitted only when there are no higher priority messages in queue. The high priority messages can interrupt the low priority messages in order to take over the spectrum for transmission. The need to differentiate between high and low-priority traffic is vital so as to be able to dynamically adapt the network to varying capacity requirements in real time and optimize the grid network. Highly prioritized messages include control, protection, and billing messages; monitoring information from sensors, including multimedia surveillance, are classified into the lower level priority while readings on the consumption patterns are the lowest level priority data traffic.

4.4 Designed SG Communication Network

The designed communication network exploits TVWS using CR to enable M2M applications in the smart grid. In this research, OMNeT++ (Objective Modular Network Testbed in C++) has been used to simulate machine-to-machine (M2M) communications (Nardini, Virdis, & Stea, 2016). OMNeT++ was chosen as the developing platform, due to its open source nature, its modular architecture, the existing documentation, and the provided Integrated Development Environment (IDE). It provides, in a user-friendly graphical representation, detailed models of the wireless propagation channel, mobility and obstacles models, and many communication protocols, especially at the MAC level (Khan, Kalil, & Mitschele-Thiel, 2013). Simulation was carried out by extending the INET Framework, (modelled for wired and wireless TCP/IP based simulations), Castalia, (developed for wireless sensor networks) and MiXiM, (developed for use in mobile and wireless simulations) (Marinho & Monteiro, 2011) (Caso, Nardis, & Holland, 2014).

4.4.1 Network Simulation

Smart Grid requires advanced communication technology to establish two-way communication networks connecting the service provider and the customers beyond the traditional power grid architecture. Figure 4.7 shows the internal SU architecture, highlighting, how the BaseCrNode module was defined in Omnet++ to include functionalities typical of a Cognitive Radio device.

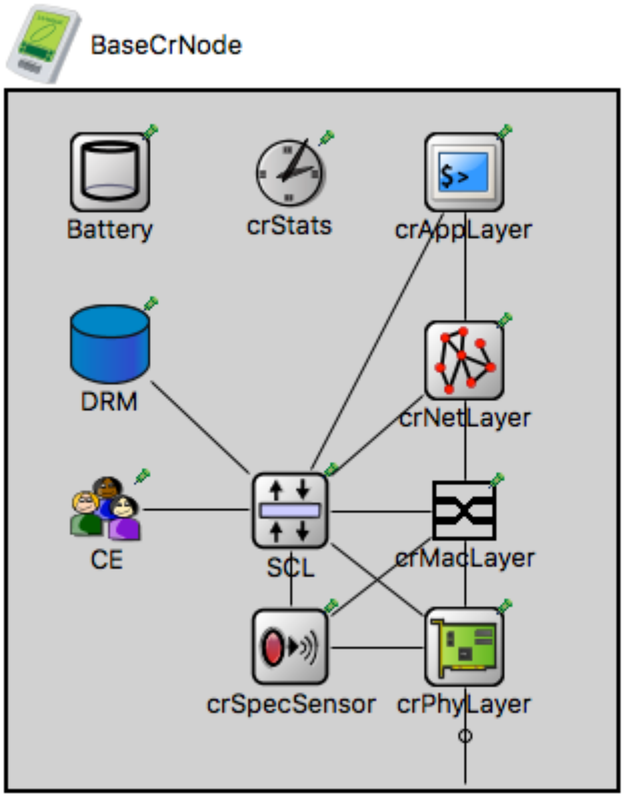


Figure 4.7: Secondary Node Architecture as modelled in Omnet++.

The modelled smart grid communication network architecture caters for the communication needs of the smart grid follows the hierarchical communications architecture of M2M communications as shown in Figure 4.9. This hierarchical heterogeneous communications architecture comprising several network segments and combining different communications technologies present higher flexibility, so they fit a wider range of Smart Grid applications with their specific requirements and constraints. It comprises of Home Area Network (HAN), Neighborhood Area Network (NAN) and Wide Area Network (WAN) with the aim of being flexible, adaptive, and scalable. In this simulated architecture, the SG power system is separated from the communication system and only the communications framework is considered. With the proposed sensing approach, the probability of interference to a PU is reduced while the benefits resulting from the cooperative sensing scheme eliminates the main weakness of time overhead that is usually associated with cyclostationary detection method. The Omnet++ codes used for the simulation can be found in Appendix II. The parameters chosen for the simulation of the network are presented in Figure 4.8 and the simulated network is shown in Figure 4.9.

```
## NETWORK Level Parameters
#network = SmartGridNetwork
**.totalChannels = 2

**.**.puEnabled = true  ## Whether Primay User is enabled or not (true/false)

## CR Node Parameters
**.**.drmEnabled = true
**.**.ceEnabled = false

## CR Layers
**.**.appLayer = "crAppLayer"
**.**.netLayer = "crNetLayer"
**.**.macLayer = "cr80222"
**.**.phyLayer = "crPhyLayer"
**.**.specSensor = "drmSpecSensor"
**.**.scl = "crScl"
**.**.drm = "testDRM"
**.**.ce = "crCognitiveEngine"
**.**.battery = "crBattery"
**.**.crstats = "crStats"

## MAC Parameters
**.**.totalFrames = 524# = 1MB (2000bytes payload/packet) # Number of packets to send per session
**.**.AckEnabled = true # Must be true # Whether frames are acknowledged at MAC level or not
**.**.rtsAttempts = 3 # How many attempts at MAC level for connection establishment before abort.
**.**.sensePerPacket = false # Data channel is sensed before every frame transmission or not?

## Sensing Module Parameters
**.**.sensingDuration = 0.000050  # 50 Microseconds
```

Figure 4.8: Simulation Environment Parameters

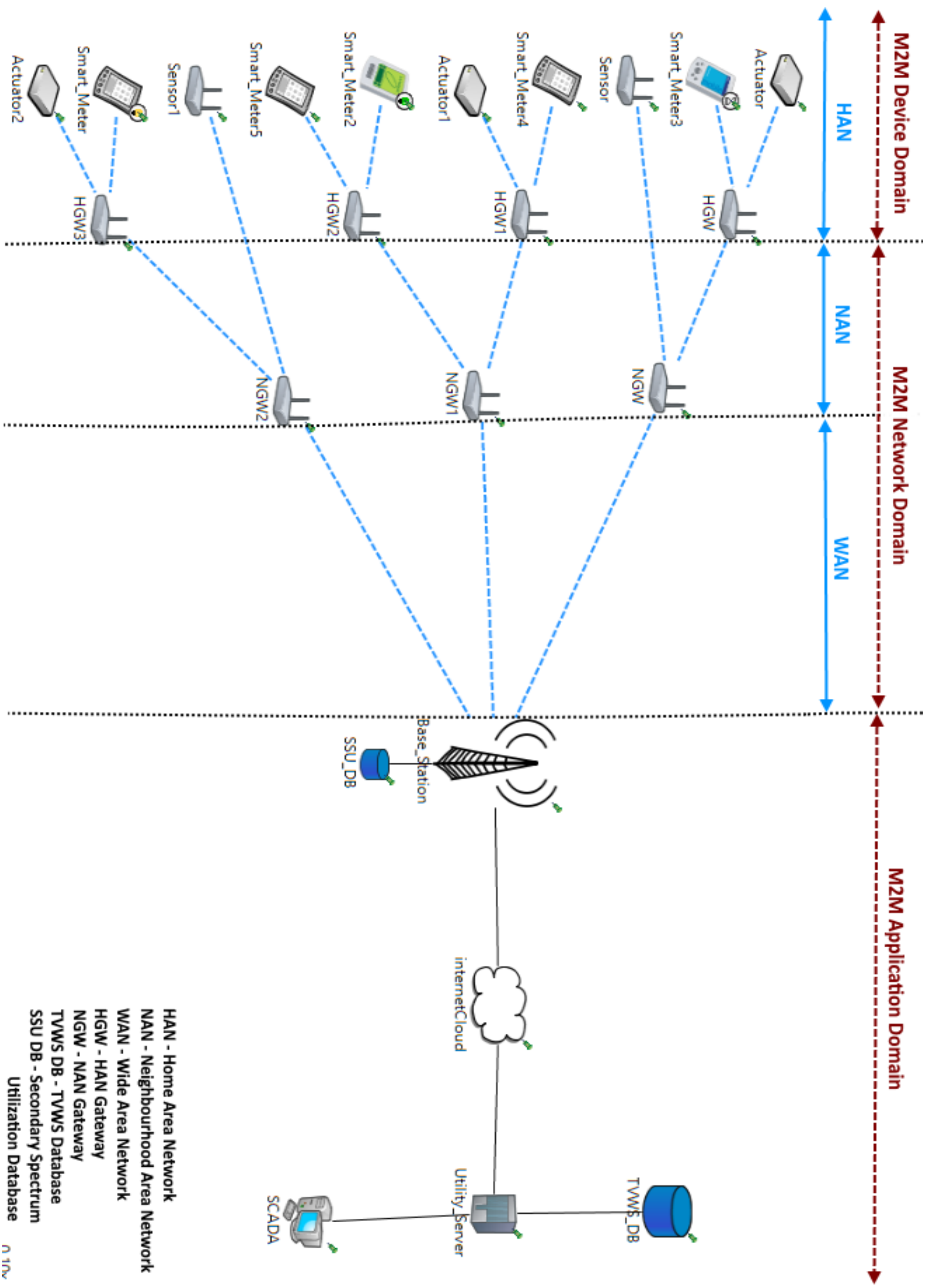


Figure 4.9: Simulated Smart Grid Communication Network.

Each modelled device (sensor, smart meter, actuator) collects load information and energy consumption data which is aggregated at the HGW and then relayed to the utility control center through the NAN and the BS. Communication within the NAN is organized using the NAN cognitive gateway (NGW), where the NGW connects multiple HGWs together. The NAN then connects to the CR base station (BS) through the NAN Gateway. The BS manages communication between multiple NANs and the utility control center as shown in Figure 4.9. Once the aggregated data reaches the BS, it is further transmitted to the remote servers of the network operator using fiber optics.

Although there are numerous possible communication technologies to build a HAN/NAN/WAN, the choice of an TVWS communication technology leverages existing infrastructure and freely available resources, while satisfying the data rate requirements of the targeted application, hence is essential for a cost-effective solution. Connecting every building in the neighborhood via wired access is less flexible and costly since such wired infrastructure does not exist. In the designed communication network, a combination of both spectrum sensing, and geo-location database (TVWS_DB) in order to protect licensed users from interference from secondary users is employed. The designed architecture can readily be deployed in any residential, commercial, or industrial complex, having numerous buildings and a large number of machine type devices.

CHAPTER FIVE

RESULTS AND DISCUSSION

In this chapter, the performance of the designed smart grid communication network is evaluated in terms of path loss, throughput and power consumption. Evaluation of the propagation models is vital because in different deployment scenarios, the performance of the designed smart grid communication network will be affected by path loss and fading characteristics. Throughput analysis is also an important consideration especially in cases of reappearance of the primary user while M2M devices battery consumption is of great concern due the large number of devices in the network.

5.1 Path-Loss Analysis

In the design of any wireless network, the fundamental task is to predict the coverage of the proposed system as all wireless networks are usually limited by the range. Path loss analysis was used to evaluate the performance of various communication technologies against the performance of the designed CM2M smart grid communications network. The path-loss (PL) is dependent on the terrain, the transmit antenna height, the receive antenna height, the frequency of operation, and other parameters. In (Holland, Bogucka, & Medeisis, 2015) a review of the application of the extended Hata propagation model was carried out. Measurements from both fixed and mobile networks deduced that the extended Hata model is the most suitable to describe the path loss in the UHF/VHF frequency bands and can be extended upto the 3.5GHz band. The extended Okumura-Hata propagation model was therefore used to calculate the path loss between the base station and the modelled CR devices. The parameters used for the path loss calculations are shown in Table 4.1 below:

In the design of any wireless network, the fundamental task is to predict the coverage of the designed system as all wireless networks are usually limited by the range. Path loss analysis was used to evaluate the performance of various communication technologies against the performance of the designed CM2M smart grid communications network. The path-loss (PL) is dependent on the terrain, the transmit antenna height, the receive antenna height, the frequency of operation, and other parameters. In (Holland, Bogucka, & Medeisis, 2015) a review of the application of the extended Hata propagation model was carried out. Measurements from both fixed and mobile networks deduced that the extended Hata model is the most suitable to describe the path loss in the UHF/VHF frequency bands and can be extended upto the 3.5GHz band. The extended Okumura-Hata propagation model was therefore used to calculate the path loss between the base station and the modelled CR devices. The parameters used for the path loss calculations are shown in Table 5.1:

Table 5.1: Parameters to calculate path loss

Parameters	**Values**
Channel Width	8MHz
Transmit Power	36.02 dBm
Distance d	0-100 km
Antenna Height Tx	100m
Antenna Height Rx	1.5m
Antenna Gain	6dBi
Receiver Sensitivity	-98dBm
Receiver Noise Floor	-114dBm
Receiver Noise Figure	5dB
Modulation	64 QAM
Frequency Band	470~698 MHz

TV white space available for fixed devices is mostly available in sparsely populated areas, such as the semi-urban and rural areas, while the densely populated metropolitan areas have few available TVWS channels (Mody, 2013) (Cacciapuoti & Caleffi, 2015). The distribution of available TV white spaces in the UHF/VHF spectrum can thus be classified into urban, semi urban, and rural settings. Using Extended Okumura-Hata path loss equations described in section 2.8.1.3, the plots for the path-loss analysis using Matlab are as shown in Figure 5.1.

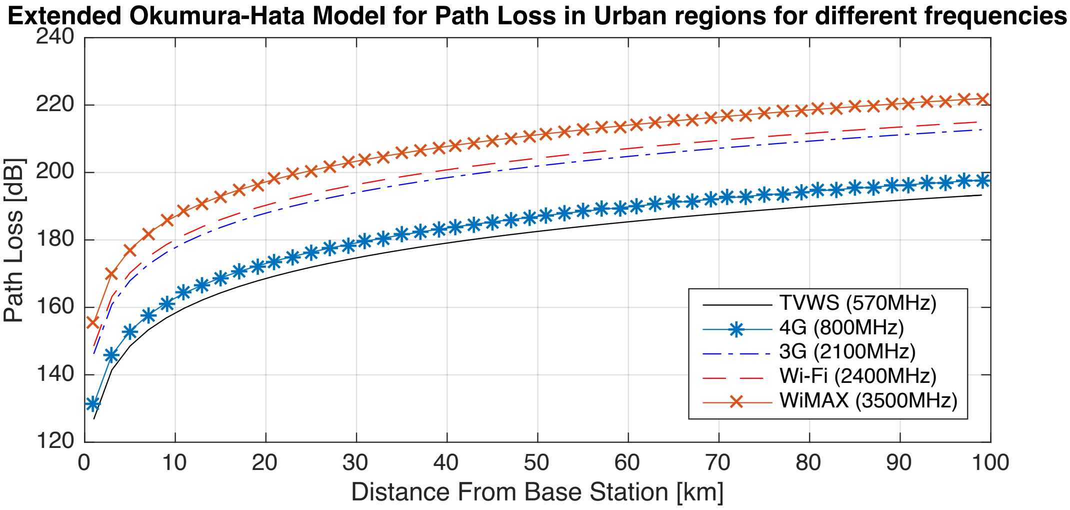


Figure 5.1: Extended Okumura-Hata Path loss Comparison.

The plot in Figure 5.1 compares the path loss for a range of different frequencies in Urban regions as modelled using the extended Hata-Okumura model. Path loss increases with increasing frequency with TVWS frequencies providing the least pathloss. The link budget between base station and WSD can then be calculated using Equation 5.1.

$$\text{Received Power (dB)} = \text{Transmitted Power (dB)} + \text{Gains (dB)} - \text{Losses (dB)} \qquad (5.1)$$

Radio propagation is a very important factor to be taken into account when designing a communication network. This is particularly important because meters may usually be located in indoor/non-exposed locations, which may potentially curtail their radio transmission range. Since the designed communication network is based on TVWS frequencies and cognitive radio technology, it can be seen, from the graph (Figure 5.1) that the propagation loss is significantly lower in low-frequency TV bands as compared to higher frequency cellular, WiMAX and Wi-Fi bands. As a result, TVWS based smart grid represents an attractive technology considering that TVWS can maintain a higher capacity, thanks to a better propagation effect.

5.2 Power Consumption

In wireless M2M communications, energy-efficiency is of utmost importance as it determines the life span of the M2M devices on the grid. Due to the high number of M2M devices in the designed communication network, combined with the fact that most of them are battery powered, they need to have low energy consumption capability so that many devices can last years without requiring battery replacement. Some devices on the smart grid are located in locations with limited supply of power while others are battery operated. Some devices especially in power generation are located in remote areas that experience infrequent human interaction. Due to the large number of devices in the smart grid it would be very uneconomical to have to replace the battery every so often considering that the grid covers large geographical regions. To ensure longevity of these M2M devices, the M2M smart meter devices need to be power efficient and accurate modelling of power consumption is required. In this regard, we investigated the battery consumption during spectrum sensing as spectrum sensing had earlier on been identified to be the most energy intensive process of the cognitive cycle as the cognitive radio devices have to continuously sense the spectrum opportunities. The battery consumption is as shown in the Figure 5.2.

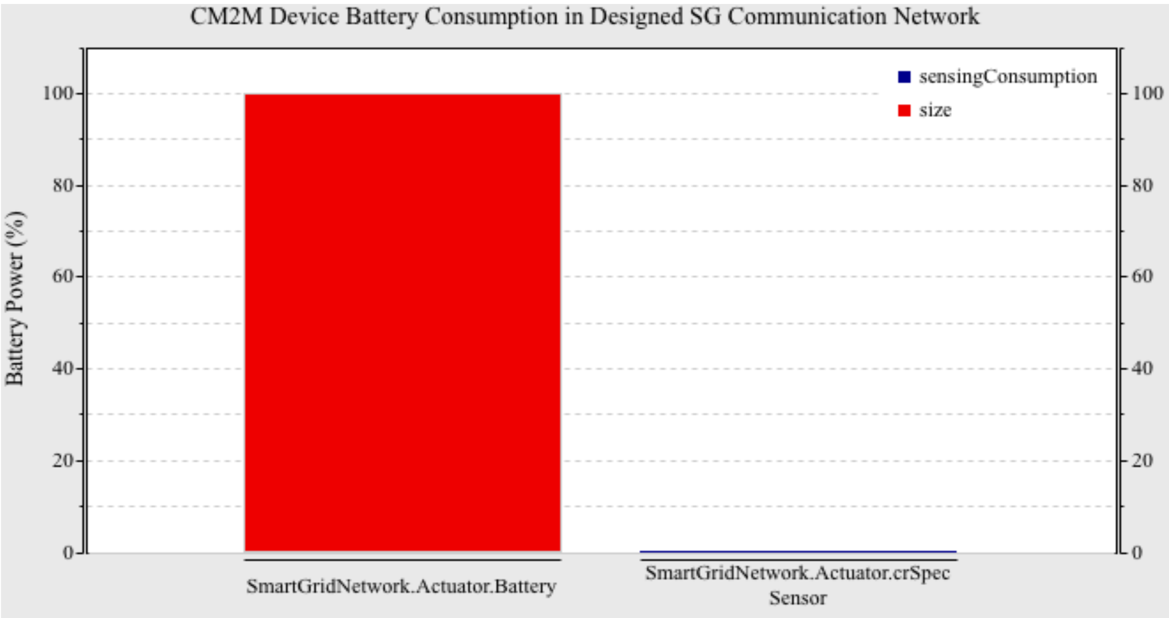


Figure 5.2: Power consumption in the designed M2M devices

Numerical results demonstrate significant energy saving and the reliability in supporting data transmissions in the smart grid. The fact that M2M devices cooperate with each other during spectrum sensing coupled with adaptive power control is noted to have contributed immensely to the minimal energy consumption resulting in significant power savings. Thus energy efficiency plays a crucial role in terms of costs and maintenance efforts of the designed communication network.

5.3 Throughput Analysis

Throughput is defined for SU as the ratio between end-to-end received packets to the generated packets. Simulations were carried out to evaluate the impact of PU reappearance on the achievable SU network throughput of the designed communication network. Figure 5.3 shows the impact of PU transmission on the achievable throughput for designed network with fixed PU transmission duration and variable arrival rate. The figure shows results of two simulation scenarios having one and two data channels for communication respectively. As evident from Figure 5.3, when the PU reappearance rate increases, the achievable throughput of CR network decreases accordingly. In the two channels scenario, the CR network can handover the communication to the vacant channel when one is occupied by PU and the drop in throughput is mainly from the migration process as it moves to another empty channel. When the PU is not activated (at point 0 on x-axis), the throughput achieved by CR network is similar in both scenarios representing the maximum achievable throughput. The throughput drops considerably in one channel scenario when the PU is activated. This is due to the fact that in one channel scenario the throughput not only gets affected by PU arrival rate but also by the PU transmission duration as it has to wait for the channel to become free again.

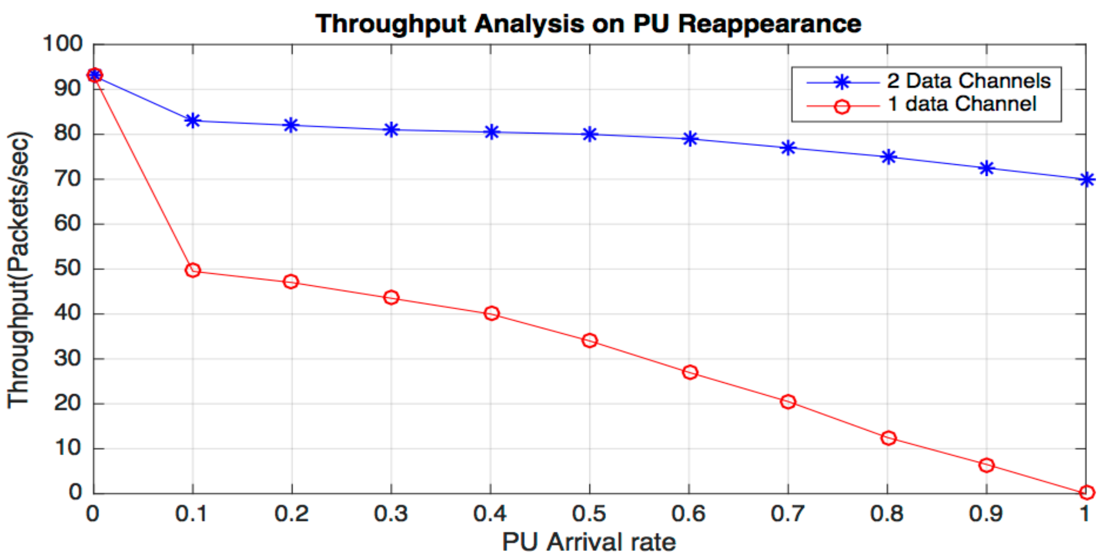


Figure 5.3: Throughput Analysis on PU reappearance.

The simulations carried out in omnet++ showed that improved throughput of the secondary network when no constraints from the primary node are imposed, while highlight a trade-off between coexistence capability and secondary network performance when the presence of primary nodes is taken into account. It can be seen from the figure that the throughput level is maintained when the number of free TV channels is high but is likely to suffer if there are no unutilized TV white spaces.

5.4 Results Validation

In this section, the methodology employed and the results obtained are compared against other existing technologies and research in order to validate the proof-of-concept application. For validation of the spectrum sensing simulation results, a comparison was made to other research works with the simulation results obtained in chapter 3. The performance comparison results given in Figure 3.15 for the different detection techniques were found to be consistent with those given in (Verma, Taluja, & Dua, 2012) (Hossain, Abdullah, & Hossain, 2012) (Rehman & Asif, 2012) (Chatziantoniou, 2014) as shown in Figure 5.4 (Rehman & Asif, 2012). Furthermore, the simulated results match closely with the theoretical results found in literature.

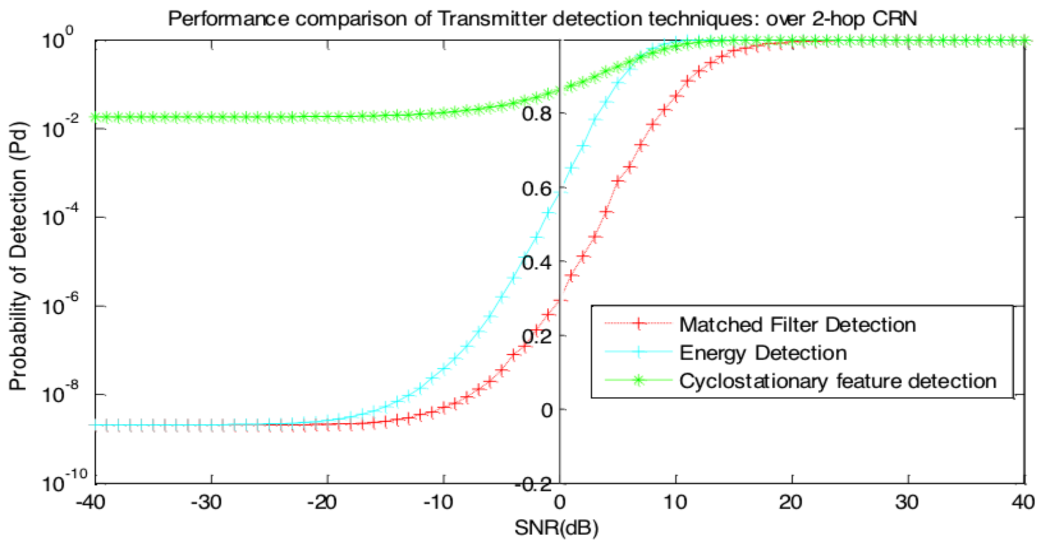


Figure 5.4: Validation of Spectrum Sensing Performance

Although there is no spectrum sensing technique recommended in IEEE 802.22 standard, any sensing technique that is employed must meet the input, output and behaviour requirements of the sensing with respect to IEEE 802.22 standard. The sensing requirements as defined in the IEEE 802.22 are shown in Table 5.2.

Table 5.2: Sensing Requirements for IEEE 802.22 standard.

Parameters	Digital TV
Channel detection time	≤ 5 ms
Channel move time	2 secs
Detection threshold (required sensitivity)	-114 dBm
Probability of detection (P_D)	0.9
Probability of missed detection (P_{MD})	0.1
Probability of false alarm (P_{FA})	0.1
SNR	-18 dB

The IEEE 802.22 standard indicates that, to maximise channel utilisation, P_D should be close to one and P_{FA} should be closer to zero. From the Figure 3.15 & Figure 5.5, it can be observed that the cyclostationary spectrum sensing method provides detection well below the -18 dB required of the IEEE 802.22 standard. It also exceeds the probability of detection value of 0.9. This validates the choice of using the cyclostationary detector as it performs well within the sensing parameters as defined by the IEEE 802.22 standard.

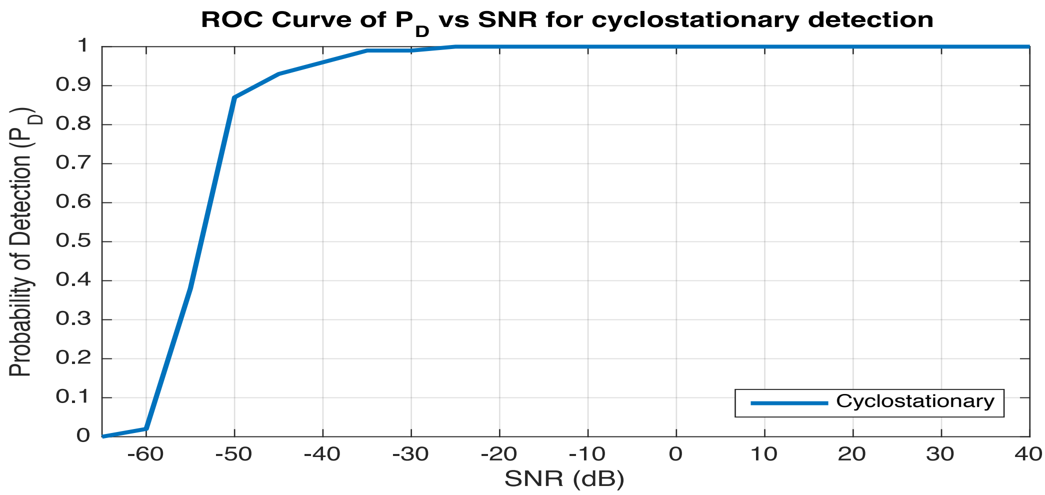


Figure: 5.5: Cyclostationary detector performance.

In (Vasudev, 2017), a research was carried out to explore the possibility of using cognitive radio for communication that allows opportunistic use of unused TV white space by secondary users if the spectrum is not being used by primary user. Although that research used NS-2 simulation software while omnet++ simulation software was preferred in this research, it was noted to employ an almost similar CPE sensing method as shown in Figure 5.5. This closely compares to Figure 4.6 of this research. However, the method employed in this research was noted to be more superior as it utilizes a priority mechanism that differentiates between the different levels of data traffic. It also utilizes history for predicting future profile of spectrum channels resulting in faster detection of vacant bands. Both researches are noted to verify the feasibility of Cognitive Radio to meet the communication requirements of data transmission in the smart grid.

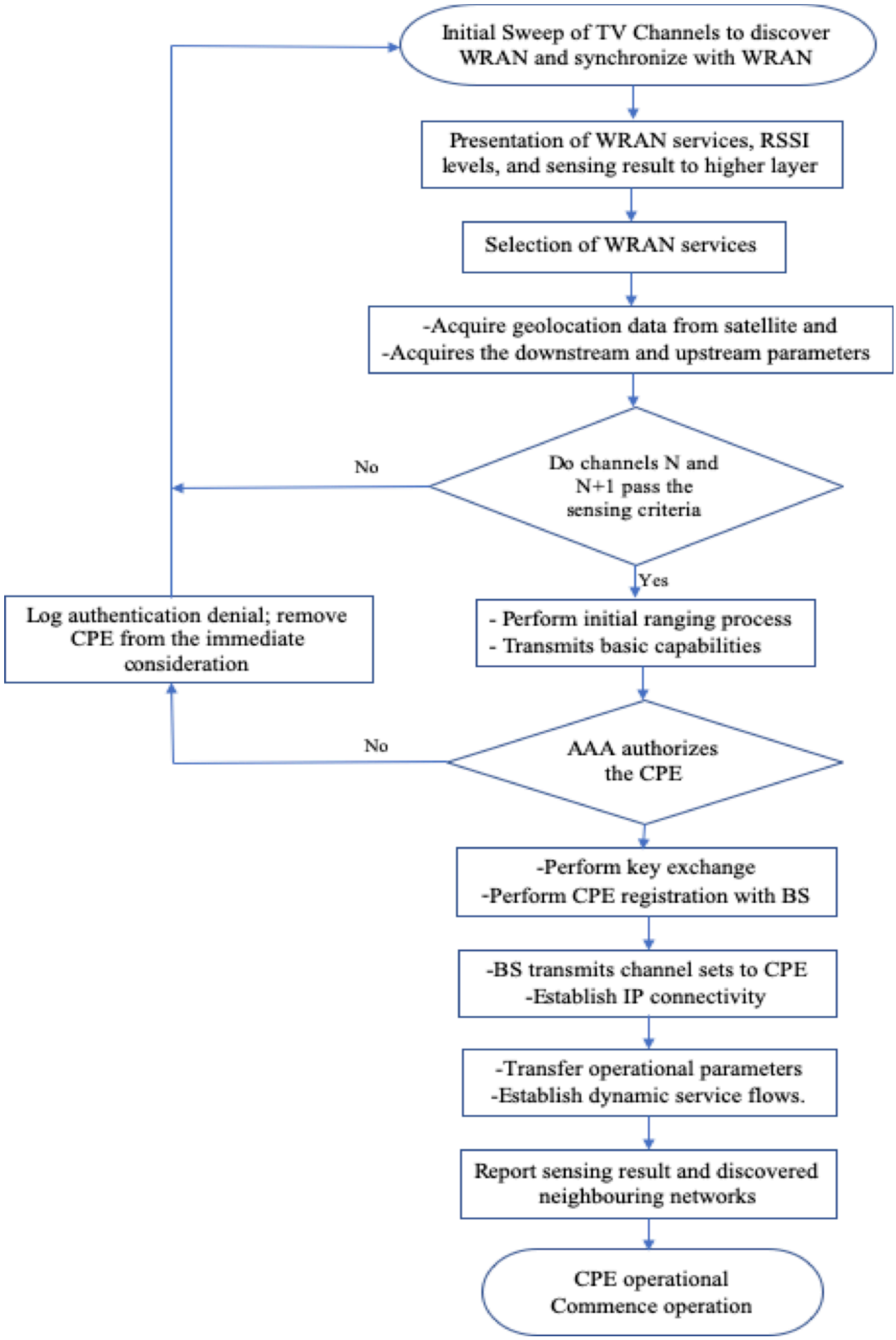


Figure: 5.6: Comparative Procedure of Spectrum Sensing at SU nodes.

CHAPTER SIX
CONCLUSION AND RECOMMENDATIONS

6.1 Conclusion

The main goal of this research was to design a smart power grid communication network over TV white space using cognitive machine-to-machine networking. To achieve this, idle spectrum in TVWS frequencies was identified as the ideal communication medium for developing the proposed CM2M smart grid communications architecture. The issue of interference is explored as it presents the biggest hindrance to exploitation of TV white spaces and it is shown that interference can be minimized by utilizing the second adjacent channel.

A survey of spectrum sensing techniques is also presented. The challenges and issues involved in implementation of spectrum sensing techniques are discussed in detail giving comparative study of various methodologies. Cyclostationary feature detection has been demonstrated to being the best model to use in a CR based smart grid communication network since it can detect PUs at very low SNR values and can separate random noise from PU signals. However, since a single CR user may find it difficult to reliably detect the activity status of licensed users due to fading, shadowing effects of the channel and receiver uncertainty issues and cooperative spectrum sensing is shown to be an effective mode of improving the detection performance by exploiting spatial diversity of the different nodes.

The designed communications network utilizes M2M communications on TV White spaces using cognitive radio technology. CR provides economical, efficient, and adaptive operations for the communication infrastructure by efficiently utilizing spectrum resources in the smart grid communication network while leveraging wireless M2M technologies to provide ubiquitous connectivity between devices along with the capability to communicate autonomously without requiring any human intervention. TVWS is ideal due to low cost, flexibility, and synergistic approach to dynamic spectrum access and is shown to provide the least pathloss for the designed WRAN communication network. TV white space has immense potential in those parts of the geographical area which are very difficult to reach and expensive to reach by optical fiber techniques and other types of technologies. It is also very applicable to developing countries where the telecommunications infrastructure is not in place and white spaces can potentially be a cost-effective way of bridging this gap easily.

This research also explored the performance evaluation of the designed communication network. The performance parameters studied are throughput, path loss, power consumption. The study found that the designed smart grid communication network meets the latency requirements of a SG to a larger extent. This thesis therefore concluded that the designed SG communication network has the capability to effectively exploit TVWS to for real-time communication.

6.2 Recommendations and Future Work

This research has shown that a smart grid communication network can be implemented by exploiting unused spectrum in TV band frequencies using M2M networking. Adopting the designed communication network provides for an effective way of enhancing spectrum utilization in TV white spaces while also enabling a communication network for the smart grid through which dynamic pricing can be effected in the smart grid. However, a number of issues and challenges still remain to be explored and further works are suggested to further enhance the designed smart grid communication network. These suggestions are as enumerated below:

- Practical Implementation

The research work in this thesis was carried out mainly based on simulations where the feasibility of the designed SG communication network was shown through the simulations. However, future practical implementation of prototypes is desired before actual rollout in order to further enhance the design and eliminate any hindsight or incorrect assumptions made during the developing of the simulation models.

- Smart Grid Security and Privacy

One of the major challenges is security since the SG devices will be online and hence vulnerable to cyber-attacks. A SG has the largest attack surface for a cyber-attack due to a large number of devices. A cyber-attack on a smart power grid would have devastating effects on reliability of widespread infrastructure given the potential cascade effects of shutting down the electricity grid since most of the devices in our homes, offices, hospitals and trains require electricity to run. Once a single device is compromised, then the whole grid could become vulnerable to cyberattacks. Such attacks on electricity supply can bring entire cities to a standstill thereby causing huge financial and economic losses. Further research is therefore required in order to fortify the designed communication network.

REFERENCES

Abhayawardhana, V., Wassell, I., Crosby, D., Sellars, M., & Brown, M. (2005). Comparison of Empirical Propagation Path Loss Models for Fixed Wireless Access Systems. *Vehicular Technology Conference, 2005. VTC 2005-Spring. 2005 IEEE 61st.* Stockholm, Sweden: IEEE.

Agrawal, S., Bhatia, R., & Bhadoria, M. S. (2016). Interference Mapping for Spectrum Sensing in Cognitive Radio. *International Journal of Innovations in Engineering and Technology, 6*(4), 696-702.

Aguirre, J. F., & Magnago, F. (2013). Viability of WiMax for Smart Grid Distribution Network. *European International Journal of Science and Technology, 2*(2), 181-196.

Aijaz, A., & Aghvami, A. H. (2015). Cognitive Machine-to-Machine Communications for Internet-of-Things: A Protocol Stack Perspective. *IEEE Internet of Things Journal, 2*(2), 103-112.

Al-Omar, B. A., Landolsi, T., & Al-Ali, A. R. (2015). Evaluation of WiMAX Technology in Smart Grid Communications. *Journal of Communications, 10*(10), 804-811.

Alonso-Zarate, J., Matamoros, J., Gregoratti, D., & Dohler, M. (2012). Machine-to-Machine (M2M) Communications in Smart Grid. In *Smart Grid Communications and Networking* (pp. 147-174). Cambridge University Press.

Aloul, F., Al-Ali, A. R., Al-Dalky, R., Al-Mardini, M., & El-Hajj, W. (2012). Smart Grid Security: Threats, Vulnerabilities and Solutions. *International Journal of Smart Grid and Clean Energy, 1*(1), 6.

Antón-Haro, C., & Dohler, M. (2015). *Machine-to-machine (M2M) Communications: Architecture, Performance and Applications.* Woodhead Publishing.

Arato, S. S., & Kalecha, P. O. (2013). UHF (700 MHz) Spectrum Band Occupancy Measurements, Analysis and Considerations for Deployment of Long Term Evolution (LTE) Deployment in Kenya. *International Journal of Scientific & Engineering Research, 4*(11), 572-580.

Australian Communications Authority. (2001). *Investigation of Modified Hata Propagation Models.* Radiofrequency Planning Group, Spectrum Planning Team. Australian Communications Authority.

Axell, E., Leus, G., Larsson, E. G., & Poor, H. V. (2012). Spectrum Sensing for Cognitive Radio : State-of-the-Art and Recent Advances. *IEEE Signal Processing Magazine, 29*(3), 101 - 116.

Beale, M., & Morioka, Y. (2011). Wireless machine-to-machine communication. *2011 41st European Microwave Conference* (pp. 1-4). Manchester: IEEE.

Bhattacharya, P. P., Khandelwal, R., Gera, R., & Agarwal, A. (2011). Smart Radio Spectrum Management for Cognitive Radio. *International Journal of Distributed and Parallel Systems (IJDPS), 2*(4), 12-24.

Butler, J. S., Flickenger, R., Aichele, C. "., Fonda, C., Forster, J., Howard, I., . . . Zennaro, M. (2006). *Wireless Networking in the Developing World.* CreateSpace Independent Publishing .

Cacciapuoti, A. S., & Caleffi, M. (2015). Interference Analysis for Secondary Coexistence in TV White Space. *IEEE Communication Letters, 19*(3), 383-386.

Caso, G., Nardis, L. D., & Holland, O. (2014). Simulation of Cognitive Radio Networks in OMNeT++. In M.-G. D. Benedetto, A. F. Cattoni, J. Fiorina, C. F. Bader, & L. D. Nardis (Eds.), *Cognitive radio and Networking for Heterogeneous Wireless Networks.* Springer International Publishing.

Chatziantoniou, E. (2014). *Spectrum Sensing and Occupancy Prediction for Cognitive Machine-to-Machine Wireless Networks.* University of Bedfordshire. University of Bedfordshire.

Chen, M., Wan, J., Gonzalez, S., Liao, X., & Leung, V. C. (2014). A Survey of Recent Developments in Home M2M Networks. *IEEE Communications Surveys & Tutorials, 16*(1), 98 - 114.

Choi, J. P., Chang, H. M., Choi, H. N., & Lee, W. C. (2012). A Study on Interference Analysis Between DVB-T2 Broadcasting Service and TV White Space Device. *2012 Fourth International Conference on Ubiquitous and Future Networks (ICUFN)* (pp. 234-235). Phuket: IEEE Communications Society.

Electronic Communications Committee . (2011). *Technical and Operational Requirements for the Possible Operation of Cognitive Radio Systems in the 'White Spaces' of the Frequency band 470-790 MHz.* European Conference of Postal and Telecommunications Administrations (CEPT), Electronic

Communications Committee . Cardiff: European Conference of Postal and Telecommunications Administrations.

Electronic Communications Committee (ECC). (2008, January 26). *CEPT Report 24: Technical considerations regarding harmonisation options for the Digital Dividend.* European Conference of Postal and Telecommunications Administrations (CEPT). Retrieved from http://www.fiercewireless.com/tech/special-reports/white-spaces-it%E2%80%99s-%E2%80%98wifi-steroids%E2%80%99-where%E2%80%99s-market

European Communications Office (ECO). (2016). *SEAMCAT Handbook* (Vol. 2). European Conference of Postal and Telecommunications Administrations (CEPT) .

Faruk, N., Ayeni, A. A., & Adediran, Y. A. (2013). Impact of Path loss models on Spatial TV white space. *European Scientific Journal , 4*, 543-547.

Faruk, N., Ayeni, A. A., & Adediran, Y. A. (2013). On the study of empirical path loss models for accurate prediction of TV signal for secondary users. *Progress In Electromagnetics Research , 49*, 155–176,.

Faruk, N., Ayeni, A. A., Adediran, Y. A., & Surajudeen-Bakinde, N. T. (2014). Improved path–loss model for predicting TV coverage for secondary access . *International Journal of Wireless and Mobile Computing, 7*(6), 565 - 576.

Fatemieh, O., Chandra, R., & Gunter, C. A. (2010). Low Cost and Secure Smart Meter Communications using the TV White Spaces. *2010 3rd International Symposium on Resilient Control Systems* (pp. 37 - 42). Idaho Falls: IEEE.

Foo, Y.-L., & Takada, J.-i. (2016, October). Coexistence of DTV and TV white space systems. *International Journal of Communication Systems, 29*(15), 1-12.

Gaddam, V., & Ghosh, M. (2010). Robust Sensing of DVB-T Signals. *2010 IEEE Symposium on New Frontiers in Dynamic Spectrum* (pp. 1 - 8). Singapore: IEEE.

Gbenga-Ilori, A. O., & Ibiyemi, T. S. (2010). Directing the Digital Dividend towards Bridging the Digital Divide. *European Journal of Scientific Research, 45*(1), 079-088.

Ghosh, G., Das, P., & Chatterjee, S. (2014). Cognitive Radio And Dynamic Spectrum Access – A Study. *International Journal of Next-Generation Networks, 6*(1), 43-60.

Ghosh, G., Das, P., & Chatterjee, S. (2014). Simulation and Analysis of Cognitive Radio System Using Matlab. *International Journal of Next-Generation Networks (IJNGN), 6*(2), 31-45.

Gungor, V. C., Sahin, D., Kocak, T., Ergut, S., Buccella, C., Cecati, C., & Hancke, G. P. (2011, November). Smart Grid Technologies: Communication Technologies and Standards. *IEEE Transactions on Industrial Informatics , 7*(4), 529 - 539.

Holland, O., Bogucka, H., & Medeisis, A. (2015). Validating the Extended Hata Model for use in UHFs. In O. Holland, H. Bogucka, & A. Medeisis, *Opportunistic Spectrum Sharing and White Space Access: The Practical Reality* (p. 736). John Wiley & Sons, 2015.

Hossain, E., & Bhargava, V. (2007). *Cognitive Wireless Communication Networks.* Springer.

Hossain, E., Han, Z., & Poor, H. V. (2012). *Smart Grid Communications and Networking.* Cambridge University Press.

Hossain, S., Abdullah, I., & Hossain, M. A. (2012). Energy Detection Performance of Spectrum Sensing in Cognitive Radio. *International Journal of Information Technology and Computer Science, 11*, 11-17.

Huang, J., Wang, H., Qian, Y., & Wang, C. (2013). Priority-Based Traffic Scheduling and Utility Optimization for Cognitive Radio Communication Infrastructure-Based Smart Grid. *IEEE Transactions on Smart Grid, 4*(1), 78-86.

Huynh, C. K., & Lee, W. C. (2012). Researching BEM in Interference Analysis of TV-Band Whitespace. *2012 Fourth International Conference on Communications and Electronics*, (pp. 180 - 185). Hue.

International Telecommunication Union. (2009). *Report ITU-R SM.2152 Definitions of Software Defined Radio (SDR) and Cognitive Radio System (CRS).* International Telecommunication Union.

International Telecommunication union. (2011). *Report ITU-R BT.2140-3: Transition from analogue to digital.*

Jang, W. M. (2014). Blind Cyclostationary Spectrum Sensing in Cognitive Radios. *IEEE Communications Letters, 18*(3), 393 - 396.

Jermyn, J., Jover, R. P., Murynets, I., Istomin, M., & Stolfo, S. (2015). Scalability of Machine to Machine systems and the Internet of Things on LTE mobile networks. *2015 IEEE 16th International Symposium on A World of Wireless, Mobile and Multimedia Networks* (pp. 1 - 9). Boston: IEEE.

Joseph Mitola, I. (2006). *Cognitive Radio Architecture: The Engineering Foundations of Radio XML.* John Wiley & Sons, Inc.

Kaabouch, & Naima. (2014). *Handbook of Research on Software-Defined and Cognitive Radio Technologies for Dynamic Spectrum Management.* IGI Global.

Kasampalis, S., Lazaridis, P. I., Zaharis, Z. D., Bizopoulos, A., Zettas, S., & Cosmas, J. (2014). Comparison of Longley-Rice, ITU-R P.1546 and Hata-Davidson propagation models for DVB-T coverage prediction. *2014 IEEE International Symposium on Broadband Multimedia Systems and Broadcasting* (pp. 1 - 4). Beijing: IEEE.

Kaur, P., & Singh, C. (2015, May). Spectrum Sensing based on Energy Detection in Cognitive Radio. *International Journal of Advanced Research in Electronics and Communication Engineering, 4*(5), 1214-1217.

Kawade, S., & Nekovee, M. (2009). Wireless options for high data-rate indoor users: Cognitive access to TV white space. *2009 First UK-India International Workshop on Cognitive Wireless Systems* . Delhi.

Kennedy, R., George, K., Vitalice, O., & W., O.-O. (2015). TV White Spaces in Africa : Trials and Role in Improving Broadband Access in Africa. *AFRICON*, (pp. 1-5). Addis Ababa.

Kethsiyal, Y. E., Pugazhendi, M. A., Kumar, V. K., & Nerenjana, J. (2014). Optimistic Technique for Smart Grid Infrastructure Using Sensor Network. *International Journal of Innovative Research & Development, 3*(2), 114-119.

Khan, A. A., Rehmani, M. H., & Reisslein, M. (2016). Cognitive Radio for Smart Grids: Survey of Architectures, Spectrum Sensing Mechanisms, and Networking Protocols. *IEEE Communications Surveys & Tutorials, 18*(1), 860 - 898.

Khan, A., Ali, M., Ahmad, I., Ullah, A., Rahman, H. U., & Rahman, H. U. (2012). WIMAX Implementation of Smart Grid Wide Area Power System Load Protection Model in MATLAB/SIMULINK. *Smart Grid and Renewable Energy, 3*(4), 282-293.

Khan, S. A., Sohail, M. F., Ghauri, S. A., & Aqdas, N. (2017). Cognitive radio based Smart Grid Communication Network. *Renewable and Sustainable Energy Reviews, 72*, 535-548.

Khan, S. N., Kalil, M. A., & Mitschele-Thiel, A. (2013). crSimulator: A discrete simulation model for cognitive radio ad hoc networks in OMNeT ++. *6th Joint IFIP Wireless and Mobile Networking Conference* . Dubai.

Ko, H.-T., Lee, C.-H., Lin, J.-H., Chung, K., & Chu, N.-S. (2014). Television white spaces: Learning from cases of recent trials. *International Journal of Digital Television, 5*(2), 149-167. Retrieved from http://www.carlsonwireless.com/white-space-hotspot/

Kouhdaragh, V., Tarchi, D., Coralli, A. V., & Corazza, G. E. (2013). Cognitive Radio Based Smart Grid Networks. *2013 24th Tyrrhenian International Workshop on Digital Communications - Green ICT* (pp. 1 - 6). Genoa: IEEE.

Krishn, R. R., & Bhuvan, N. T. (2016). CR simulator: A Wireless System for IOT. *International Journal of Advanced Research , 4*(8), 56-60 .

Kulkarni, P., Gormus, S., Fan, Z., & Motz, B. (2012, July). A Mesh-Radio-Based Solution for Smart Metering Networks. *IEEE Communications Magazine, 50*(7), 86-95.

Kumar, R. (2014). Analysis of Spectrum Sensing Techniques in Cognitive Radio. *International Journal of Information and Computation Technology, 4*(4), 437-444.

Lee, H.-K., Kim, D. M., Hwang, Y., Yu, S. M., & Kim, S.-L. (2013, April). Feasibility of cognitive machine-to-machine communication using cellular bands. *IEEE Wireless Communications, 20*(2), 97-103.

Lee, Y. L., Saad, W. K., El-Saleh, A. A., & Ismail, M. (2015). Improved Detection Performance of Cognitive Radio Networks in AWGN and Rayleigh Fading Environments. *ScienceDirect*.

Liu, Y., Xie, S., Zhang, Y., Yu, R., & Leung, V. C. (2012). Energy-Efficient Spectrum Discovery for Cognitive Radio Green Networks. *Mobile Networks and Applications, 17*(1), 64–74.

Lyubchenko, S., Kermoal, J.-P., & Devendec, M. L. (2010). Implementation of Cognitive Radio in SEAMCAT. *20th International Wroclaw Symposium on Electromagnetic Compatibility*, (pp. 17-21). Wroclaw.

Lyubchenko, S., Kermoal, J.-P., & Devendec, M. L. (2011). Spectrum sensing capabilities in SEAMCAT. *10th International Symposium on Electromagnetic Compatibility* (pp. 658 - 663). York: IEEE.

Mahesh, B. C., & Rao, B. P. (2014). Design and Modeling of Propagation Models for WiMAX Communication System at 3.7GHz & 4.2GHz. *IPASJ International Journal of Electronics & Communication, 2*(1), 1-7.

Marinho, J., & Monteiro, E. (2011, January). Cognitive Radio Simulation based on OMNeT++/MiXiM. *Proceedings of the 11th Conferencia sobre Redes de Computadores*, (pp. 1-8).

Mauwa, H., Bagula, A. B., Zennaro, M., & Lusilao-Zodi, G.-A. (2015). On the Impact of Propagation Models on TV White Space Measurements in Africa. *2015 International Conference on Emerging Trends in Networks and Computer Communications* , (pp. 148 - 154). Windhoek.

Miah, M. S., Rahman, M. M., Singh, B. C., & Islam, A. (2012). Evaluation and Performance Analysis of Propagation Models for WiMAX. *nternational Journal of Advanced Co mputing, Engineering and Application , 1*(1), 16-26.

Mikeka, C., Thodi, M., Mlatho, J. S., Pinifolo, J., Kondwani, D., Momba, L., . . . Moret, A. (2014). Malawi Television White Spaces (TVWS) Pilot Network Performance Analysis. *Journal of Wireless Networking and Communications , 4*(1), 26-32.

Misic, V. B., & Misic, J. (2014). *Machine-to-Machine Communications: Architectures, Technology, Standards, and Applications.* CRC Press.

Mitola, J. (1993, April). Software Radios: Survey, critical evaluation and future directions. *IEEE Aerospace and Electronics Systems Magazine, 8*(4), 25-36.

Mody, D. A. (2013). IEEE 802.22 –Cognitive Radio-based Regional Area and Smart Utility Networks. *ITU Regional Radio-communications Seminar for Arab Countries: Cognitive Radio and TVWS Workshop.*

Mukherjee, T., & Nath, D. A. (2015). Cognitive Radio-Trends, Scope and Challenges in Radio Network Technology. *International Journal of Advance Research in Computer Science and Management Studies, 3*(6), 87-108.

Nardini, G., Virdis, A., & Stea, G. (2016). Simulating device-to-device communications in OMNeT++ with SimuLTE: scenarios and configurations. *OMNeT++ Community Summit*, *abs/1609.05173.*

Nautiyal, G., & Kumar, R. (2013). Spectrum Sensing In Cognitive Radio Using Matlab. *International Journal of Engineering and Advanced Technology, 2*(5).

Ndonye, M. M., Khaemba, D. J., & Bartoo, D. P. (2015). Digital Migration and the Battle of Terrestrial Titans in Kenya: Issues and Prospects. *International Research Journal of Engineering and Technology (IRJET), 02*(03), 2302-2308.

Nekovee, M. (2010). Cognitive Radio Access to TV White Spaces: Spectrum Opportunities, Commercial Applications and Remaining Technology Challenges. *2010 IEEE Symposium on New Frontiers in Dynamic Spectrum (DySPAN)* (pp. 1 - 10). Singapore: IEEE.

Nirajan, K., Sudeep, S., Suman, S., & Lamichhane, B. (2015). Performance Comparison of Energy Detection Based Spectrum Sensing for Cognitive Radio Networks. *International Refereed Journal of Engineering and Science, 4*(8), 01-07.

Niyato, D., Xiao, L., & Wang, P. (2011). Machine-to-Machine Communications for Home Energy Management System in Smart Grid. *IEEE Communications Magazine, 49*(4), 53 - 59.

Pal, R. U., Indurkar, P. R., & Lakhe, P. R. (2015). Review of Performance of Energy Detection, Matched Filter Detection and Cyclostationary Detection Based Spectrum Sensing Under Different Wireless Channels. *International Journal of Engineering Research (IJOER), 3*(2), 6-9.

Phong, N. H., Bao, V. N., & Tue, H. H. (2013). An Improved White Space Prediction Algorithm for Cognitive Radio Systems. *REV Journal on Electronics and Communications, 3*(3–4), 93-102.

Popescu, V., Fadda, M., Murroni, M., Morgade, J., & Angueira, P. (2014). Co-Channel and Adjacent Channel Interference and Protection Issues for DVB-

T2 and IEEE 802.22 WRAN Operation. *IEEE Transactions on Broadcasting, 60*(4), 693-700.

R.Gill, & A.Kansal. (2014, July). Comparative Analysis of the Spectrum Sensing Techniques Energy Detection and Cyclostationary Feature Detection . *International Journal of Advanced Research in Electrical, Electronics and Instrumentation Engineering (IJAREEIE), 3*(7), 10601-10608.

Rahman, S., Hossain, N., Sayeed, N., & Palash, M. (2013, January). Comparative Study between Wireless Regional Area Network (IEEE Standard 802.22) and WiMAX and Coverage Planning of a Wireless Regional Area Network Using Cognitive Radio Technology. *International Journal of Recent Technology and Engineering (IJRTE), 1*(6), 161-163.

Rehman, A. U., & Asif, M. (2012). *Spectrum Sensing Techniques for 2-hop Cooperative Cognitive Radio Networks: Comparative Analysis.* Blekinge Institute of Technology, Department of Electrical Engineering. Blekinge Institute of Technology.

Saeed, R. A., & Shellhammer, S. J. (2011). *TV White Space Spectrum Technologies: Regulations, Standards, and Applications.* CRC Press.

Saggar, H., & Mehra, D. (2011). Cyclostationary Spectrum Sensing in Cognitive Radios Using FRESH Filters. *Advances in Wireless Cellular Telecommunications: 1st ICEIT National Conference on Technologies & Services*, (pp. 1-6). New Delhi.

Sarkar, N. I. (2012, MAY). Spectrum Handoff Management in Cognitive Radio Networks: Solutions, Modeling, and Future Research. *11th International Conference on Wireless Networks.* Retrieved from https://www.researchgate.net/publication/243055397_Spectrum_Handoff_Management_in_Cognitive_Radio_Networks_Solutions_Modeling_and_Future_Research

Subhani, S., Shi, H., & Cobben, J. (2015). A survey of technical challenges in wireless machine-to-machine communication for smart grids. *2015 50th International Universities Power Engineering Conference* , (pp. 1-6). Stoke on Trent.

Subhedar, M., & Birajdar, G. (2011). Spectrum Sensing Techniques in Cognitive Radio Networks: A Survey. *International Journal of Next-Generation Networks, 3*(2), 37-51.

Tan, S. K., Sooriyabandara, M., & Fan, Z. (2011). M2M Communications in the Smart Grid: Applications, Standards, Enabling Technologies, and Research Challenges. *International Journal of Digital Multimedia Broadcasting, 2011*, 1-8.

Telecommunications Management Group, Inc. (2017). *Digital Migration Process in Kenya.* GSMA.

Tse, D., & Viswanath, P. (2005). *Fundamentals of Wireless Communications.* Cambridge University Press.

Vasudev, D. (2017). *Design and Performance Evaluation of Cognitive Radio for Real-Time Communication in Smart Grid.* Victoria University. Sydney: Victoria University.

Verma, P. K., Taluja, S., & Dua, R. L. (2012). Performance analysis of Energy detection, Matched filter detection & Cyclostationary feature detection Spectrum Sensing Techniques. *International Journal Of Computational Engineering Research, 2*(5), 1296-1301.

Vieira, R. D., Souza, E. B., Cavalcante, A.´., Pirhonen, R., Kafle, P., Malkov, A., & Li, Z. (2010). *Interference Analysis of Coexistence Scenarios in TV White Spaces.* Nokia Technology Institute (INdT). Manaus, Brazil: Nokia.

Vo, Q. D., Choi, J.-P., Chang, H. M., & Lee, W. C. (2010). Green Perspective Cognitive Radio-based M2M Communications for Smart Meters. *2010 International Conference on Information and Communication Technology* (pp. 382 - 383). Jeju: IEEE.

Waddell, M., & Harrold, T. (2012, April). *Measured DVB-T Protection Ratios in the presence of Interference from White space Devices.* BBC, Research & Development. WHP 226: BBC Research & Development White Paper.

Werbach, K., & Mehta, A. (2014). The Spectrum Opportunity: Sharing as the Solution to Wireless Crunch . *International Journal of Communication, 8*, 128–149.

Wu, G., Talwar, S., Johnsson, K., Himayat, N., & Johnson, K. D. (2011). M2M: From Mobile to Embedded Internet. *IEEE Communications Magazine, 49*(4), 36-43.

Xin, C., & Song, M. (2015). *Spectrum Sharing for Wireless Communications.* Springer.

Yadav, P., Chatterjee, S., & Bhattacharya, P. P. (2012). A Survey on Dynamic Spectrum Access Techniques in Cognitive Radio. *International Journal of Next-Generation Networks , 4*(4), 27-46.

Yu, F. R. (2011). *Cognitive Radio Mobile Ad Hoc Networks.* Springer.

Zanella, A., Bui, N., Castellani, A., Vangelista, L., & Zorzi, M. (2014). Internet of Things for Smart Cities. *Internet of Things Journal, IEEE, 1*(1), 22 - 32.

Zhang, Y., Yu, R., Nekovee, M., Liu, Y., Xie, S., & Gjessing, S. (2012). Cognitive Machine-to-Machine Communications: Visions and Potentials for the Smart Grid. *IEEE Network, 26*(3), 6 - 13.

Zhang, Y., Yu, R., Xie, S., Yao, W., Xiao, Y., & Guizani, M. (2011). Home M2M Networks: Architectures, Standards, and QoS Improvement. *IEEE Communications Magazine, 49*(4), 44 - 52.

APPENDICES

APPENDIX I: MATLAB PSEUDO-CODE SPECTRUM SENSING COMPARISON

The matlab code used to compare the spectrum sensing techniques is as follows:

```
clc
close all
clear all
L = 1000;
Pf=0.6;
SNR_dB=[-40:1:40]; %in db2
snr= 10.^(SNR_dB./10);

for i=1:length(SNR_dB)
    Detect=0;
     for kk=1:10000 % Number of Monte Carlo Simulations
        Noise = randn(1,L);
        Signal = sqrt(snr(i)).*randn(1,L); %---Real valued Gaussian Primary User
Signal--%

        Recv_Sig = Signal + Noise; % Received signal at SU
        Energy = abs(Recv_Sig).^2; % Energy of received signal over N samples

        Test_Statistic =(1/L).*sum(Energy); %-Computation Test for energy
detecton-%
         Threshold = (qfuncinv(Pf)./sqrt(L))+ 1;  %-----Theoretical value of Threshold--
---%

        if(Test_Statistic >= Threshold)  % Check whether the received energy is greater
than threshold, if so,(Probability of detection) counter by 1
           Detect = Detect+1;
        end
```

```
end
        Pd(i) = Detect/kk;
        Pm(i)=1-Pd(i)
end
 plot(SNR_dB,Pd);
 hold on

Dn = 1;             % Noise Varince
Eb = 10.^(0.1*SNR_dB);  % primary signal variance
n=5;     % number of Samples
b=2*randi([0, 1], 1,n)-1;  % BPSK Signal
m0=0;      % Mean H0;%
m1=Eb;     % Mean H1
 s0=Dn*Eb;   % variance H0
s1=Dn*Eb;   % variance H1
n_e = 10000;      % number of iterations
alpha=1;  % For noise Uncertainity alpha<1 , If alpha=1 means no noise
uncertainity,
Base= 0:0.05:1;
Pd_sim = zeros(1,length(Pf));
Pf_sim = zeros(1,length(Pf));

h=waitbar(0,'Simulating');
Th = qfuncinv(Pf)*sqrt(s0)+m0;  % Threshold
Th=Th*alpha;

for k1 = 1:length(SNR_dB)
    waitbar(k1/length(SNR_dB))
       n0 = 0;n1 = 0;
     for m = 1:n_e
         v0 = sqrt(Dn)*randn(1,n); % AWGN Noise
         z0 = sum(b.*v0); %
         if z0  > Th(k1) % .
```

```
            n0 = n0 + 1;
        end
            v1 = b + v0;           %Signal+ Noise
              z1 = sum(v1.*b); %
        if z1  > Th(k1) % .
            n1 = n1 + 1;
        end
    end
    Pf_sim(k1) = n0/n_e;
    Pd_sim(k1) = n1/n_e;
end

Pd=qfunc((Th-m1)./sqrt(s1)); % Theoritical Probaility of Detection
 plot(SNR_dB,Pd);
 hold on
delete(h);

L = 64;
Sim_Times = 100;
wsize=64; % 64 point hamming window
nfft=2048; % fft size
len=100;
Pd_sim = zeros(1,length(Pf));

for i=1:length(SNR_dB)
    %h= waitbar(i/length(SNR_dB), 'Simulating');
            snr=10.^(SNR_dB(i)./10);  % Linear Value of SNR
      Over_Num = 0;
          for kk=1:Sim_Times % Number of Monte Carlo Simulation

        %whos sn snr SNR L
        s = sqrt(snr).*randn(1,L); % Real valued Gaussina Primary User Signal
        n = randn(1,L); %AWGN noise with mean 0 and variance 1
```

```
y = s + n; % Received signal at SU

 Ts=1/L;
lx=length(Pf);
%Set up variables
nn=0:floor(lx-L);
ln=length(nn);
%N point FFTs of the signal are computed
        y1=y.*exp(-2*pi*1i);
        y2=y.*exp(2*pi*1i);

 %define hamming window size
window = hamming(L);
 yy1=y1*window;
 yy2=y2*window;
yyy1=fft(yy1,nfft);
yyy2=fft(yy2,nfft);
%take correlation
out=yyy1.*conj(yyy2);
    aa=sum(out)/square(window);
    Smax=max(aa);  %find max

%compare Smax with estimated thorotical value
variance=1/(2*snr);

Lamda=sqrt(((2*variance^4)/(2*L+1))*qfuncinv(Pf));
  %whos aa th SNR Pf L Scorr Smax var Variance i Lamda
  Pd_sim(i)= sum(Smax>Lamda);

     %-----Theoretical value of Threshold-----%
if(Smax >= Lamda) % Check whether the received energy is greater than threshold,
if so, increment Pd (Probability of detection) counter by 1
        Over_Num = Over_Num+1;
```

```
        fprintf('For %d\n',Over_Num);
      end
end
Pd(i) = Over_Num / Sim_Times;
  fprintf('For %d\n',Pd(i));
end
plot(SNR_dB, Pd,'LineWidth',3);
hold on
title('Performance Comparison of Transmitter Detection Techniques');
     grid on
     xlabel('SNR (dB)');
     ylabel('Probability of Detection (Pm)');
legend('Energy Detection', 'Matched Filter', 'Cycostationary', 'Location', 'southeast');
     hold on
```

APPENDIX II: OMNET++ CODE FOR COMMUNICATION NETWORK DESIGN

The omnet++ code used to simulate the communication network design is as follows:

```
package SmartGridNetwork;
//import statements
network SmartGridNetwork extends baseCrNetwork
{
  parameters:
    int numDCs = default(2);           // Number of DCs
    int numNodes = default(18);        // Number of nodes
    int count;
types:
channel TVWS extends datarateSpectrum   // TVWS connection
    {
            datarate = 2.04Mbps;
    }

submodules:  //Sample modules
    Actuator: BaseCrNode {
      @display("p=580.464,170.136;i=device/device");
      address = 1;
      neighbors = "2";
      cbattery = "crBattery";
      ceEnabled = true;
      drmEnabled = true;
      cappLayer = "crAppLayer";
      cnetLayer = "crNetLayer";
      cphyLayer = "crPhyLayer";
      cmacLayer = "crMacLayer";
      cspecSensor = "crSpecSensor";
      cdrm = "crDrm";
```

```
        cscl = "crScl";
        cce = "crCognitiveEngine";
        ccrstats = "crStats";
    }

    Smart_Meter: BaseCrNode {
        @display("p=660.528,5724.576;i=device/palm;i2=status/yellow;ls=red");
        address = 3;
        neighbors = "5";
        drmEnabled = true;
        cbattery = "crBattery";
        ceEnabled = true;
        cappLayer = "crAppLayer";
        cnetLayer = "crNetLayer";
        cphyLayer = "crPhyLayer";
        cmacLayer = "crMacLayer";
        cspecSensor = "crSpecSensor";
        cdrm = "crDrm";
        cscl = "crScl";
        cce = "crCognitiveEngine";
        ccrstats = "crStats";
    }
HGW1: BaseCrNode {
        @display("p=1731.384,2201.76;i=device/accesspoint;bgb=494,448");
        address = 7;
        neighbors = "2";
        cbattery = "crBattery";
        ceEnabled = true;
        drmEnabled = true;
        cappLayer = "crAppLayer";
        cnetLayer = "crNetLayer";
        cphyLayer = "crPhyLayer";
        cmacLayer = "crMacLayer";
```

```
    cspecSensor = "crSpecSensor";
    cdrm = "crDrm";
    cscl = "crScl";
    cce = "crCognitiveEngine";
    ccrstats = "crStats";
}

NGW: BaseCrNode {
    @display("p=3012.408,1210.968;i=device/accesspoint;bgb=494,448");
    address = 1;
    neighbors = "2";
    cbattery = "crBattery";
    ceEnabled = true;
    drmEnabled = true;
    cappLayer = "crAppLayer";
    cnetLayer = "crNetLayer";
    cphyLayer = "crPhyLayer";
    cmacLayer = "crMacLayer";
    cspecSensor = "crSpecSensor";
    cdrm = "crDrm";
    cscl = "crScl";
    cce = "crCognitiveEngine";
    ccrstats = "crStats";
}

Base_Station: ENB {
    @display("p=4553.64,2632.104;is=vl;i=device/antennatower");
    configFile = "";
}

SSU_DB: testDRM {
    @display("i=abstract/db;bgb=576,436;p=4613.688,3632.904;is=s");
}
```

```
internetCloud: inet.node.internetcloud.InternetCloud {
    parameters:
        @display("p=5824.656,2542.032;is=l");

}
Utility_Server: inet.node.inet.StandardHost {

    @display("p=7085.664,2542.032;i=device/server");
}
SCADA: inet.node.inet.StandardHost {
    @display("p=7085.664,3632.904");
}
TVWS_DB: NodeW {
    @display("p=7085.664,1561.248;i=abstract/db");
}


connections allowunconnected:
    TVWS_DB.pppg++ <--> fiberline <--> Utility_Server.pppg++;
    Utility_Server.pppg++ <--> fiberline <--> SCADA.pppg++;
        Smart_Meter3.ports++ <--> TVWS <--> HGW.ports++;
    Smart_Meter4.ports++ <--> TVWS <--> HGW1.ports++;
    Actuator1.ports++ <--> TVWS <--> HGW1.ports++;
    Smart_Meter2.ports++ <--> TVWS <--> HGW2.ports++;
    Smart_Meter5.ports++ <--> TVWS <--> HGW2.ports++;
    Actuator2.ports++ <--> TVWS <--> HGW3.ports++;
    Smart_Meter.ports++ <--> TVWS <--> HGW3.ports++;
    Sensor1.ethg++ <--> TVWS <--> NGW2.ports++;
    HGW.ports++ <--> TVWS <--> NGW.ports++;
    HGW3.ports++ <--> TVWS <--> NGW2.ports++;
    HGW2.ports++ <--> TVWS <--> NGW1.ports++;
    HGW1.ports++ <--> TVWS <--> NGW1.ports++;
```

```
    NGW1.ports++ <--> TVWS <--> Base_Station.pppg++;
    NGW2.ports++ <--> TVWS <--> Base_Station.pppg++;
    NGW.ports++ <--> TVWS <--> Base_Station.pppg++;
    Sensor.ethg++ <--> TVWS <--> NGW.ports++;
    Actuator.ports++ <--> TVWS <--> HGW.ports++;
    Base_Station.pppg++ <--> fiberline <--> SSU_DB.sclInterface;
    internetCloud.pppg++ <--> fiberline <--> Utility_Server.pppg++;
    internetCloud.pppg++ <--> fiberline <--> Base_Station.pppg++;
}
```

APPENDIX III: LIST OF PUBLICATIONS

The following are the publications by the author in the course of the research period:

[1] K. Kimani, K. Langat and V. Oduol, "Coexistence and Interference Analysis in TV White Spaces," *International Journal of Advanced and Applied Sciences (IJAAS),* vol. 4, no. 7, pp. 39-49, July 2017.

[2] K. Kimani, K. Langat and V. Oduol, "TV White Spaces Opportunistic Spectrum Access for Wireless Regional Area Networks," in *Sustainable Research and Innovation (SRI) Conference*, Juja, 2017.