DEVELOPMENT OF A RADIO SPECTRUM UTILISATION TECHNIQUE FOR COGNITIVE RADIOS

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CERTIFICATION

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DEDICATION

This work is dedicated to the glory of God, the giver of life, wisdom, strength, and all good things.

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ABSTRACT

Parts of licensed radio spectrum for data transmission are idle because they are not used at some points in time or location by the user. Cognitive radios which are software radios equipped with sensors and other functionalities are being developed to opportunistically use this idle licensed spectrum. Cognitive radios use dynamic spectrum access methods classified as overlay and underlay to utilise idle television frequency in the radio spectrum. However, simultaneous transmissions of data by licensed and cognitive radio users are not possible in overlay, while restriction is on the usage of the idle spectrum in underlay. Consequently, the potentials of cognitive radios are not effectively maximised. Therefore, this research was aimed at the development of a band access technique in radio frequency to improve the usage of the idle television frequency.

The matched filtering technique of overlay for detecting idle licensed signal and interference temperature management of underlay for controlling interference were adapted to develop a new technique referred to as Matched Filtering-Interference Temperature Management (MAFITM). A conceptual transmission model for three different scenarios representing overlay, underlay and MAFITM techniques was created for television frequency access. Simulation of the three techniques in the television frequency band that covered 54 to 862 MHz and three different licensed signal transmission powers was implemented with Java programming language. A cognitive radio access point was simulated to transmit between nodes for the three different scenarios in the presence and absence of licensed television signal. The first, second and third transmission scenarios were simulated using overlay, underlay, and MAFITM techniques respectively. The results generated were compared using the performance metrics of transmission distance, data rates, spectrum efficiency and margin of interference in the presence and absence of licensed signal.

In the absence of licensed signal, for both MAFITM and overlay techniques the transmission distance, the maximum achievable data rate and the spectral efficiency (100 km, 163 Mb/s and 9.537 b/s/Hz), respectively were significantly higher compared with those of underlay technique (25 m, 44 Mb/s and 12.429 b/s/Hz), respectively. In the presence of licensed signal, transmission of data was possible in MAFITM and underlay techniques but not in overlay technique. With the presence of licensed signal, for MAFITM technique, the maximum transmission distance, the maximum achievable data rate, the spectral efficiency and margin of interference were (3.5 km, 789 Kb/s, 0.045 b/s/Hz and 0.81), respectively. For underlay technique the maximum transmission distance, the maximum achievable data rate, the spectral efficiency and margin of interference were (25 m, 2.81 Mb/s, 0.001 b/s/Hz and -0.04), respectively. The results reflected a better utilisation of the licensed spectrum using the MAFITM technique.

The developed technique produced an improved utilisation of spectrum in areas with stronger presence of licensed signal and allowed data transmission alongside licensed signal without restriction. Matched Filtering-Interference Temperature Management technique is recommended to enhance the effectiveness of cognitive radios in utilising idle licensed frequencies.

Keywords: Data transmission, Cognitive radio, Matched filtering, Interference temperature management, Idle licensed television frequency.

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CHAPTER ONE

INTRODUCTION

1.1 Background of the Study

Data generated from a source that is needed to be transmitted to a desired destination requires a communication pathway which may be wired or wireless. Out of these two communication pathways, technologies using wireless system is rising astronomically with the expectation that it will reach about one hundred billion users by the year 2025 (Steenkiste *et al.*, 2009). The rise in the number of new wireless systems or technologies that want to enter the market implies that allocation of more radio frequency spectrum is needed.

This increase in the usage of wireless systems indicates that this wireless communication pathway must be properly managed for efficient utilisation (Steenkiste *et al.*, 2009). This is true because it is important to allow many users as possible to use the radio spectrum but it is also important to ensure that there is a manageable value of interference between different users. The processes together with the rules of using spectrum bands are controlled by individual countries and also by global monitoring organisations. The International Telecommunication Union, Radio Communication (ITU-R) sector manages the radio spectrum at the global level while agencies are put in place to manage radio spectrum for their respective nation so as to ensure that there will not be interference among radio systems in that country. ITU-R assigns radio frequency bands based on region and also regularise the rules which different agencies in their countries must strictly follow in the management of radio frequency bands in their respective countries

(Odufuwa, 2010). Both the ITU-R and different national bodies are to adopt the manner in which radio frequency bands are used and to transmit, thereby avoiding interference.

To control the usage of radio frequency spectrum, different users secure the right to use different frequency bands for their services to avoid interference in their respective transmissions (Odufuwa, 2010). This policy of managing spectrum is referred to as licensing where only the users that have paid for the frequency band could use the licensed band within a specified location. There are other open spectrums free to be used without restriction in a coordinated manner to reduce interference. These bands are referred to as unlicensed bands. The implication of the policy of exclusive licensed frequency band is that whenever the system that has the right to transmit in that frequency is not active; such frequency band will be lying idle as no other system will be allowed to use it.

Dynamic Spectrum Access (DSA) provides the possibility of improving spectrum efficiency in a licensed band. This spectrum access method tolerates unlicensed users or radio systems to use an inactive spectrum but leave the band when the licensed user becomes active again. It is used to improve spectrum sharing and thereby reduces idleness. Radios based on DSA use radio functionalities that use software for their operations. This class of radios are referred to as software defined radio (SDR) (Yadav *et al.*, 2012). The efficient utilisation of spectrum bands is the target of designing technologies to exhibit the property of DSA which is spectrum sharing. Cognitive radio (CR) technology that resourcefully utilise licensed radio frequency bands while legitimate users are absent is one of these technologies (Steenkiste *et al.,* 2009).

One major spectrum band that has been found to be underutilised at some point in time, location or frequency is the TV band. This makes the Federal Communication Commission (FCC) of United States of America to propose its usage by unlicensed users in the year 2004 and this eventually steered the formation of a standard referred to as IEEE 802.22 that enables cognitive radios to coexist with TV bands.

Cognitive radio came into existence in the later years of 1990s (Perez-Romero *et al.* 2012). This radio is conscious of other signals operating in a particular spectrum and thereby alters its present transmission values to more favourable ones to avoid causing interference (Kokare and Kamble, 2014). The definition of this radio by Biswas (2016) is quoted as follows:

> "*Cognitive Radio is an intelligent wireless communication system that is aware of its surrounding environment and uses the methodology of understanding-by-building to learn from the environment and adapt its internal states to statistical variations in the incoming RF (radio frequency) stimuli by making corresponding changes in certain operating parameters in real-time*".

From the above definition, cognitive radios are based on software and can use their capability for performing spectrum sensing so as to consider the present status of their environment and decide if their transmission will not cause any interference to other signals. The impression that cognitive radio could help to proffer solution to the problem of inefficient utilisation of radio frequency bands is placed on the capability of its functionalities. CRs are able to sense a desired frequency band and compute intelligently, the appropriate transmission parameters that might allow coexistence in that band. In using licensed spectrum, CRs uses many sensing techniques which could broadly be classified into either overlay or underlay to detect unused frequency.

The development of cognitive radios spurred researchers all over the world to show their interest and desire to address different aspects of the technology. According to Perez-Romero *et al.*, (2012) some of the areas where CR have been applied include Vehicular network environments, Smart Grid Applications, Dynamic Spectrum Access among many others.

1.2 Statement of the Problem

Different DSA methods in cognitive radios are Overlay and Underlay (Clancy and Abaugh, 2007; Nawaf and Xiuhua, 2010; Kokare and Kamble 2014). However, the benefits of accessing spectrum dynamically through DSA are not fully utilised. Figure 1.1 as presented by Mitran, (2008) depicts the model for overlay. In this figure, a cognitive radio, known as secondary user (SU) uses the spectrum only when a primary user (PU) that has been licensed to use the band is not active and cannot do so otherwise (Cave *et* *al*, 2007; Mitran, 2008). Figure 1.2 as presented by Mitran, (2008) depicts the model for underlay. In the figure, both the PUs and SUs can coexist but the secondary users must transmit with an agreed limited transmission power to avoid degrading the quality of the signal of the PUs. In this model, the transmission of SU signals are restricted not minding the absence of PU signals. This is observed as a shortcoming of this model because there is no PU signal to be degraded when there is optimum utilisation of the PU radio spectrum by the SU.

The increase in utilisation that will be experienced if secondary users can transmit in the presence and absence of licensed signal without causing detrimental interference is what spurred this research. This research used Matched Filtering for Overlay while Interference Temperature Management was used for Underlay.

1.3 Justification of the Research

This research addressed the shortcomings identified above by using the two approaches together to improve spectrum utilisation by developing a new DSA technique called Matched Filtering-Interference Temperature Management (MAFITM). In MAFITM model, cognitive radio users will use available radio frequency bands optimally during the inactive periods of the primary users' signal. They can also increase their transmission potentials by computing the right transmission parameters when primary users' signals are active. For example, a licensed television channel like Galaxy Television, could trade their licensed frequency band by allowing another company providing internet services to their customers to use it in a controlled manner. The analogy is that somebody that has a spare vehicle parked at the garage instead of allowing it to be idled can make it available for hiring for commercial purposes to generate income.

The specific contribution that this research is expected to make is to further open up the spectrum, that is spectrum utilisation, most especially the licensed digital television spectrum for the use of cognitive radios.

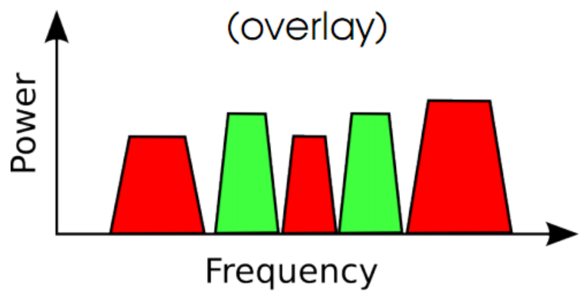

Figure 1.1: Utilisation of Radio Frequency by Licensed and Unlicensed Users in Overlay Approach

Source: Mitran, 2008

Legend: Unlicensed Users

Licensed Users

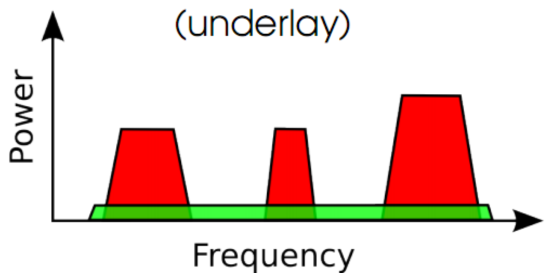

Figure 1.2: Utilisation of Radio Frequency by Licensed and Unlicensed Users in Underlay Approach

Source: Mitran, 2008

Legend: Unlicensed Users

Licensed Users

1.4 Aim and Objectives of Research Work

The aim of this research work is to design an improved spectrum utilisation technique in the limited and inefficiently used spectrum for wireless technologies, through the developed spectrum utilisation technique in cognitive radios. This aim is achieved through the following objectives:

i. development of a mathematical model for MAFITM spectrum access technique;
ii. simulation of the existing models of Overlay and Underlay and the MAFITM model ;
iii. determination of the behaviours of the three models in a no PU signal, low PU signal and high PU signal environments and;
iv. comparison of MAFITM model with the specification benchmark of IEEE 802.22.

1.5 Research Methodology

This research used mathematical approach to achieve the stated aim and objectives. The following steps were taken to accomplish the research goal:

i. development of a mathematical model for the MAFITM model;
ii. design of a cognitive radio network, creating scenarios for the three models;
iii. development of a sensing algorithm which employs Matched Filtering technique for detection of signals and Interference Temperature Management for controlling harmful interference that might be caused by a cognitive radio when the licensed user is active;
iv. simulation of the existing models and the MAFITM model using Java programming language and;
v. comparison of the results of simulation obtained in (iv) above using the performance metrics of data rates, area coverage, spectrum efficiency and margin of interference.

1.6 Scope of Research

The scope of the research is to show improved spectrum utilisation by developing a new model of utilising radio spectrum in cognitive radios. This model is implemented in the television frequency bands. Therefore, the research is aimed at using cognitive radios to improve the utilisation of idle licensed TV signals.

1.7 Thesis Outlines

The organisation of the thesis is such that Chapter one discussed the background information of study, introduced the problem statement, aim and objectives, the methodology to achieve the stated aim, justification and the scope of study. Chapter two presented the theoretical background with respect to the research study and also reviewed relevant literatures. Chapter three described in details the methodology and the implementation of the research while Chapter four discussed the result. Chapter five summarised the research, presented conclusion and recommendations, with further areas of research.

CHAPTER TWO

LITERATURE REVIEW

This chapter reviews the relevant literatures needed for the proper understanding and implementation of issues this research addressed. A general overview of communication technology is presented in section 2.2, while section 2.3 discussed wireless communication systems and section 2.4 discussed spectrum management in wireless systems. Section 2.5 discussed the architecture of cognitive radios, while the details of spectrum sensing in cognitive radios are discussed in section 2.6. The discussion of the two major techniques implemented in this research, Matched Filtering and Interference Temperature Management is done in section 2.7 and section 2.8 respectively. The area of application of this research, IEEE 802.22 standard is presented and discussed in section 2.9. The chapter concluded with a discussion on television spectrum which is the main issue in IEEE 802.22 standard.

2.1 Communication Technology

The goal of exchanging information between its source and its destination in today's technology has resulted, according to Williams and Sawyer (2003), into the gradual merger of computing and communications. Communications technology, also called telecommunications technology, entails exchange of information through electromagnetic devices and systems over a distance. With the use of wireless technology, data and information from one system, either computer or telecommunication devices can be transmitted to other systems across geographical areas (Strangio, 2006). With the help of computer technology, communication technology generally known as information communication technology today is an outcome of series of discoveries and inventions that has been evolving from many centuries ago up till the present time.

2.1.1 Data Communication and Transmission

The term data, defined as a collection of facts in raw forms that become information after processing covers an extensive variety of applications. In sending data to the desired destination, the distance covered could be a very small distance or a very large distance (Williams and Sawyer, 2003).

The rate of data transmission determines the capacity of the channel and it is a function of frequency and bandwidth. A factor that determines the value of frequency of a wave that carries signal or data is the number of cycles it repeats in a second (Strangio, 2006). The higher the number of cycles per second, the more the amount of data sent in bit in a second through a channel. Bandwidth defines the range of frequencies that are allowed for a channel. It is a statement of the range of frequency between a lower band frequency and an upper band frequency in a communication channel. The wider the bandwidth of a channel, the more the capacity of the channel and this implies faster data transmission (Gans *et al.*, 2005).

The rate of data transmission also depends on how bits of messages are transfer from the transmitter to the receiver (Strangio, 2006). The transfer could either be serial or parallel transmission. In serial data transmission, bits are transmitted sequentially, one after the other through a channel. Parallel data transmission involves bits being transmitted through separate channels simultaneously. Parallel data transmission is definitely faster in transmission time but also is more costly to transmit data when compared with serial transmission (Strangio, 2006).

During data transmission between transmitters and receivers, the direction of transmission associated with the communication channel is another factor affecting how data is transmitted (Williams and Sawyer, 2003). Simplex transmission is used to describe transmission in only one direction as in the case of a television station which sends its signal to its viewers but do not expects the receivers to send any signal in return.

In a transmission whereby, a party can send data to the other party and data can be reversed, but not at the same time, it is called half-duplex transmission. Examples of half-duplex transmission occur in marine and walkie-talkie radios in which both parties must take turns talking by means of exchanging replies or feedback in communication (Strangio, 2006). Full-duplex is when data is exchanged between two parties in both direction and at the same time as in the case of telephone systems (Williams and Sawyer, 2003).

2.1.2 Data Communication Channels

The pathway or communication channel of data transmission is either wired or wireless and it is the medium through which data reach its destination form its source (Williams and Sawyer, 2003). Different types of wired channels are twisted-pair wire, coaxial cable, and fibre-optic cable. Different types of wireless channels include infrared transmission; AM/FM broadcast radio, microwave radio, and communication satellite.

Infrared wireless transmission sends data signals using infrared-light waves in a line of sight communication over a short distance. AM/FM broadcast radio as a wireless transmission medium sends data over long distances. Microwave radio transits voice and data through the atmosphere at super-high-frequency radio waves. As with infrared waves, microwaves are line-of sight; they cannot bend around corners or around curvature, so there must be an obstructed view between transmitter and receiver.

Communication satellites are microwave relay stations that are transmitting signal from the earth surface to the orbit and from the orbit back to the earth surface.

2.1.3 Wireless Communications Systems

According to Goldsmith (2005) and (Gans *et al.*, 2005), the growth of wireless communications technology is at a fast rate and many wireless applications are using it because of its great impact on human every day to day activity. This technology is used for transmission of texts, audios, still pictures, videos, live events and many other messages wirelessly over either short or long distances. The astronomical increase of communications systems using wireless channel means that the future is bright for wireless systems in terms of market prospect. However, there must be proper management of wireless transmission channels for efficient usage.

2.2 Wireless Communication Systems and Spectrum Utilisation

The evolution of radio technology can be viewed as a constant effort to increase efficient spectrum utilisation. In ensuring efficient spectrum utilisation, there is separate spectrum allocated for licensed users and unlicensed usage (Berggren *et al.*, 2004). The ability of diverse networks to co-exist in the unlicensed spectrum band, made IEEE to establish standards that cover a wide range of applications as listed in Table 2.1.

Spectrum privatisation and the need for coordinated development of standards and technologies that allows effective higher frequencies utilisation are good steps taken to achieve the development of systems based on wireless communications (Odufuwa, 2010). Ultra Wide Band (UWB) and Fourth Generation (4G) technologies are classic samples of high capacity technology that can share radio frequency band, since there are not enough new radio frequencies available.

Table 2.1: Wireless Standards and their Applications (Source: Norton, 2007)

Standard	**Application**	**Trade name**	**Modulation Format**	**Industry Coordination Organisation**
802.11b	WLAN	Wi-Fi	DSSS	http://www.wi-fi.org/
802.11a/g	WLAN	Wi-Fi	OFDM	http://www.wi-fi.org/
802.15.1	WPAN	Bluetooth	FHSS	http://www.bluetooth.com
802.15.3	High Rate WPAN	Wi-Media	DSSS	
802.15.3a	Higher Rate WPAN	Alt-PHY	UWB/OFDM	http://www.multibandofdm.org/
802.15.4	Low Rate WPAN	ZigBee	DSSS	http://www.zigbee.org/

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2.3 Spectrum Management

Various types of electromagnetic radiations of different wavelengths are referred to as electromagnetic spectrum while radio spectrum means usable electromagnetic spectrum for radio communication. Wireless communication systems are generally referred to as radios and should not be misunderstood with the Broadcast radios. A radio is any device that can superimpose data or information or baseband signal on high frequency waves known as carrier waves in a technique called modulation and then send it to another device that can process the modulated signal (Strangio, 2006). In other words, a device that modulates input signal and send it through the radio frequency to the desired destination is a radio. Radios make use of segment of the larger electromagnetic spectrum known as radio waves. The management of the radio waves or in another term radio spectrum is what is referred to as radio spectrum management or simply radio management. The radio spectrum is divided into eight different frequency bands which different types of radio communication systems use for communication.

Sharma and Saini (2014), defined spectrum management as a means of selecting free spectrum to maximise its usage for transmission. The radio frequency band which ranges from 3 KHz to 300 GHz is separated into bands of frequencies which are allocated for a particular use and users as shown in Figure 2.1. Among many notable radio communication systems that make use of radio spectrum are broadcast radio, Bluetooth radio and microwave radio (Cave *et al.,* 2007).

The fact that there is proliferation of wireless technologies and their applications that requires radio frequency spectrum shows that the spectrum must be managed in order to ensure a coordinated and efficient usage. Spectrum supervisory body or administrators are at two major levels. The first body is ITU-R which manages spectrum internationally by dividing the world into three regions for the allocation of frequency. Nigeria falls within Region 1. The second body manages spectrum within national region with the establishment of agencies to monitor and supervise its operations.

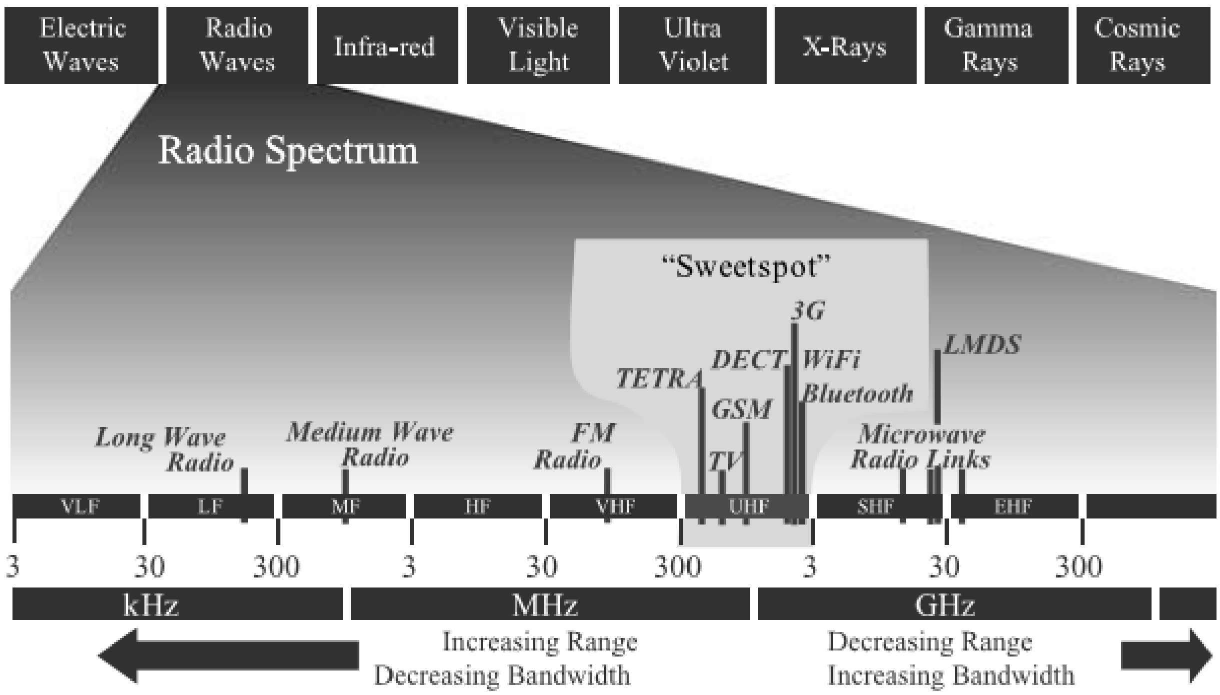


Figure 2.1 Radio Frequency Spectrum (Source: Cave *et al.*, 2007)

2.3.1 Elements of Spectrum Management

Spectrum management consist of key elements that ensure proper coordination and management of the spectrum among competing users or systems. These elements include spectrum standards, spectrum licensing, spectrum policies and spectrum planning (Sandeep and Singh, 2017). While spectrum standards ensure that interference of different signals and rights and obligations of users are well managed, spectrum licensing determines whether a user or radio system could transmit in a frequency band with exclusive or inclusive right (Peha, 2000). Exclusive right means that only specified users are licensed to use specified frequency band but inclusive right allows transmission of different users' signals in unlicensed frequency bands at low transmission power and coverage area to avoid interference. Spectrum policies entails the protection of frequency allocated to licensed users against unintentional or unlawful use while Spectrum planning outlines a structure which include measures of reducing interference (Berggren *et al.*, 2004).

2.3.2 Spectrum Utilisation and Efficiency

The need for spectrum regulation is based on the belief that spectrum is a renewable but limited resource. Literatures have shown that spectrum is increasingly being demanded for by various new wireless applications and making it available for new services and considering the existing spectrum management and incumbent users is a complex task (Odufuwa, 2010). There is need to manage spectrum in effective way so as to maximise its usage in meeting up with new demand. Thus, efficiency and utilisation of spectrum is a critical aspect of spectrum management as measurement has shown that there are plenty of unused spectrums (Odufuwa, 2010). According to Kalliola (2004), if spectrum is effectively managed in term of sharing, the entrance of new technologies or applications that requires spectrum will not be difficult.

Spectrum efficiency is seen as how the spectrum is being used optimally without much idleness. Hranac (2012), define spectrum efficiency as the measure of data in bits transmitted in a second in a specified bandwidth. This definition states how efficiently a radio frequency band of given bandwidth can carry. With exclusive right for licensed spectrum usage, wastage of radio frequency band is imminent. Unlicensed usage of radio frequency unlocks the door of higher spectrum utilisation by allowing sharing among different users but this may reduce the quality of service if not properly coordinated.

2.3.3 Spectrum Management Functions

The static spectrum allocation policy whereby exclusive right is given to a band in a particular location has been shown to be deficient because a significant amount of spectrum is underutilised (Yadav *et al.,* 2012). A corrective approach to this shortcoming is dynamic spectrum access where spectrum is opportunistically shared with licensed users. However, as stated by Sandeep and Singh (2017), the possibility of different users both licensed and unlicensed to co-exist in an adaptable way can be achieved by using the following five spectrum management functions.

i. Spectrum sensing: To check and detect the available white space or channel suitable for its transmission.
ii. Spectrum decision: To select spectrum holes or white space once the spectrum holes are found (Sandeep and Singh, 2017).
iii. Spectrum sharing is the allocation of selected spectrum holes or white space to the unlicensed users for transmission as long as licensed users are inactive on the channels (Sandeep and Singh, 2017).
iv. Spectrum scheduling is deciding the allocated spectrum holes for competing unlicensed users (Sharma and Saini, 2014).
v. Spectrum mobility: To cleverly leave a radio frequency band occupied when a primary user is detected, and then continue its transmission by switching to another spectrum (Seyedzadegan, 2013).

2.3.4 Technologies to Improve Spectral Efficiency

Whenever a system with exclusive right to transmit in a given radio spectrum is not transmitting, the particular band will be lying idle because no other user can transmit in the band. It is therefore important to adopt novel method that can use these exclusive bands more efficiently where possible because there will be an improvement in the efficiency of the scarce radio spectrum. The following subsections discuss some of the technologies by which radio spectrum can be improved.

2.3.4.1 Modulation Technology

Modulation is the method used to change the signal characteristics of the signals to be transmitted by varying the properties of a carrier wave in accordance with that of the signal to be transmitted. A modulation technique that is considered to be spectral efficient is the orthogonal frequency-division multiplexing (OFDM). It is efficient because it can handle the problems of interference which can impair the quality of signal transmission. Instead of using single carrier wave as in the case of many other modulation techniques, OFDM technique improves signal quality by splitting the signal to be transmitted over different frequencies of the carrier wave (Zemen, 2008; Soltani, 2009). This makes OFDM to have the advantage of mitigating interference as compared to other single carrier modulation methods (Frenzel, 2009).

2.3.4.2 Fourth Generation (4G) Technology

Fourth generation technology is a cellular network technology that offers higher data transmission speed. Fourth generation technologies create higher bandwidth for many simultaneous data transfer thereby providing higher spectral efficient technology. The two main 4G standards are the third Generation Partnership Project-Long Term Evolution (3GPP-LTE) and the Worldwide Interoperability for Microwave Access (WIMAX). The first 4G type, 3GPP-LTE has a capacity of up to 100 Mbit/s in the downlink and 50 Mbit/s in the uplink. With these systems it is possible to have data transfer ten times faster than the ordinary 3G technology (Motorola, 2007). It provides enrichments to 3G to meet the requirements of 4G technologies. The second type of 4G technology provides much better capacity and also covers longer distance with higher number of users than Wi-Fi system (Upadhyaya and Bicholia, 2017). Wi-MAX is based on OFDM and can operate in the radio frequency between 2 GHz and 11 GHz and 66 GHz producing large bandwidth (Omerovic, 2010; Seyedzadegan, 2013).

2.3.4.3 Antenna Technologies

Antenna technologies for improved spectral efficiencies include Smart antenna and Multiple-input and multiple-output (MIMO) antenna. MIMO antenna technology uses more than one antenna to increase performance. MIMO uses the multiple antennas at both the transmitter and the receiver to achieve high rate, high reliability, and long range transmission (Bliss *et al.*, 2005). Smart antenna signals emission is different from regular antenna as its transmission is only focused in specific path unlike regular antennas that produces Omni-directional emission. This results into lower transmission power requirement and this means that lower interference against other signal is achieved.

2.3.4.4 Ultra Wideband Techniques

A high data capacity wireless transmission technology is Ultra Wide Band (UWB) technology. It transmits data with very low power for a short distance. The federal communication commission of the United States has authorized that UWB signals can function between the frequency of 3.1 GHz and 10.6 GHz with transmissions requiring longer coverage area using band groups #1 and #2, and shorter coverage area transmissions using band groups #3 and #4 as shown in Figure 2.2. (ECMA International, 2005). Figure 2.3 shows ultra wide band transmissions sharing frequency bands with other technologies.

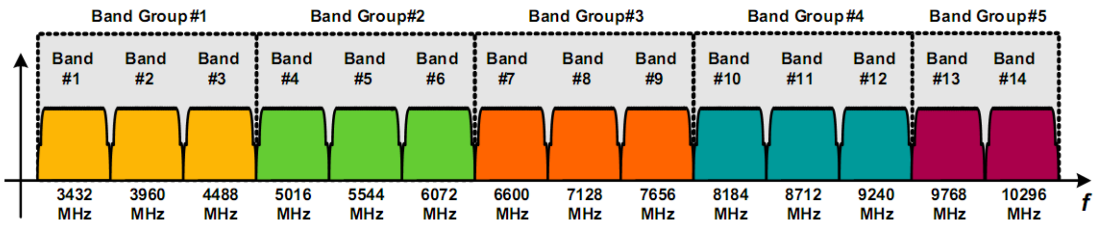


Figure 2.2: Ultra Wide Band Transmission
Source: ECMA International, Ecma/GA/2005/038, 2005

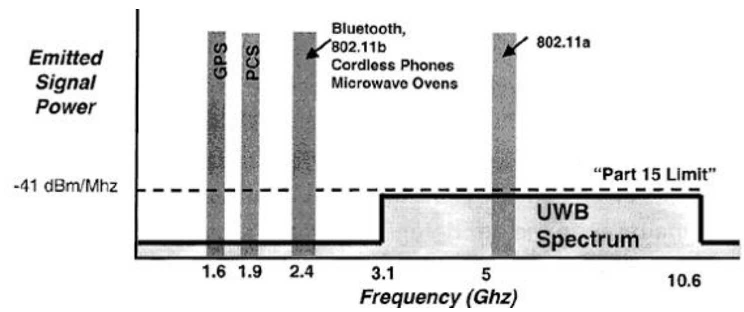


Figure 2.3: Ultra-Wideband Spectrum Sharing
Source: Ahmad *et al.*, 2003.

2.3.5 Dynamic Spectrum Access

A promising technology that eases the spectrum scarcity problem and increase spectrum utilisation is Dynamic spectrum access (DSA). DSA permits unlicensed users to access the free spectrum holes rightly owned by inactive licensed users in the licensed spectrum bands. The reason for the use of DSA is that spectrum licensee should permit unlicensed users to the spectrum in a coordinated approach (Yadav *et al.,* 2012).

Different literatures have classified dynamic spectrum access methods into overlay and underlay methods (Mitran, 2008). A situation where unlicensed users resourcefully share the spectrum with licensed users is the overlay method. In this method, primary users ensure almost no interference occurs between licensed users and unlicensed users. In the underlay method, the unlicensed users access the spectrum by transmitting at a low transmission power at all time in the licensed spectrum. According to Yadav *et al.* (2012), with emerging technologies like cognitive radios, accessing spectrum dynamically now attracts greater participation of interest. Radios based on dynamic spectrum access are discussed below.

2.3.5.1 Software Define Radio

Before now, the operations of radios have been performed mainly by hardware functionalities. To change transmission parameters such as frequency or power, it will be done manually by changing the switch position of the radio. In the recent years, the operations of radios are now controlled by software using the existing hardware platform. These categories of radios are called software defined radio (SDR). The conception of SDR was the aftermath of the advances in processors, RF technology, and software (Clancy, 2006). SDRs are programmable radios in which radio parameters such as modulation scheme, coding scheme and transmitting power can be modified to favour improved data transmission (Martin, 2012).

The progresses in SDR have permitted the growth of production of sophisticated radio system for enhancing dynamic spectrum access. For example, a single SDR transceiver is clever enough to function as a smart device (SearchNetworking, 2000).

2.3.5.2 DARPA's Next Generation Radio (XG)

The introduction of SDR brought a new perspective to how the operations of radios are considered. The reason for this being that SDR is able to use programmable processing similar to that of modern computers. In the year 2006, the ‘Defence Advanced Research Projects Agency’ (DARPA) developed what is called next Generation (XG) radio using the principles of SDR (DARPA, 2015). The implementation was carried out using a number of XG radios using the same radio frequency and the development demonstrated the capabilities of SDR to use DSA in order to provide dramatic improvements in spectrum utilisation (DARPA, 2015).

2.3.5.3 Cognitive Radios

A software radio uses programmable processing to select better transmission parameters to obtain optimum transmission after noting that the present status of its transmission is not favourable anymore. However, it does not have any idea about its environment in the sense that the changes made to its transmission may actually cause impairment or degrade the quality of another signal that is using the signalling features that the SDR has shifted to. For example, a SDR that shifted its transmission frequency may cause interference to another signal that is currently using that same frequency. A type of software radio that considers its environment to avoid degrading any other signal before making changes in its own feature is cognitive radio.

Cognitive radios as defined and introduced in chapter one of this thesis are designed to use dynamic spectrum access efficiently. They are systems that enable effective sharing and coexistence of radio frequency because of their spectrum mobility property (Verma *et al.*, 2012). Cognitive radio is projected to advance dynamic spectrum access by allowing primary users to lease their spectrum while protecting the owner from detrimental interference that can impair its transmission.

According to Sudakaran and Suganthi (2017), for cognitive radios to have a successful transmission, they must ensure that:

i. There is proper usage of bandwidth and frequency

ii. They need to establish excellent link in transmission

iii They should be intelligent in managing lost connections

iv. They should enforce the policies regulating the usage of unlicensed spectrum.

2.3.6 Comparison of the Technologies on Spectrum Efficiency

In a comparative study carried out to compare the technologies to improve spectrum efficiency, the following parameters were used:

i. Data Rate: Describes the impact of the technology to increase capacity.
ii. Number of Users: Describes the technology's impact on the number of simultaneous users.
iii. Interference Mitigation: Describes the impact of the technology to reduce interference.
iv. Spectrum Agility: Describes the impact of the technology to enable mobility from one band to another.
v. Spectrum Usage Policy: Describes the impact of the technology to protect the right of the licensee.

Table 2.2a explained the ratings used for the comparison while the 4G technologies are compared in Table 2.2b. The comparison in Table 2.2b shows that LTE and WIMX have facilities for high data rates and not too strong interference control measures among high number of users. There is no spectrum usage policy implementation among the users of LTE and WIMAX (Seyedzadegan, 2013). The modulation technique of OFDM/OFDMA, the antenna configuration of MIMO and Smart Antenna technology permit moderate data rates and moderate number of users that share the spectrum in a moderate interference control measure. In UWB, high data rate with high number of users could be achieved with moderate interference control. Data rate and number of users are moderate in SDR and XG. Interference control is moderate in SDR but it is high in XG. A moderate data rate is achieved with a high number of users that share the spectrum using a high interference control mechanism. Spectrum agility is low in most of the technology compared except in SDR which has a reasonable mechanism for allowing users to move to other frequencies if the need arises. Only XG and CR have high facilities for spectrum agility. There is no policy measures put in place in the usage of shared spectrum in the technologies discussed except in XG and CR where radio spectrum is shared with mutual agreement.

Table 2.2a: Meanings of Ratings for Spectral Efficiency Technology

Ratings of Impact of Technology	Meaning
HIGH	The technology has appreciable impact on spectrum efficiency
MEDIUM	The technology has average impact on spectrum efficiency
LOW	The technology has negligible impact on spectrum efficiency
NONE	Technology not implemented

Table 2.2b: Comparison of Technologies on Spectrum Efficiency

Technology	Data Rate	Number of Users/ Application	Interference Control	Spectrum Agility	Spectrum Policy Measures
LTE	High	High	Medium	Low	None
WIMAX	High	High	Medium	Low	None
OFDM/OFDMA	Medium	Medium	Medium	Low	None
MIMO	Medium	Medium	Medium	Low	None
Smart Antenna	Medium	Medium	Medium	Low	None
UWB	High	High	Medium	Low	None
SDR	Medium	Medium	Medium	Medium	None
XG	Medium	Medium	High	High	High
Cognitive Radio	Medium	High	High	High	High

The following characteristics of cognitive radio make it a preferred technology among the DSA technologies listed in Table 2.2b.

i. Awareness of its environments
ii. Adaptability to change of state or condition in spectrum
iii. High interference mitigation properties
iv. Policy to protect licensee

2.4 Cognitive Radio Architecture

The radio functionality that performs dynamic spectrum access is non-trivial because the detection of free radio frequency bands that is, white spaces or spectrum holes over wide frequency band requires accurate sensing of the spectrum. It needs to identify the licensed users and also determine the possibility of transmission, manage its network of communication without causing interference. However, all these functionalities are embedded into cognitive radios effective dynamic spectrum usage. Figure 2.4 shows the eight basic components of cognitive radios architecture.

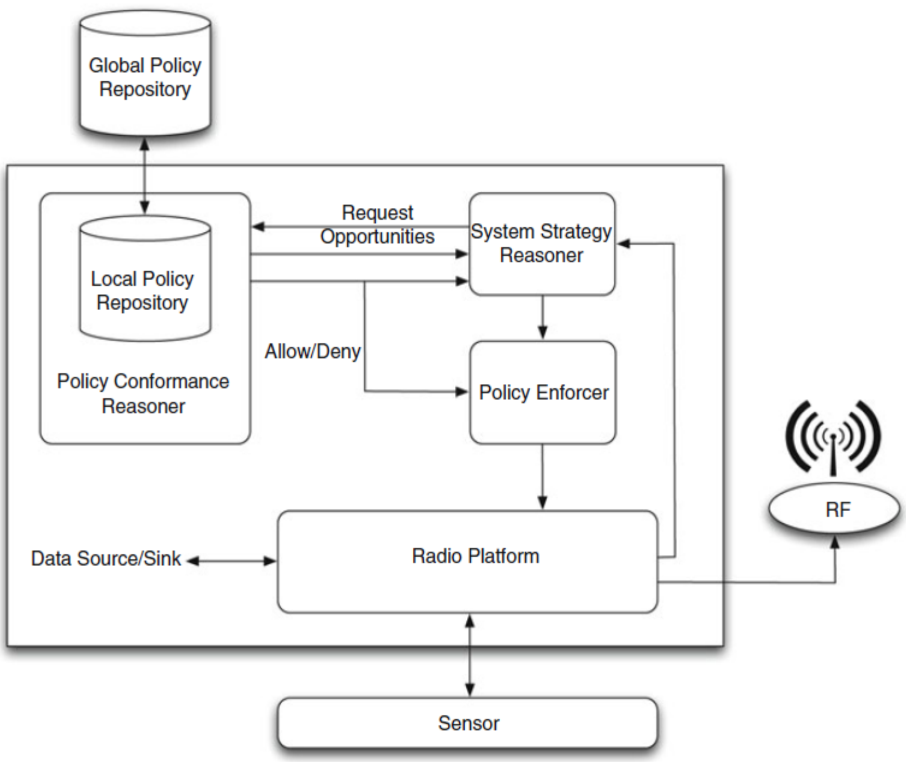


Figure 2.4: Basic Architecture of a Cognitive Radio (Source: Li and Kokar, 2013)

Li and Kokar (2013) described these eight components as follows:

1. Sensors: In a cognitive radio that implements DSA, sensors are used to collect information from the external environment and identify spectrum holes and determine the possibility of transmission.
2. Radio Frequency (RF): Transmission and reception of radio signals is achieved by this component.
3. Radio Platform: The processing of signal and the control of programmable instruction is provided by this component. It provides interfaces to communicate with other components of cognitive radios architecture.
4. System Strategy Reasoner (SSR): The optimisation of the performance of the radio is carried out intelligently by selecting the parameters that gives the best performance of the radio and this is done by this component.
5. Policy Conformance Reasoner (PCR): It executes the active policy set to ensure that the behaviours of the radio satisfy the constraints imposed by external regulations and policies
6. Policy Enforcer (PE): The PE acts as a gate keeper between the SSR and the Radio Platform. It ensures that all the transmission decisions sent from SSR to the Radio Platform comply with the active policy.
7. Global Policy Repository: The Global Policy Repository stores all the policies and specific subsets configured for specific networks. The Global Policy Repository is shared across the network.
8. Local Policy Repository: The Local Policy Repository is within the SSR. It can download the policies from the Global Policy Repository through an interface. A radio node can store multiple sets of policies, but only one set of policies is active at any time.

Cognitive radio network comprises of nodes that are communicating intelligently because they are aware of their transmission. The network carefully and intelligently controls information transfer within the network.

2.5 Techniques of Sensing and Sharing Spectrum in Cognitive Radios

Techniques of sensing and sharing spectrum in cognitive radios are discussed under three main categories of overlay, underlay and other sensing techniques.

Overlay method performs spectrum sensing when a cognitive radio is about to transmit data. After the sensing is performed, cognitive radio either detects the activeness or inactiveness of licensed user signal (Nawaf and Xiuhua, 2010; Kokare and Kamble 2014). If the sensed frequency band is not free, the cognitive radio will have to shift to different licensed band to perform sensing of primary user signal because simultaneous transmission with the licensed user is not allowed (Cave *et al*., 2007). If the presence is still detected and there is no more frequency band, it will stop the transmission of its packets and wait for a specific time to repeat the process. Whenever the absence of licensed user signal is confirmed, it transmits its packets. The major overlay sensing techniques are classified as transmitter detection, primary receiver detection and cooperative sensing (Verma *et al.,* 2012).

The major primary transmitter detection methods in overlay spectrum sensing are matched filtering (MF), energy detection (ED) and Cyclostationarity feature detection.

The signalling characteristics of the licensed signal to be detected are needed by matched filters. (Rawat and Yan, 2011). The best option for detecting licensed user signal is matched filtering when the signalling characteristics of the licensed signal to be detected are known (Varalakshmi *et al.*, 2016).

Energy detection uses energy detector for confirming the availability or otherwise of the licensed signal in the band (Salem *et al.*, 2014). It is simple as there is no much complexity in the implementation because there is no need for the signalling characteristics of the licensed signal to be known for detection (Shobana *et al.*, 2013; Varalakshmi *et al.,* 2016).

The statistical features of signal are used in Cyclostationarity feature detection in identifying licensed user's presence (Varalakshmi *et al.,* 2016). There is better accuracy than energy detection method but a lower accuracy compared to matched filters (Sharma and Saini, 2014; Verma *et al.*, 2012)

Receiver detection of licensed signal by unlicensed user is from primary user's radio frequency leakage power (Kokare and Kamble, 2014). To improve spectrum sensing, cooperative sensing is carried out using centralized server based detection, external detection and distributed detection. Cognitive radio using Underlay Technique cannot transmit beyond set limit even with the absence of primary user's signal in the spectrum band (Verma *et al.*, 2012).

In other to achieve better and reliable spectrum sensing, researchers have proposed different sensing methods that use two or more sensing techniques of overlay or underlay at the same time. This is because any one of the sensing techniques alone cannot give optimum results. These other spectrum sensing methods could be a combination of any two methods of overlay to form an overlay/overlay technique, or a combination of any method of overlay with a method of underlay to form an overlay/underlay technique or an approach that employs two different technologies or methods other than sensing methods to achieve reliable spectrum sensing.

Most literatures that employ overlay/overlay methods combined energy detection and cyclostationary feature detection. Table 2.3a presents a summary of literatures that used overlay/overlay methods with the table showing the type of sensing methods used, the aim, result, conclusion and areas of application of the methods. Table 2.3b presents literatures that used a combination of overlay/underlay while Table 2.3c shows other combination methods different from overlay or underlay.

The distinct feature of this research is that it used matched filtering technique in overlay for sensing of primary user signal and interference temperature management in underlay for transmitter power control of secondary user to prevent interference to licensed user signal. Also, the area of application of the developed method of this research is different from those of the reviewed literatures that have presented one form or the other of overlay and underlay methods. The new method developed in this research is applied to

IEEE 802.22 standard where cognitive radio technology is used for vacant spectrum in the television band. The reason for the choice of matched filtering for overlay spectrum sensing over other methods is that it has the highest accuracy in detecting primary signals and its high implementation complexity is not an issue because it is used for detecting a single type of licensed signal which is digital television signal. The choice of interference temperature management for underlay is based on its use by spectrum regulatory body that is the Federal communication commission (FCC) of the United States and also because of its simplicity of implementation in the quantifying and managing of interference (Federal Communications Commission, 2003).

Table 2.3a: Literatures with Overlay/Overlay Techniques in Cognitive radios

S/N	Title	Author	Method	Aim/Result	Conclusion/ Areas of Application
1	Low Complexity Enhanced Hybrid Spectrum Sensing Architectures for Cognitive Radio Equipment	Khalaf et al. (2010)	Combination of energy detection and mono-cycle detection, which exploits Cyclostationarity property of the signals	The new adaptive architectures allow the sensing at lower SNR and with a decreasing algorithmic complexity.	It is an overlay/overlay. Considered wireless networks in general using different signal to noise ratios (SNRs)
2	Hybrid Spectrum Sensing Algorithm for Cognitive Radio Network	Shirazi et al. (2012)	Energy Based Detection and Cyclostationary Feature Detection.	It compares the probability of detection of PU signal	It is an overlay/overlay technique. Considered wireless networks in general
3	Joint Optimization Using Hybrid Spectrum Sensing In Cognitive Radio Networks	Arlin and Hari. 2013	Combination of energy detection and cyclostationary detection	This paper proposes an adaptive spectrum sensing in which cognitive radio can adopt one-order cyclostationary or energy detector for spectrum sensing on the basis of estimated SNR	Overlay/overlay. Considered the accuracy and performance of OFDM systems and CDMA systems.
4	A Novel Hybrid Approach for Spectrum Sensing in Cognitive Radio	Gawde et al. 2015	Combination of energy and matched filter based detectors	To have a reliable spectrum sensing and detection of primary signal	It is an overlay/overlay technique. Considered wireless networks in general using different values of SNR like -25,-16 to -7 dB,
5	Spectrum Sensing for Cognitive Radio Using Hybrid Matched Filter Single Cycle Cyclostationary Feature Detector	Joshi et al. 2015	Combination of Hybrid Matched Filter and Single Cycle Cyclostationary Feature Detector	To enhance the detection of low SNR signal. Show significant improvement in the probability of detection and false alarm.	It is an overlay/overlay technique. Considered wireless networks in general using different values of SNR
6	Performance Evaluation of Hybrid Model for Spectrum Sensing in Cognitive Radio	Kadam et al., 2015	Combination of matched filter, energy detection and cyclostationary detection	For optimal spectrum sensing. Performance analysis of the model based on the Probability of detection and probability of false alarm.	It is an overlay/overlay technique. Considered wireless networks in general using SNR of -10 dB.
7	Hybrid spectrum sensing Technique based on energy and Cyclostationary techniques in cognitive radio: A Review	Roohi and Dhillon (2016).	Energy detection and Cyclostationary detection	Proposed the development of energy detector and cyclostationary detector. These detectors are to be combined for improved spectrum sensing.	It is an overlay/overlay technique. Considered wireless networks in general
8	A Research On Non Cooperative Hybrid Spectrum Sensing Technique	Ramandeep and Sharma (2017)	Combination of energy and cyclostationary sensing approaches	Aimed at improving sensing accuracy, and energy consumed.	It is an overlay/Overlay. Considered wireless networks in general

Table 2.3b: Literatures using overlay/underlay Techniques in Cognitive radios

S/N	Title	Author	Method	Aim/Result	Conclusion/ Areas of Application
1	Hybrid Overlay/Underlay Spectrum Sharing in Cognitive Radio Networks	Rong and Zhu 2011	User classification and Convex Optimization	Cognitive users are divided into four groups and allocated different spectrum sharing patterns. An optimal power allocation scheme is acquired through the convex optimization method.	It is an overlay/underlay technique. Considered wireless networks in general.
2	Hybrid Overlay/Underlay Cognitive Radio Networks With MC-CDMA	Jasbi (2014)	Uses multiple access method of MC-CDMA for underlay and orthogonal variable spreading factor (OVSF) codes for overlay	The method utilises interference mitigation capability and also suppresses Primary User interference.	It is an overlay/underlay technique. Spectrum utilisation technique in CDMA networks.
3	Hybrid Spectrum Sharing Power Allocation Concept in Cognitive Radio Networks	Kailas et al. 2015	Spectrum sensing for overlay and distributed power bidding and allocation algorithm for underlay.	An auction-based power-allocation scheme is used to solve the problem of power competition of multiple SUs	It is an overlay/underlay technique. No specific sensing method. Considered wireless networks in general.
4	Performance of Cognitive Radio Network with Novel Hybrid Spectrum Access Schemes	Bhowmick, et al. 2016.	Employs an energy detection for overlay and power control for underlay	Sensing parameters such as sensing time, channel estimation error, tolerable interference threshold, maximum allowable transmit power of CR is investigated	It is an overlay/underlay technique. Considered wireless networks in general.
5	Performance Analysis of Hybrid Cognitive Radio Systems with Imperfect Channel Knowledge	Kaushik, et al.(2016)	Presents an approach applicable to any sensing technique for interweave (overlay) and power control mechanism at the Secondary Transmitter (ST) for underlay.	Focused on channel characterization and regulatory power control	It is an overlay/underlay technique. Considered Orthogonal Frequency Division Multiplex (OFDM) system
6	Hybrid Spectrum Sensing Method for Cognitive Radio	Khobragade and Raut 2017	Five spectrum sensing technique used to create a hybrid spectrum sensing method. Match Filter detector, Energy detector, GLRT, Robust Estimator Correlator and Temperature based detector.	The sensing problem is tackled with the use of a spectrum sensing method based upon Centralized Coordination concept	It is an overlay/underlay technique. Considered wireless networks in general. Performance metrics include detection accuracy, complexity, robustness, flexibility of design choices.

Table 2.3c: Literatures using Other Methods Different from Overlay or Underlay Techniques in Cognitive radios

S/N	Title	Author	Method	Aim/Result	Conclusion/ Areas of Application
1	A Hybrid Spectrum Sensing Method for Cognitive Sensor Networks	Zahmati et al. (2014)	Combined primary network sensing and the secondary network sensing. It used only energy detection method	Finds the optimal sensing period based on both primary and secondary networks' properties.	It is an overlay design. It is about the best time to perform sensing. Area of application is IEEE 802.15.4/ZigBee radio
2	Intelligent Hybrid Cooperative Spectrum Sensing: A Multi-Stage Decision Fusion Approach	Elgadi, et al. (2017)	Fuzzy logic for local fusion and Neural networks for global fusion of cooperative sensing	The paper focused on probability of detection and percentage accuracy during spectrum sensing.	It is an overlay design. Area of application is Cellular network tested at different SNR ranging from -25dB to 5dB.
3	Spectrum sharing via hybrid cognitive players evaluated by an M/D/1 queuing model	Kotobi and Bilén 2017	cooperative and non-cooperative spectrum sensing	Evaluate the improvement in performance of a cognitive radio network with this spectrum sensing using an M/D/1 queuing model.	It is an overlay design. Considered wireless networks in general.
4	Novel Hybrid Spectrum Handoff for Cognitive Radio Networks	Nisar et al., 2013	Proactive Decision and Reactive Decision Spectrum Handoff.	The paper is concerned about Spectrum handoff necessitated by the reappearance of the primary user on the frequency channels occupied by the secondary user at that time and location.	It is an overlay design. Considered wireless networks in general.
5	Hybrid Spectrum Sharing Through Adaptive Spectrum Handoff for Cognitive Radio Networks	Lertsinsrubtavee et al. (2014)	Static and dynamic spectrum sharing with respect to bandwidth.	Reduces the number of handoffs significantly	It is an overlay design. Considered wireless networks in general.
6	Hybrid Spectrum Sharing with Cooperative Secondary User Selection in Cognitive Radio Networks	Kader 2014	The method not properly defined. Secondary users can access the licensed spectrum along with the primary system.	The paper focused on Primary and secondary outage probability. The approach is to select the best secondary user among many competing for the available spectrum.	It is an overlay design. Considered wireless networks in general.
7	A unified spectrum sensing and throughput analysis model in cognitive radio networks	Ming-Fong et al. 2013	The energy detection scheme is employed for the spectrum sensing in the network	It creates a unified spectrum sensing and throughput analysis model, which is suitable for overlay, underlay, and overlay/underlay paradigms in the CR networks	It is an overlay design. Considered wireless networks in general.
8	Performance Improvement of Hybrid Cognitive Radio Networks with AF Relay	Satheesan and Sudha 2015	The methods are not sensing techniques	Allocation of optimum power to secondary users	It is an underlay design. Considered wireless networks using 20dBm SNR

2.6 Matched Filtering

Optimum receiving filters can be designed for the detection of pulses with known shape buried in additive noise of almost any known spectral density (Carlson and Crilly, 2010). These optimum filters, called matched filters, have extensive applications in digital communication, radar systems and the like (Carlson and Crilly, 2010). In signal processing, a matched filter is obtained by correlating a known signal, or pilot signal, with an unknown signal to detect the presence of the known signal in the unknown signal (Bancroft, 2002). The matched filters are the optimal linear filters for maximizing the signal to noise ratio (SNR) in the presence of additive noise as they are able to peak out the signal component at some instant and suppress the noise amplitude at the same time (Shobana *et al.,* 2013). For any confirmation of the presence of a known signal in the received signal, matched filter output is compared to a threshold value. The presence of the known signal is detected when matched filter output equal or exceed the value of the threshold. Detection is represented as H_1 otherwise the signal is absent and it is represented as H_0 in the Figure 2.5.

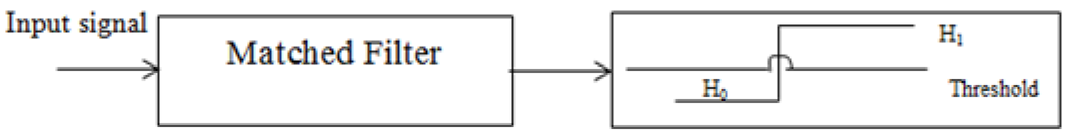


Figure 2.5: Matched Filters

2.6.1 Detection of Signals in Matched Filters

For detection to be possible, matched filters must be able to process the primary user signal. The implication of this is that cognitive radio needs to have good understanding of the characteristics of the signal of primary users (Bancroft, 2002). Interestingly, most primary users have a kind of signal known as pilot; this signal transmitted along with their transmission, can then be used for articulate detection of the main signal by matched filters as shown in Figure 2.6 as it contains necessary features to identify the primary user signal.

Consider a signal s(t) with additive white Gaussian noise n(t) as $r(t) = s(t) + n(t)$. A basic matched filter with impulse response h(t) as shown in Figure 2.6 is said to be matched to a finite duration signal s(t) over a duration of T seconds if $h(t) = s(T - t)$ (Hani, 2013). This property of matched filter is illustrated in Figure 2.7. The output of the matched filter in response to the matching signal is at its maximum at $t = T$. If signal s(t), which is zero outside the interval [0, T], is applied to the filter matched to it with impulse response $h(t) = s(T - t)$), the output will be zero outside [0, 2T].

The impulse response h(t) of the matched filter which is derived from the frequency response function is used to quantify a matched filter. Considering the input signal of the matched filters, the impulse response indirectly gives the approximate value of the amplitude and phase of the output. This could be derived by using either the calculus of variations or the Schwarz inequality (Carlson and Crilly, 2010).

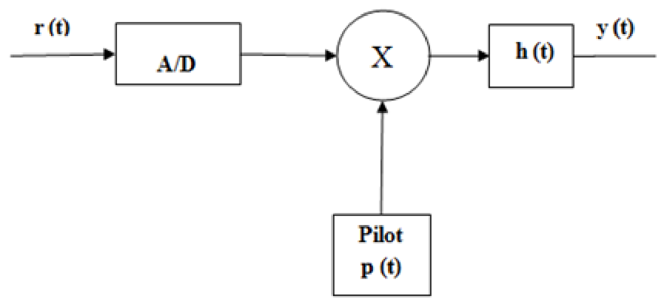


Figure 2.6: Detection of Signal Using Matched Filters

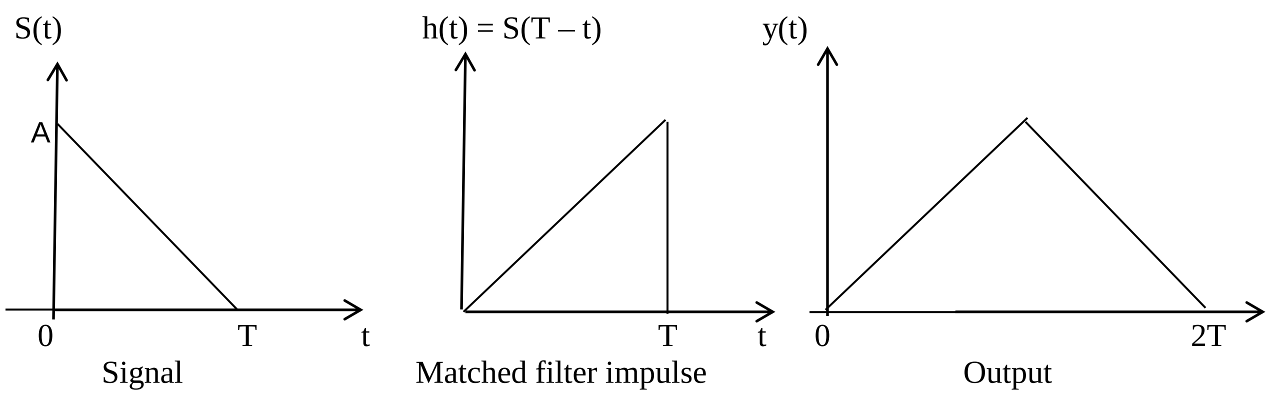


Figure 2.7: Properties of Matched Filters (Source: Bancroft, 2002)

2.7 Interference Temperature Management

In 2003, the Federal Communications Commission (FCC) introduced the concept of interference temperature (IT) for quantifying and managing interference where cognitive radios using licensed spectrum would avoid causing harmful interference to primary user signal (Clancy and Abaugh, 2007). Interference temperature describes the temperature equivalent measured in Kelvin (K) of the radio frequency power of unwanted signal that could interfere with the desired signal that are existing within the bandwidth.

The model illustrated in Figure 2.8, was proposed to allow unlicensed users transmit simultaneously with the licensed signal (Clancy, 2007). Interference temperature management is significant in discussing means of allowing multiple users in a radio frequency band since unlicensed user is permitted to reuse the radio frequency band of the licensed user only if unlicensed user does not impair the primary user signal (Clancy, 2007).

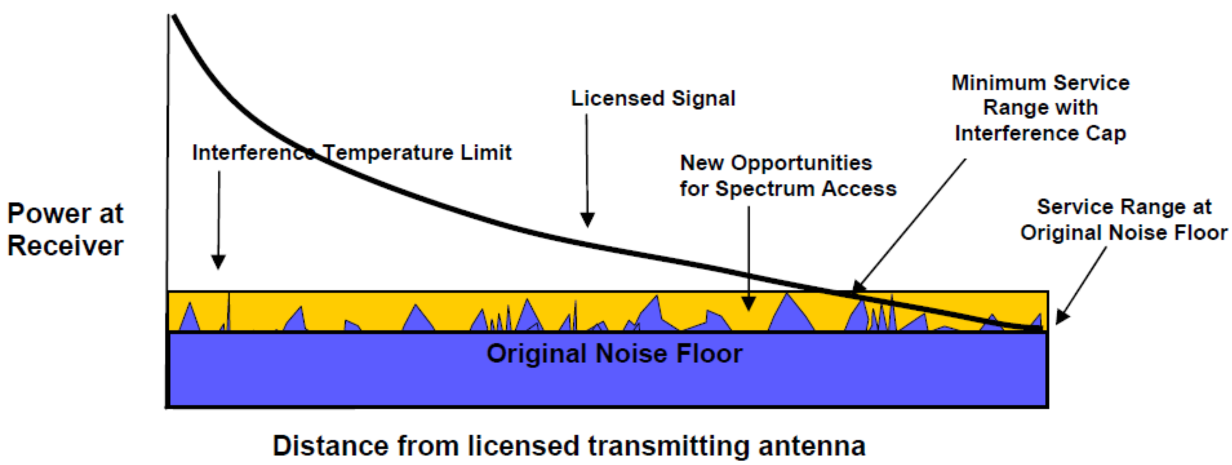


Figure 2.8: Interference Temperature Management in a Single Frequency
Source: (Federal Communications Commission, 2003).

2.7.1 Interference Temperature Model

For computing and handling the likely degradation of primary signal when secondary users are operating in the licensed radio spectrum, interference temperature model was proposed. The model is such that unlicensed users can regulate their signal properties to ensure that the interference they will generate will not be more than the regulated value (Clancy, 2007). Interference temperature management uses two models to address interference temperature measurement. These are the ideal and the generalized models (Kokare and Kamble, 2014).

The ideal model assumes the knowledge of the radio frequency characteristics that is the particular frequency and bandwidth of licensed signal. The generalized model assumes that the unlicensed user is without the knowledge of the radio frequency characteristics therefore, the measurement of interference temperature limit is done considering the whole frequency band.

The value of interference temperature limit is given by the equation

$$T_I(f_i, B_i) + \frac{Mi\,P}{KBi} \leq T_L \qquad \text{-------- (2.1)}$$

T_I = the interference temperature in Kelvins

f_i = Frequency measured in Hertz

B_i = Bandwidth measured in Hertz

M_i = effect of attenuation factor between transmitter and receiver

P_I = the average interference power in Watts

T_L = the interference temperature limit in Kelvins.

K = Boltzmann's constant (1:38 x 10^{-23} J/K)

The eventual goal of measuring interference temperature is to ensure that the interference of the environment with that generated by the unlicensed transmitter should not be more than the regulated limit.

2.8 IEEE 802.22 Standard Specifications

The IEEE Standard 802.22 defines the procedures for operation of cognitive radios in VHF and UHF television broadcast bands between 54 MHz and 862 MHz (IEEE Std

802.22a™, 2014). The most prominent target application of IEEE 802.22 Wireless Regional Area Networks (WRANs) is wireless broadband access in rural and remote areas.

The topology of IEEE 802.22 specifies a fixed point-to-multi point wireless air interface. A base station (BS) which manages its own cell transmits in the downstream direction to all associated consumer premise equipment which responds back to the BS in the upstream direction. The BS ensures that the cell performs distributed sensing of different TV channels to be aware of the availability of the channels. The spectral efficiencies specified are in the range of 0.5 bit/(sec/Hz) up to 5 bit/(sec/Hz) in a 6 MHz TV channel corresponding to a data rate of 18 Mbps. A total of twelve simultaneous users have been considered which leads to 1.5 Mbps and 384 kbps per CPE in the downstream direction and the upstream direction respectively. The BS coverage range, is up to 100 Km at 4 Watts CPE effective isotropic radiated power (EIRP) (Mody and Chouinard , 2010). IEEE 802.22 uses Orthogonal Frequency Division Multiplexing (OFDM) as transport mechanism and different modulation methods like QPSK, 16-QAM and 64-QAM are supported (Cordeiro *et al.*, 2006). The standard also supports Time Division Duplex (TDD) frame structure (Mody and Chouinard , 2010).

For each CPE radio, the standard specifies the use of two separate antennas. The first one is for directional communication between BS and CPE and the other Omni-directional for sensing licensed transmissions. The BS leaves a radio frequency band if primary signals are detected above the threshold values. For DTV the threshold is -116 dBm, for analogue TV it is -94 dBm and for wireless microphones the threshold is -107 dBm measured in a 200 KHz bandwidth (Cordeiro *et al.,* 2006). Figure 2.9 compares the standard with other wireless standards.

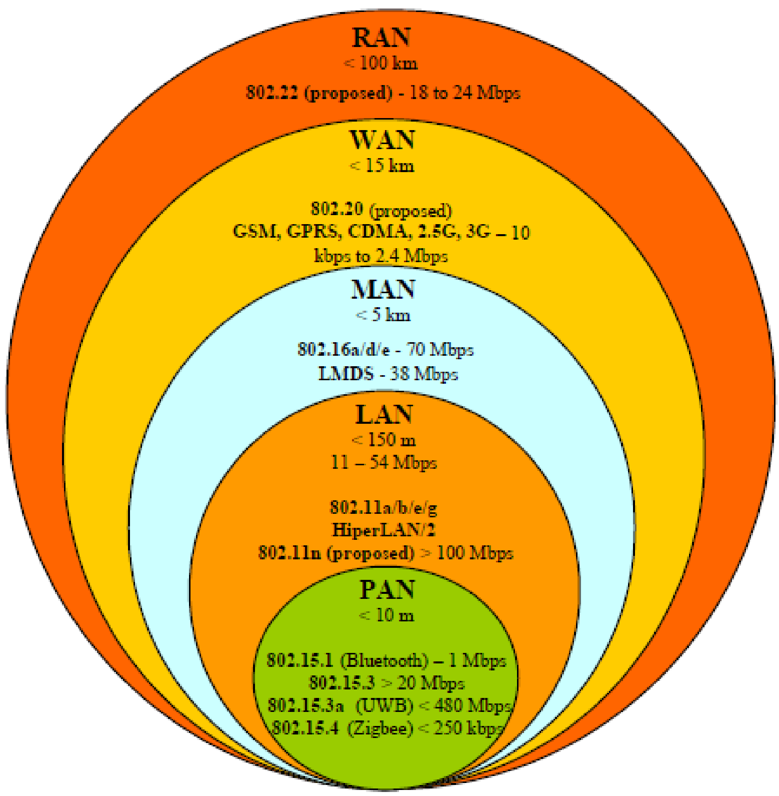


Figure 2.9: 802.22 WRAN Networks versus Other Standards
Source: (Cordeiro *et al.*, 2006).

Link budget analysis has shown that it would be difficult to meet the 802.22 requirements of about 18 Mbps at minimum service coverage of 30Km by using just one TV channel for transmission (Cordeiro *et al.,* 2006). The use of channel bonding by aggregating contiguous channels allows this requirement to be met (Rehmani *et al.,* 2012, Bukhari *et al.,* 2016). Channel bonding (CB) is a technique through which multiple contiguous channels can be combined to form a single wide band channel. There are two channel bonding schemes namely, contiguous channel bonding and non-contiguous channel bonding. This research adopts the contiguous channel bonding because of its simplicity. Radio frequency bandwidth is limited to three contiguous channels only and for 6 MHz TV channels; this implies a bandwidth of 18 MHz.

2.9 Television Spectrum

TV band has been identified as one of the licensed band that is underutilised. The VHF and especially the UHF bands are highly attractive to newer technologies because of their propagating characteristics. Lower frequencies are affected more by atmospheric noise and higher frequencies are susceptible to attenuation making the UHF band desirous for telecommunication. More so, this band is also underutilised at many locations at some point in time as there are several spaces within these spectrum bands that are not used by licensed television services. In Nigeria, according to Gbenga-Ilori and Sanusi (2014), 75.1% of the channels in the VHF and UHF bands are available as TV white space in all the states as shown in Figure 2.10.

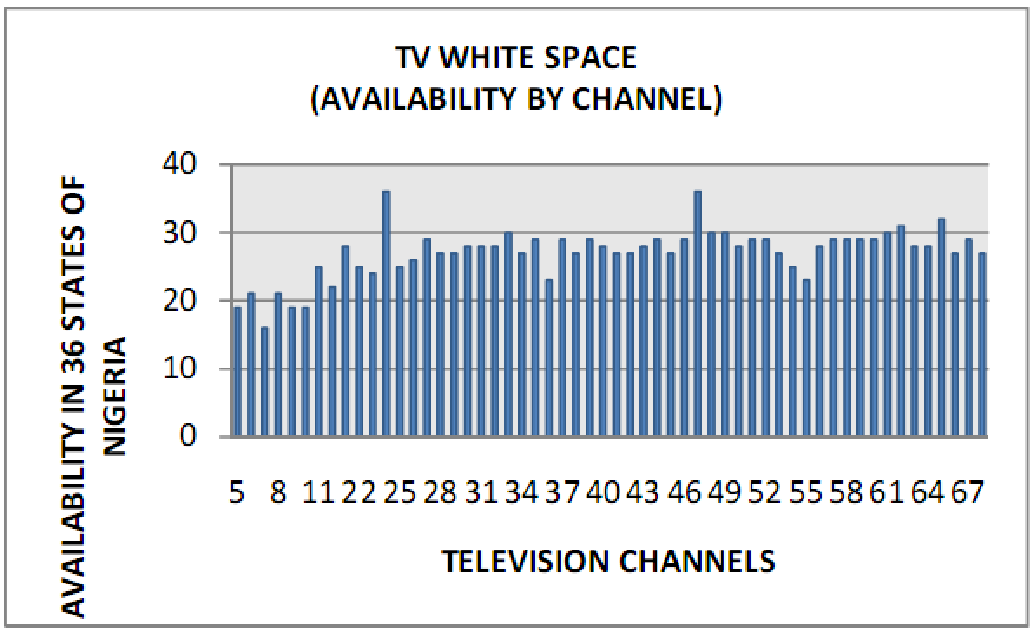


Figure 2.10: Available TV White Space by Channel
(Source: Gbenga-Ilori and Sanusi, 2014)

However, the use of these bands for broadcast services is regulated by the GE-06 agreement which contains frequency plans for both analogue television and digital television services. The TV channel plan for the VHF and UHF bands is based on 6 MHz frequency channels numbered 2 to 69 covering a frequency range of 54MHz to 862MHz. It should be noted that in some countries, not all the internationally allocated spectrum is available for broadcasting. For example, in US television operates from channel 2 to 69 in VHF and UHF, in Argentina and Chile UHF channels 14-20 inclusive are not currently available, in Nigeria channels 2 to 7 are being utilised for land mobile broadcasting for cordless systems. Appendix A shows that TV bands in Nigeria falls in the segment 2 and segment 3 of National Frequency Allocation Table 2014.

The decision of spectrum managers to mandate the switchover to digital television (DTV) is because of the numerous benefits to be derived in using this limited resource. DTV is more efficient than analogue television in terms of spectrum efficiency because the format of DTV signals allows data compression for lower bandwidth requirement thereby transmitting more programs over the same frequency used by one analogue television. The digital switch over is expected to open up more spectrum in the TV band for other wireless usage. DePardo *et al.* (2007) presented a feasibility study of secondary transmissions into the TV spectrum, and concluded that if properly implemented, secondary transmission in the television band is possible without significant impact upon DTV reception. With this possibility, television bands can have improved spectrum utilisation.

Although, there are handfuls of disadvantages of DTV signals, the long term benefit makes it imperative to switch over from analogue signal to digital signal. The Table 2.4 gives a summary of advantages and disadvantages of DTV signals according to Cochran (2010).

Table 2.4: Advantages and Disadvantages of DTV signals (Source: DePardo et al., 2007)

Advantages	Disadvantages
1. Long term operating costs can be lower 2. Better delivered signal quality 3. Ability to tailor channels for greater range or greater capacity 4. Ability to offer more channels (programming) in the same bandwidth/spectrum 5. Greater flexibility in delivered audio/video quality 6. Can free up valuable spectrum for police/fire/safety or other applications 7. Greater control over Digital Rights Management	1. Initial cost of start-up/transition to DTV can be expensive 2. Not as resistant to multipath interference as analogue networks 3. Signal quality does not degrade gracefully as in an analogue system 4. Additional planning is necessary depending on type and mix of content offered 5. Additional planning is necessary to achieve required signal to noise ratio

CHAPTER THREE

METHODOLOGY

This chapter presents a step by step approach adopted to design a cognitive radio network that will be able to achieve the aim and objectives of this research. Also, it presents the mathematical formalism of the developed model and details of simulated parameters.

3.1 Existing Models

Different approaches have been followed to implement the overlay and the underlay models in cognitive radios. This research used the matched filtering approach for the overlay and the interference temperature management defined by the FCC for the underlay. The existing model implemented for the overlay using matched filtering method is shown in Figure 3.1 where the DTV signal to be detected is received and converted to digital from analogue.

The signal is processed by the matched filter with impulse response h(t) using the transmitted DTV pilot signal p(t) for synchronisation because the matched filter needs to have a prior knowledge of the DTV signal. Sampling of the output of the matched filter is done and this is compared to a set threshold, in this case -116 dBm for DTV signal as stated in IEEE Std 802.22a™ (2014). A decision to transmit is made if the sampled output is above the threshold otherwise, it will decide to vacate the channel. The disadvantage is that it does not allow cognitive radios to transmit even if transmission may not cause harmful interference when the DTV signal is present. Figure 3.2 shows the flowchart of the model.

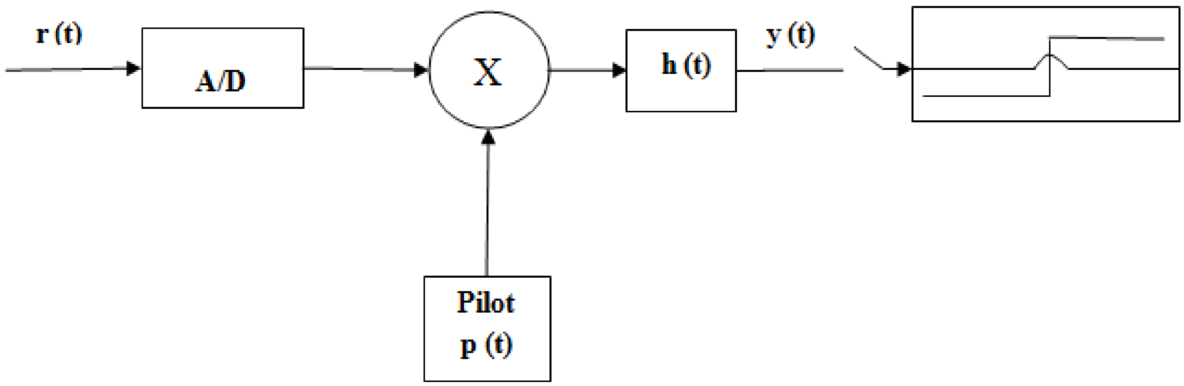


Figure 3.1: Overlay Model using Matched Filter (Source: Wild and Ramchandran, 2004)

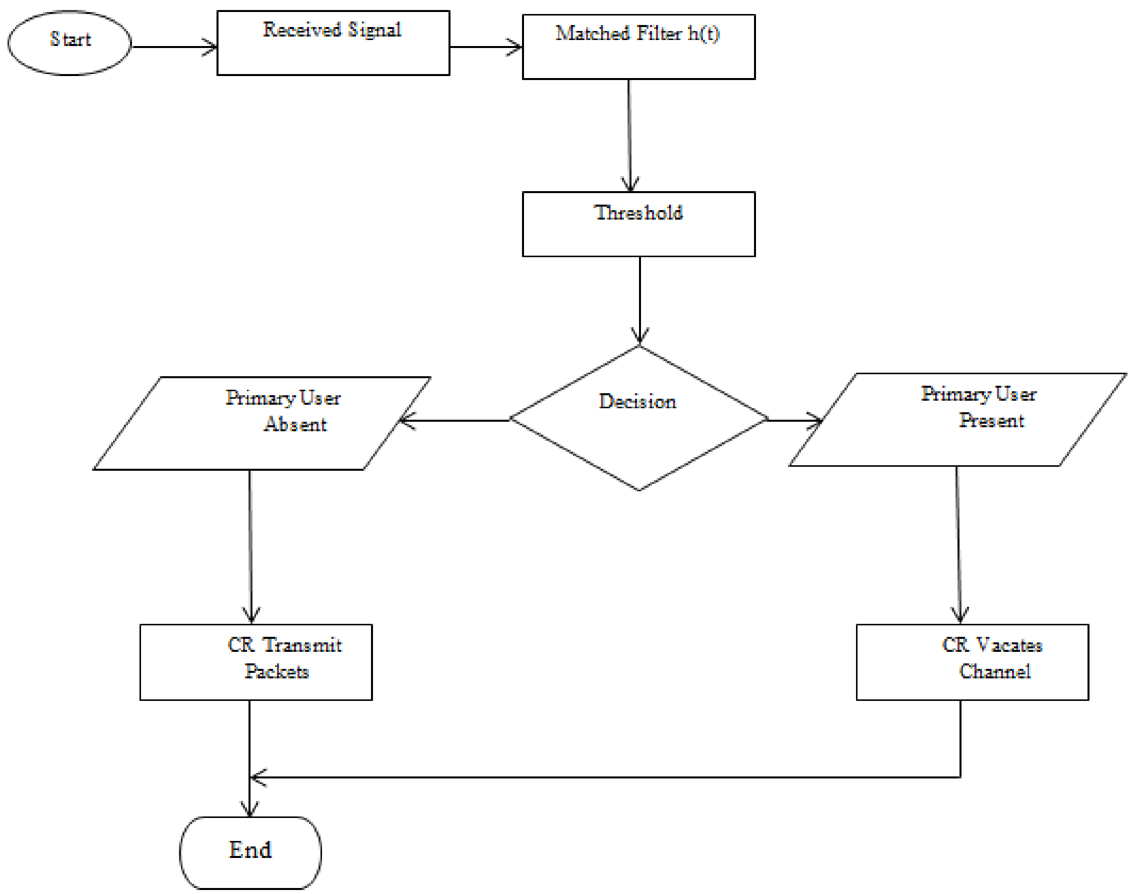


Figure 3.2: Flowchart of Matched Filter Detection

The existing model for the underlay as proposed by FCC is presented Clancy (2007) using Interference Temperature Multiple Access (ITMA) protocol as shown in Figure 3.3. The model measures the interference temperature T_I to be contributed by the cognitive radio to ensure that it will not transmit above the interference temperature limit. After measuring the $T_{I,}$ other transmission parameters are determined for optimum transmission. The disadvantage is that even at the non-detection of the signal of the primary user, the transmission is still constrained by the interference temperature limit.

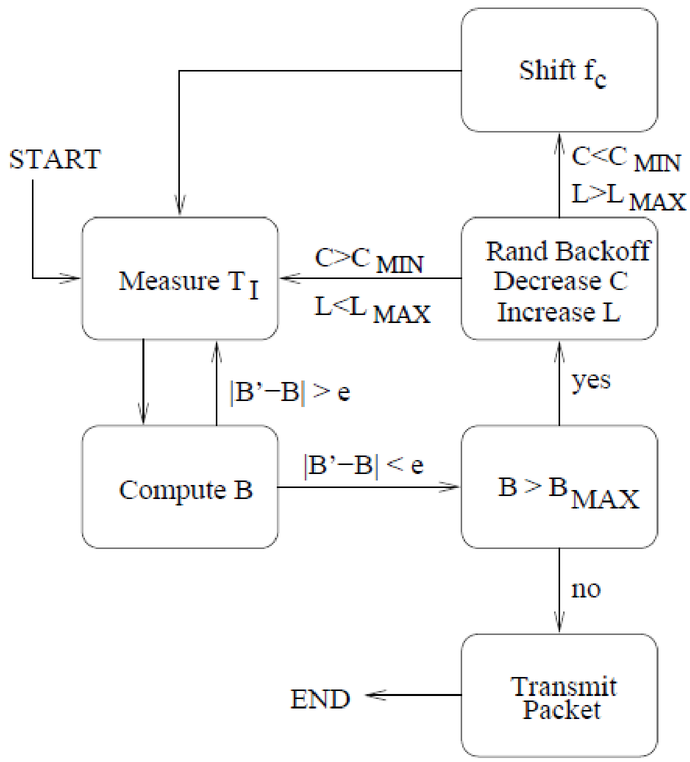


Figure 3.3: Underlay Model using Interference Temperature Management
(Source: Clancy, 2007)

3.2 MAFITM Model

The MAFITM model is an improvement on the existing Matched Filtering and Interference Temperature Management models. The reasons for choosing these two existing models are important and specific to IEEE.802.22. Firstly, literatures have confirmed that Matched Filtering has the highest accuracy of detecting primary user signals but also with the highest complexities while Energy Detection has the lowest accuracy but also the simplest in terms of implementation (Verma *et al.*, 2012; Shobana *et al.*, 2013; Salem *et al.*, 2014; Sharma and Saini, 2014; Varalakshmi *et al.*, 2016).

The complexity of implementing Matched Filtering is because of the complexities of implementation of many matched filters for detecting different PU signals that may be present in a wide band spectrum. What this means is that for PU signals to be detected, the number of PU signals will determine the number of matched filters to be used and each of the filters must have a previous awareness of each of the PU signal present in the wide band spectrum. The weakness of energy detection is remedied by using it with another detector. Most literatures considered the sensing technique of energy detection, together with cyclostationary feature detection to improve probability of detection of PU signals.

Secondly, the use of Interference Management Temperature for underlay is worthwhile because it is specified by Federal Communications Commission of United States of America as means of controlling the interference produced by CRs against PUs. There are other CR transmitter power controls to regulate interference to PU signal as discussed in Rong and Zhu (2011), Kailas *et al.* (2015), Bhowmick, et al. (2016), and Kaushik, *et al.* (2016), however the simplicity of implementation of Interference Management Temperature makes it a better choice for this research.

The distinct features of the MAFITM model are the methods of improving spectrum utilisation which focuses on spectrum sharing and the area of application. The method hybridised Matched Filtering and Interference Temperature Management, while the area of application is IEEE 802.22 standard. The applications of CRs in literatures have been practically discussed regarding general wireless systems but this research considered the application of CR in IEEE 802.22 which means that only one type of PU signal is to be detected. This removed the complexity of implementation while the high accuracy of Matched Filtering is utilised.

As discussed in section 2.6.3, there have been the developments of other models in cognitive radios with Tables 2.3a – 2.3c showing the summary. As at present, no known literature has applied these other approaches to IEEE 802.22. Khobragade and Raut (2017) that developed a spectrum sensing method with five spectrum sensing techniques which include Match Filter detector, Energy detector, Generalized Likelihood Ratio Test (GLRT), Robust Estimator Correlator and Temperature based detector focussed on spectrum sensing problem. The area of application of the work is general wireless networks and performance metrics used include detection accuracy, complexity, robustness, and flexibility of design choices.

The reason for applying this technique to this standard is to extend the standard to urban areas where there is likelihood of higher DTV spectrum usage, because as at present, the standard is only defined for rural application where there is likelihood of free DTV spectrum.

For simplicity Figure 3.4 is adopted to create three scenarios thereby developing a conceptual framework for the three models. The figure shows a cognitive radio node (CR_i) within the coverage of a cognitive radio access point CR_{AP} and a DTV transmitter. The distance of CR_i from the primary user transmitter is x km and its distance from its access point CR_{AP} is y km, the distance between primary user transmitter and CR_{AP} is z km. Thus, the position of CR_i is represented within the model as $CR_i <x_i, y_i>$. For the MAFITM model, with License signals' absence, a cognitive radio CR_i uses the available 'N' number of TV frequency bands without constraint and when license signals reappears, the CR_i continues to use the bands but with constraints guided by appropriate reduction in CR_i transmitting power P_{cri} to prevent the impairment of the primary user. In implementing this network model, the presence or absence of the primary user signals must be confirmed. In a case where the presence of the primary signal is confirmed, the interference temperature must be measured to determine the appropriate parameters for the transmission of secondary signal. Figure 3.5 shows the architecture of the MAFITM model, while Figure 3.6 shows the step by step procedures of its operations through a flowchart. Both cognitive radio node and cognitive radio access point sense their environment to detect the presence of licensed user signal. If licensed signal is not detected, then communication between the two radios is initiated. With detection of a licensed signal, the cognitive radios compute the appropriate transmission power and then test if transmission will be possible at that transmission power. If the signal strength is greater than the minimum detectable signal, communications occur between the two radios otherwise, the radios will have to shift to another frequency band to start again the process of detecting a favourable frequency band that could be used for transmission. This model, as shown in Figure 3.7 will reduce idleness of licensed television frequency bands whenever the primary user is not using it.

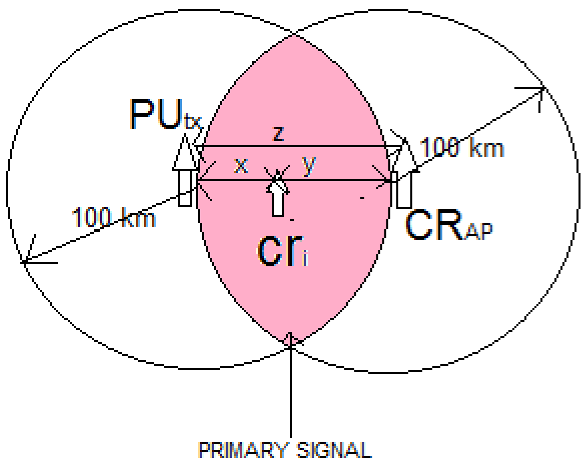


Figure 3.4 Conceptual Framework for the Three Models

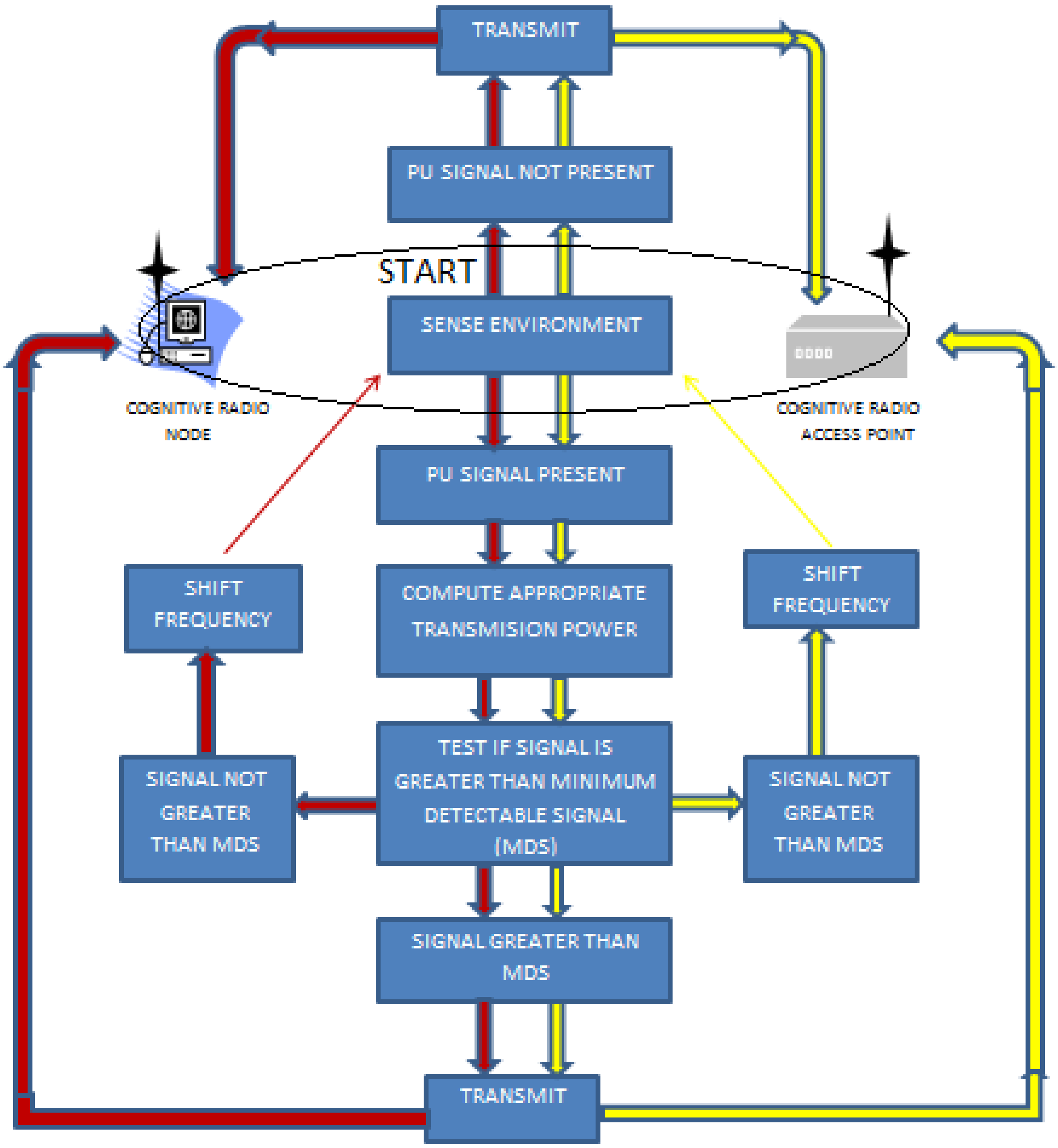


Figure 3.5: Architecture of the MAFITM Model

Legend: Signal Flow of Cognitive Radio Node

Signal Flow of Cognitive Radio Access Point

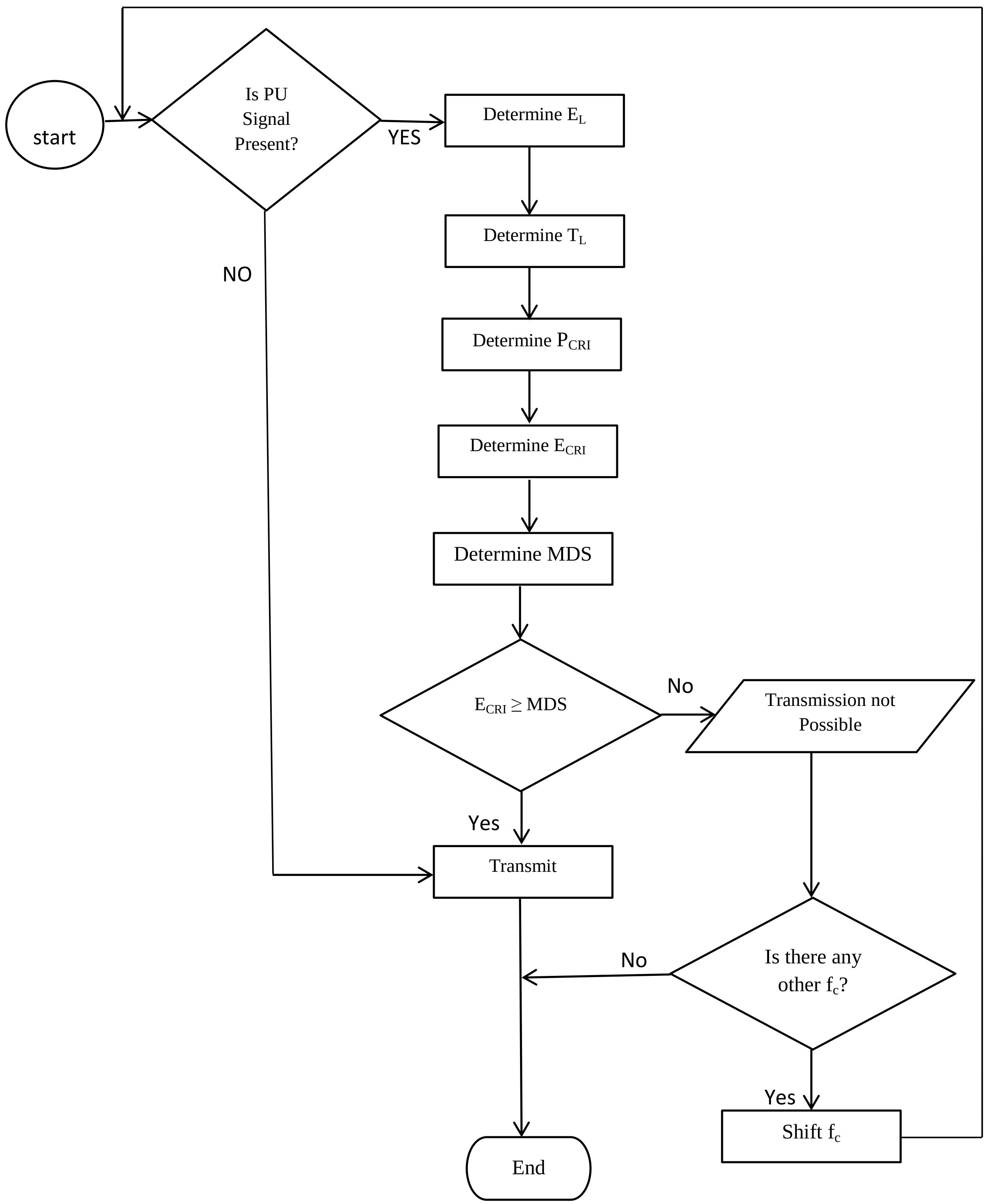


Figure 3.6 Flowchart of the MAFITM model

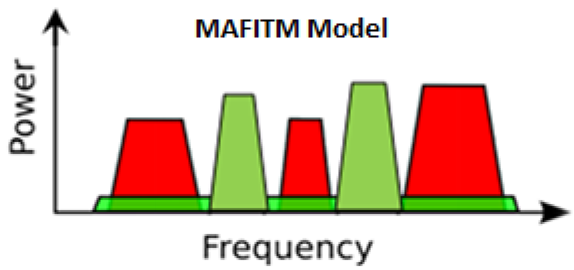


Figure 3.7: Coexistence of Primary and Secondary Users in the MAFITM Model

Legend: Unlicensed Users

Licensed Users

The algorithm is described through the following steps

Step 1: Test for primary signal

E_p is measured as the power in watts of the TV signal received at distance x_i at the centre frequency f_i. The flux density and link equation can be used to calculate the power received:

$E_p = \phi \times A$ .... (3.1)

where ϕ = flux density = $\frac{EIRP}{4\pi x^2} = \frac{P_t G_t}{4\pi x^2}$ (W/m²)

EIRP = effective isotropic radiated power of DTV transmitter

P_t= Power of DTV transmitter; G_t=Gain of DTV transmitter

A = area of antenna = $\frac{Gr\lambda^2}{4\pi}$ (m^2)

Where Gr= cognitive radio receiver antenna gain

λ = wavelength of the signal = $\frac{c}{f}$

where c = speed of light in air = 3×10^8 m/s

$\therefore$ $E_p = \frac{P_t G_t G_r}{(4\pi x f/c)^2}$............ (3.2)

Equation (3.2) is the link equation where $(4\pi x f/c)^2$ is the path loss. Assuming a gain of 0 dBi for both G_t and G_r, which implies that the entire signal at the antennae is fully utilised, equation (3.2) reduces to

$E_p = \frac{P_t}{(4\pi x f/c)^2}$ .... (3.3)

E_p is the signal to be detected by the matched filter and is equivalent to r (t) which is the sum of the signal s(t) to be detected and the noise n(t). This is illustrated in Figure 3.1. The signal at the output of the filter, at the observing instant t is given by

$y_t = \frac{2E_p}{N_0}$ -------- (3.4)

where N_0 is the Noise Figure of the frequency band

y_t is then compared with a threshold power 'P_L' to determine the presence of primary signal. IEEE Std 802.22a™ (2014) specified that a cognitive radio vacates a DTV channel if primary user signals are detected above -116 dBm.

If $\frac{2E_p}{N_0} \geq P_L$, then the presence of a primary signal is confirmed otherwise primary signal is absent. The transmitting power of CR_i will then be maximum allowable power. IEEE Std 802.22a™ (2014) specifies a maximum transmitting power $P_{cri(max)}$ of 4 W for cognitive radios.

Step 2: Measurement of Interference Temperatures

Adopting the interference threshold ($\Delta T/T$) of 5% of PU signal as stated in 'FCC 03-289' (2003), as allowable interference, the energy of the interference caused by cognitive radio 'E_{Lcri}' is determined as:

$E_{Lcri} = 0.05 \times y_t$ -------- (3.5)

The interference temperature limit 'T_{Lcri}' is determined as:

$T_{Lcri} = \frac{E_{Lcri}}{B_i K}$ -------- (3.6)

A cognitive radio node 'CR_i' will have to compute the equivalent interference temperature 'T_{cri}' that will be introduced by cognitive radio transmission. 'T_{cri}' is then used to determine the appropriate transmission power 'P_{cri}' of the cognitive radio that will ensure that the primary user signal is not degraded. The computation is as follows:

$T_{cri} = T_{Lcri} - T_I$ -------- (3.7)

Where T_I is the interference temperature due to the noise power in the channel bandwidth

Thus, the allowable transmission power of CR_i is given as:

$P_{cri} = T_{cri} \times B \times K$ -------- (3.8)

Step 3: Test Successful Transmission

For a successful transmission, the energy of the signal 'E_{cri}' of CR_i received should be greater than or equal to the energy of minimum detectable signal $E_{cri(mds)}$ of CR_i.

$$E_{cri} = \frac{P_{cri}}{(4\pi y f/c)^2} \text{-------- (3.9)}$$

To know the minimum power level at which a system receiver can detect an incoming signal, the minimum detectable signal (MDS) corresponds to the noise floor of system receiver which is determined by the noise power, $N_P = KT_IB$. This is then converted to dBm to derive an expression for the minimum detectable signal $E_{cri(mds)}$ of CR_i as follows:

$E_{cri(mds)} = 10 \log_{10} KT_IB$. -------- (3.10)

If $E_{cr\,i} \geq E_{cri(mds)}$ then transmission is successful otherwise it is not. The Pcri that satisfied the condition will now be used by CR_i to transmit packets.

3.3 Simulation Parameters

To simulate the above algorithm, the parameters of the variables needed are selected based on the interference temperature criteria, Management Information Base (MIB) for cognitive radio and DTV standard. These parameters are discussed briefly in this section.

The interference threshold ΔT/T is a criterion used by the International Telecommunications Union (ITU) and it is a measure of the amount of interference that can be tolerated by a licensed system. ΔT/T corresponds to the interference to noise ratio and the conservative analysis is based on a ΔT/T threshold equal to 5 % as given in FCC 03-289 (2003).

For Underlay transmission, the interference temperature limit is determined by using the minimum transmission power of cognitive radio of -64 dBm to produce the minimum interference.

$$T_L = \frac{Pcri}{KB} \quad \text{-------- (3.11)}$$

Where P_{cri} = -64 dBm, K= 1.38X 10^{-23} J/K and B (Bandwidth) using three 6 MHz TV contiguous channels = 18 MHz

Therefore $T_L = \frac{10^{-6.4} \times 10^{-3}}{1.38 \times 10^{-23} \times 18 \times 10^{6}} = 1.6 \text{ X } 10^{6}$ K

According to IEEE 802.22 standard, the cognitive radio vacates a channel if primary user signal is detected above -116 dBm, therefore this value is selected as the PU signal detection threshold.

The transmission power of cognitive radio is specified to be in the range of 63.5 dBm maximum and -64 dBm minimum (IEEE Std 802.22a™, 2014). However, the IEEE 802.22 standard group has limited the maximum cognitive radio transmission power to 36 dBm. Therefore, -64 dBm and 36 dBm are selected as the minimum and maximum transmission power of cognitive radios, respectively.

TV operates from channel 2 to 69 in VHF and UHF bands. Each channel is 6 MHz wide giving a total frequency range of 54 to 862 MHz. This range is divided into five bands and a centre frequency is taken from each band for simulation. The centre frequencies selected are 66 MHz in band I, 82 MHz in band II, 196 MHz in band III, 470 MHz in band IV and 830 MHz in band V.

The minimum detectable signal (MDS) is the receiver's sensitivity to incoming signal. The MDS is taken to be the noise floor of receiver systems and is determined as follows

MDS $=10\log_{10}(K \times T_I \times B)$ -------- (3.12)

Where K= Boltzmann's constant (1.38×10^{-23} J/K)

T_I=Absolute Temperature 290K

B= bandwidth (18 Mhz)

MDS= 7.94×10^{-11} mW = -101 dBm

= 7.94×10^{-14} W = -131 dBW

Noise figure values typically vary over a convenient range between 1 dB and 15 dB (Loy, 1999). Considering the range of frequencies for this research that is 54 to 862 MHz, the frequency fall into third category of frequency range where the noise figure that covers 100 MHz to 100 GHz is less than 10 dB (ITU-R P.372-8, 2003; Hasan and Ellingson, 2007). For an additive white Gaussian noise, a noise figure of 5 dB is assumed appropriate for this frequency range.

Television transmitters produce effective isotropic radiated power which ranges from 100 W to 50 KW. To model a low PU signal a transmission power of 100W is assumed and to model a high power, 10 KW and 50 KW are taken as the transmission powers.

A time factor T_{ON} is used to express a time 't' where there is intermittent ON and OFF of the PU signal. T_{ON} = 1 means that for the entire time 't' under consideration, the PU signal is present. T_{ON} = 0 implies that for the entire time 't' under consideration, the PU signal is absent. The percentage of time for which PU signal is either ON or OFF is expressed as a fractional value between 1 and 0. The values of T_{ON} selected are 0, 0.2, 0.4, 0.6, 0.8, and 1.0.

The Single Entry Interference (SEI) protection criteria for Fixed Satellite Service (FSS) carriers, which has been developed on the basis of the relevant ITU-R Recommendations is taken to be 12.2 dB (Tham, 2014). This is used to determine the margin of carrier to interference ratio.

The summary of the simulation parameters is given in Table 3.1.

Table 3.1: Simulation Parameters

Simulation Parameters	Symbols	Value
Interference Threshold	$\Delta T/T$	0.05
Interference Temperature Limit	T_L	1.6×10^6 K
PU Signal Detection Threshold	PU_{TRE}	-116 dBm
Maximum radio power	$PCRI_{MAX}$	36 dBm
Minimum radio power	$PCRI_{MIN}$	-64 dBm
Minimum Detectable Signal	MDS	-101.5 dBm
Centre frequency	f_c	66, 82, 196, 470, 830 MHz
CR bandwidth	B	18 MHz
Noise figure	N_O	5 dB
Absolute Interference Temperature	T_I	290 K
PU Transmit Power	PU_{EIRP}	100 W, 10 KW, 50 KW
Distance between CR Access Point and PU Transmitter	y	5 Km
Distance between CR Access Point and CR Node	x	0 – 100 Km
Time Factor	T_{ON}	0, 0.2, 0.4, 0.6, 0.8. 1.0
Single Entry Interference Protection Criteria	$C/I_{required}$	12.2 dB

3.4 Performance Metrics

Each of the three scenarios that described the two existing models and the developed models is to be compared based on the following performance metrics.

3.4.1 Data Rates

This is the average data transfer measured in each of the model. It describes the achievable capacity that could be obtained in the respective models. Data rate is expressed using the Shannon-Hartley theorem of channel capacity:

$$C = B\ log_2\ (1 + \frac{M_i P_{cri}}{(KBT_I + E_p)})\ \text{b/s}\ \text{--------}\ (3.13)$$

Where:

$M_i =$ Attenuation factor between CR_i and primary user (depends on distance between primary user transmitter and secondary user transmitter)

P_{cri} = Signal of cognitive radio

E_p = Signal of the licensed TV

KBT_I = Noise floor

3.4.2 Coverage Area

Transmission coverage area will also be used to compare the models. Assuming line of sight transmission, the modified Friis transmission equation (Shaw, 2013) for free space loss is used to calculate the transmission distance:

$$y = \frac{C}{4\pi f}\frac{\sqrt{P_{cri}}}{\sqrt{E_{cri}}}\ \text{--------}\ (3.14)$$

Where:

P_{cri} = Transmission power of Cognitive radio

E_{cri} = Received signal from Cognitive radio access point

3.4.3 Spectral Efficiency (SE)

This is the amount of information transferred per bandwidth of the CR.

$SE = \frac{C}{B}$ b/s/Hz -------- (3.15)

Where C = Capacity in b/s

B = Bandwidth in Hz

3.4.4 Margin of the Carrier to Interference Ratio

This is used for interference assessment and states the likelihood of the CR signal being a harmful signal or not. According to Tham 2014, margin is calculated as follows:

Margin = $C/i - C/I_{required}$ -------- (3.16)

Where C is the power of the desired carrier, i is the power of the interference signal, C/i is the ratio of the power of the desired carrier to the power of interference signal in dB and $C/I_{required}$ is the single entry interference (SEI) protection criteria for the desired signal in dB. $C/I_{required}$ for digital carrier like DTV as stated in Table 2 of Recommendation ITU-R S 741-2 12.2dB.

3.5 Implementation

The simulator developed has three main modules these are the simulator interface, results frame and model codes. The simulator interface accept input parameters for the simulation, the results frame gives the output of the simulation, while the model codes function at the back end of the simulator for the implementation of the models.

The screenshot of the simulator shown in Figure 3.7 has inputs for entering the transmitting power for the primary user signal, centre frequency to be used for transmission by cognitive radio, distance of cognitive radio access point from primary user transmitter and number of cognitive radio nodes. Figure 3.8 shows the available options of primary user transmitting power in Watts in the screenshot of the simulator, while Figure 3.9 shows the available options of centre frequency of transmission in Hertz.

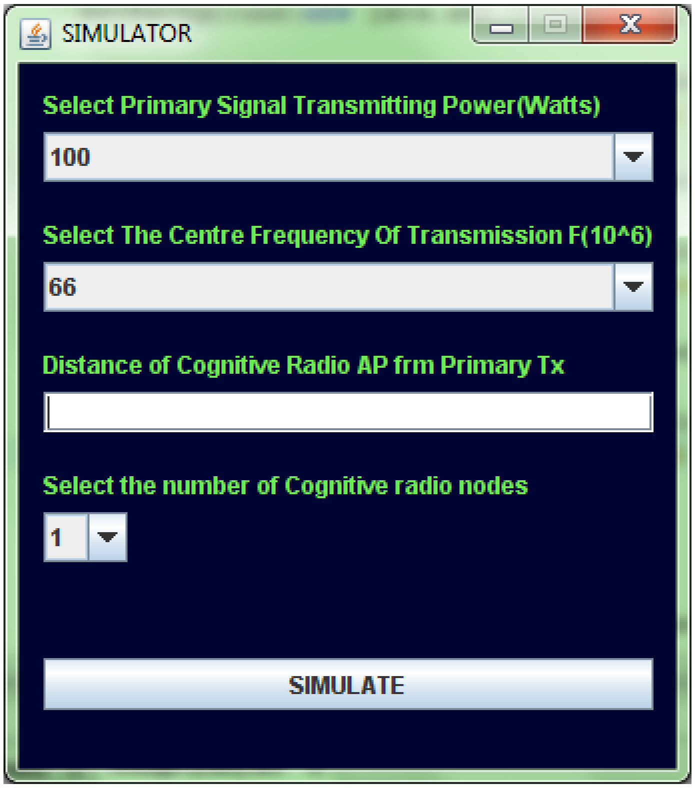


Figure 3.8: Screenshot of the simulator

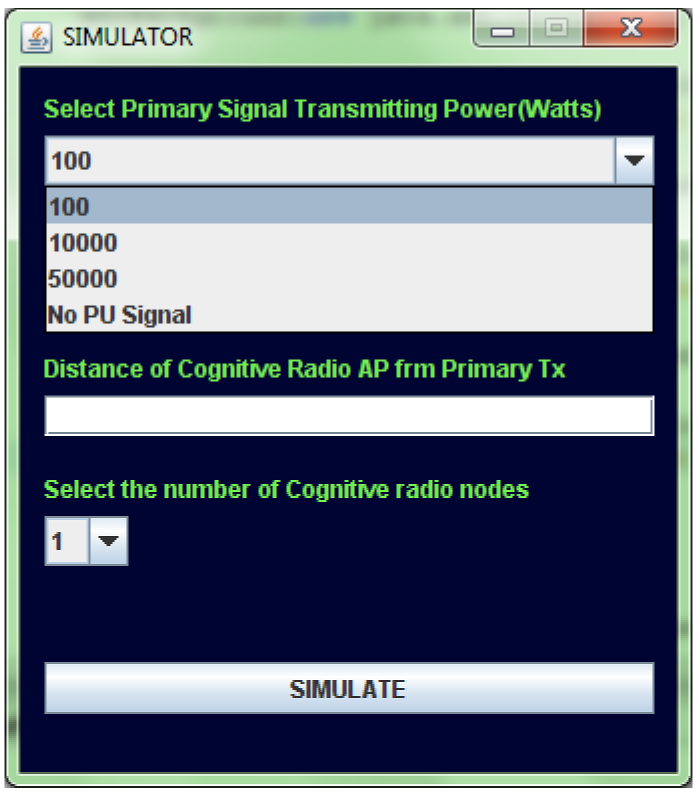


Figure 3.9: Screenshot of the Simulator Showing Available Options of Transmission Power of Primary User Transmitter

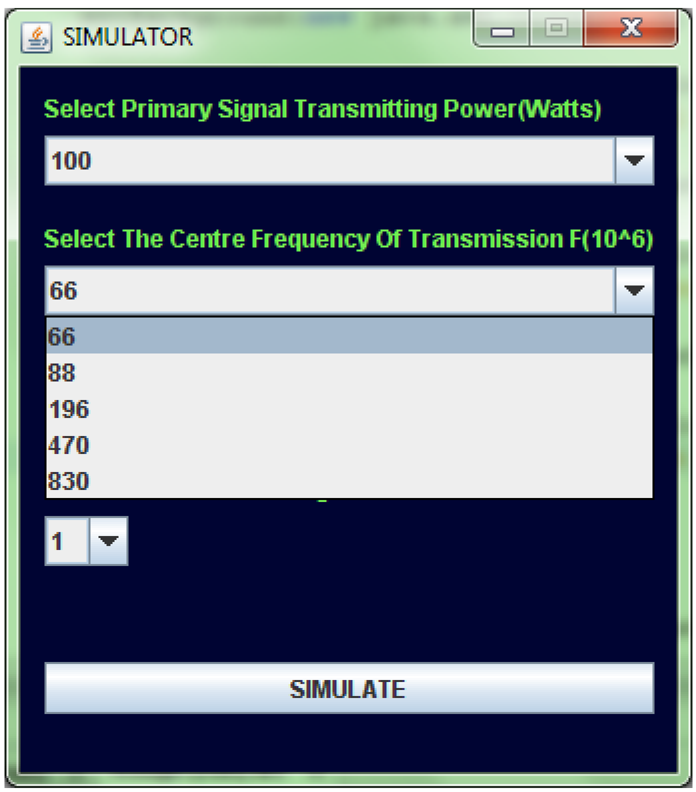
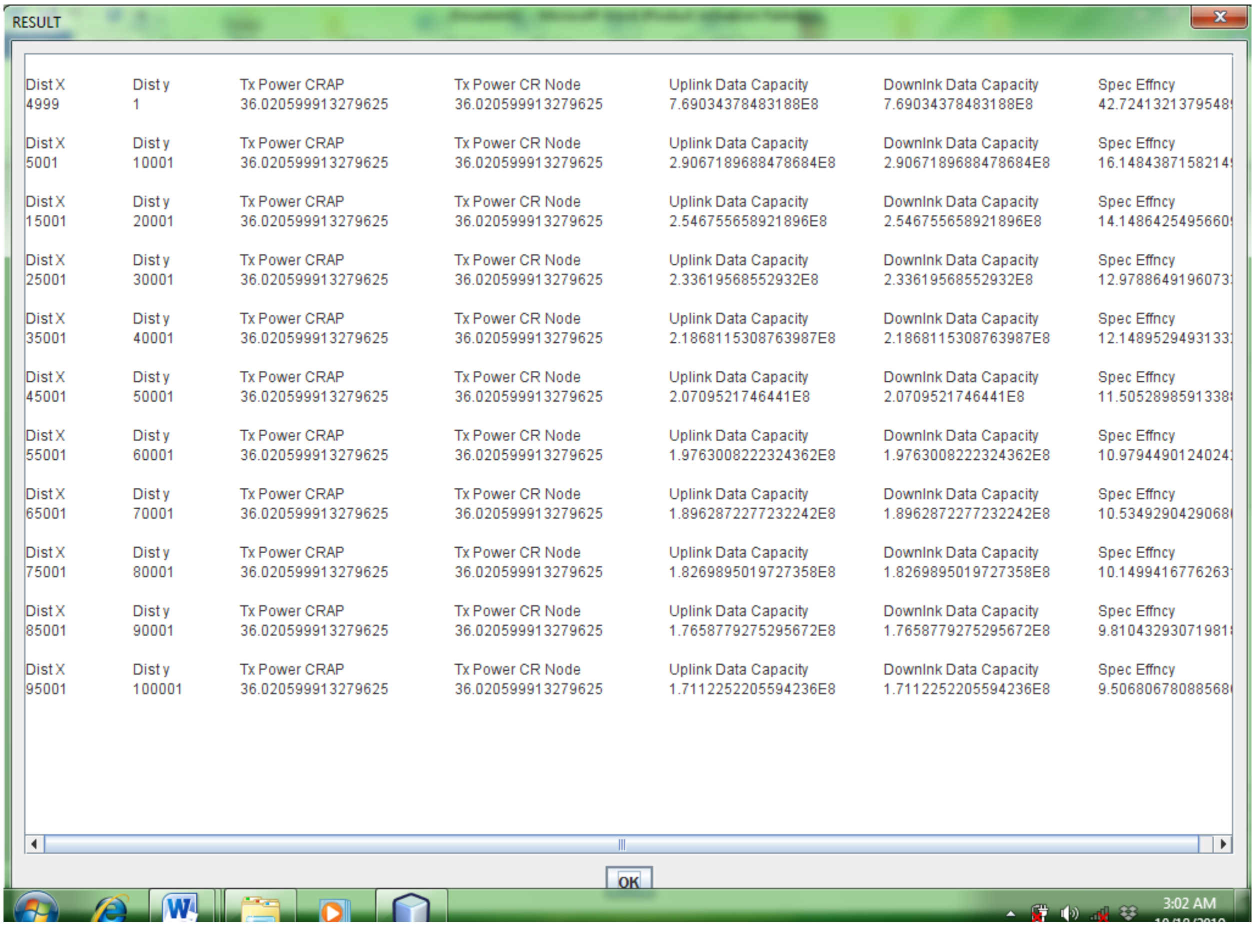


Figure 3.10: Screenshot of the Simulator Showing Available options of Centre Frequency

Few samples of result frames that show the output of the simulated transmission of cognitive radio in the absence and presence of primary user signal are presented. The output of results with “No PU Signal” for transmission power of primary transmitter and 66 MHz for centre frequency of transmission were presented as samples for transmission of cognitive radio in the absence of primary user signal. Figure 3.10 shows the output of simulation for overlay and MAFITM while Figure 3.11 shows that of underlay for these parameters.

The output of results with 100 W and 50 KW for low and high transmission power of primary transmitter, respectively and 66 MHz for centre frequency of transmission are presented as samples for transmission of cognitive radio in the presence of primary user signal. For MAFITM transmission, Figure 3.12 shows the output for low primary user transmission power at 100 W at 66 MHz centre frequency, while Figure 3.13 shows the output for high primary user transmission power at 50 KW at 66 MHz. For overlay, as shown in Figure 3.14, transmission is not possible because overlay transmission does not permit secondary user to transmit when the presence of primary user signal is detected. Figures 3.15 and 3.16 show the output of the underlay transmission for low and high primary user transmission power, respectively.



Dist X	Dist y	Tx Power CRAP	Tx Power CR Node	Uplink Data Capacity	Downlnk Data Capacity	Spec Effncy
4999	1	36.020599913279625	36.020599913279625	7.69034378483188E8	7.69034378483188E8	42.724132137954
5001	10001	36.020599913279625	36.020599913279625	2.9067189688478684E8	2.9067189688478684E8	16.148438715821
15001	20001	36.020599913279625	36.020599913279625	2.546755658921896E8	2.546755658921896E8	14.148642549566
25001	30001	36.020599913279625	36.020599913279625	2.33619568552932E8	2.33619568552932E8	12.978864919607
35001	40001	36.020599913279625	36.020599913279625	2.1868115308763987E8	2.1868115308763987E8	12.148952949313
45001	50001	36.020599913279625	36.020599913279625	2.0709521746441E8	2.0709521746441E8	11.505289859133
55001	60001	36.020599913279625	36.020599913279625	1.9763008222324362E8	1.9763008222324362E8	10.979449012402
65001	70001	36.020599913279625	36.020599913279625	1.8962872277232242E8	1.8962872277232242E8	10.534929042906
75001	80001	36.020599913279625	36.020599913279625	1.8269895019727358E8	1.8269895019727358E8	10.149941677626
85001	90001	36.020599913279625	36.020599913279625	1.7658779275295672E8	1.7658779275295672E8	9.810432930719
95001	100001	36.020599913279625	36.020599913279625	1.7112252205594236E8	1.7112252205594236E8	9.506806780885

Figure 3.11: Screenshot of the Output for Overlay and MAFITM Transmission in the Absence of Primary User using 66 MHz Centre Frequency

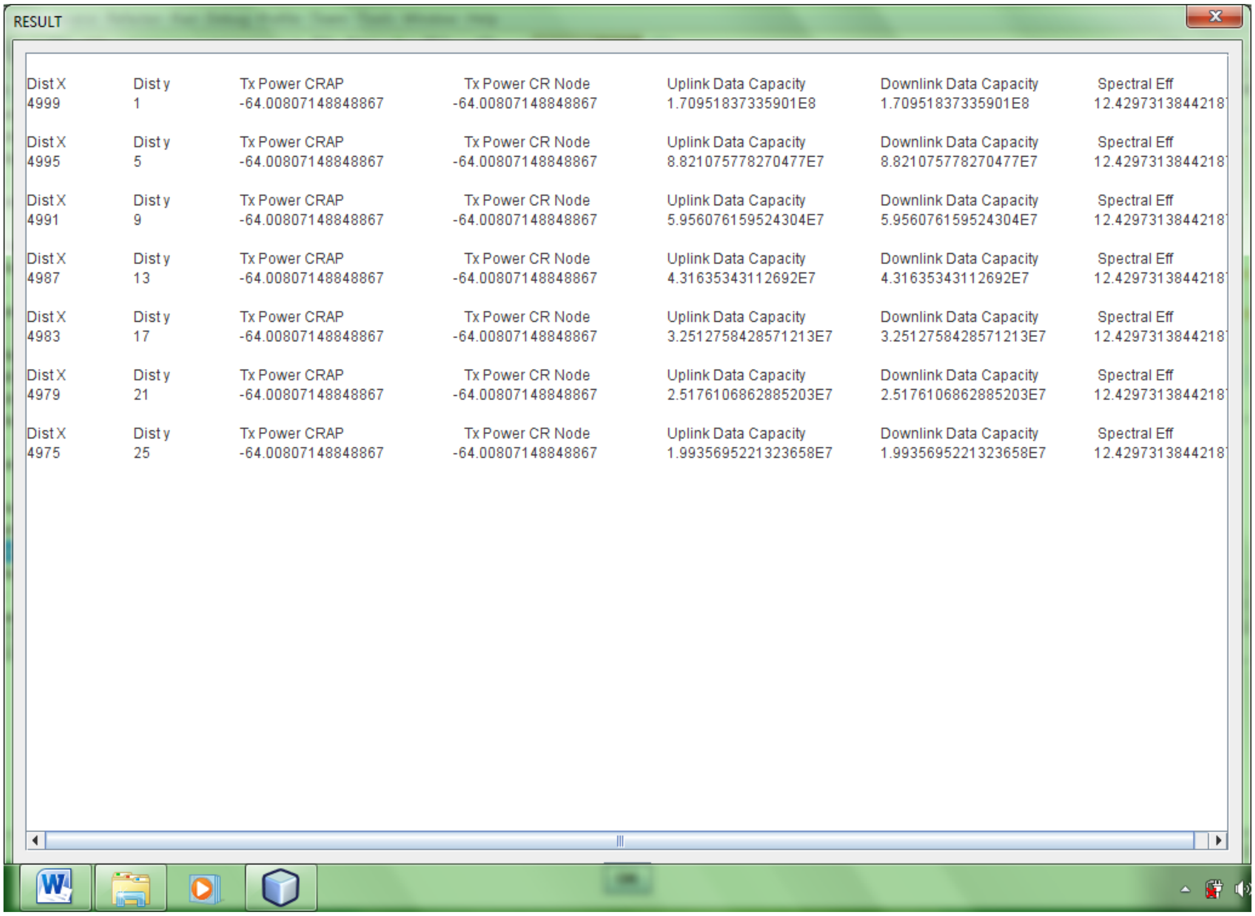


Figure 3.12: Screenshot of the Output for Underlay Transmission in the Absence of Primary User using 66 MHz Centre Frequency

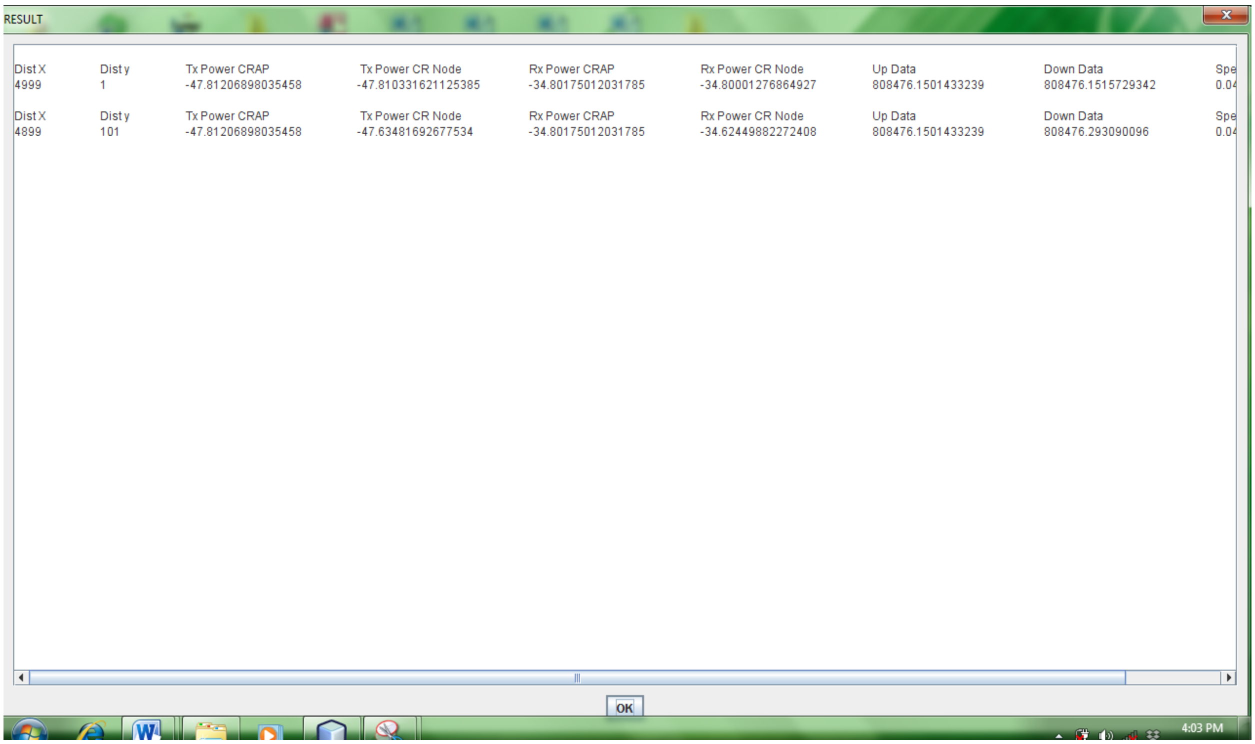


Figure 3.13: Screenshot of the Output for MAFFITM Transmission with Low Primary User Transmission Power of 100 W and 66 MHz Centre Frequency

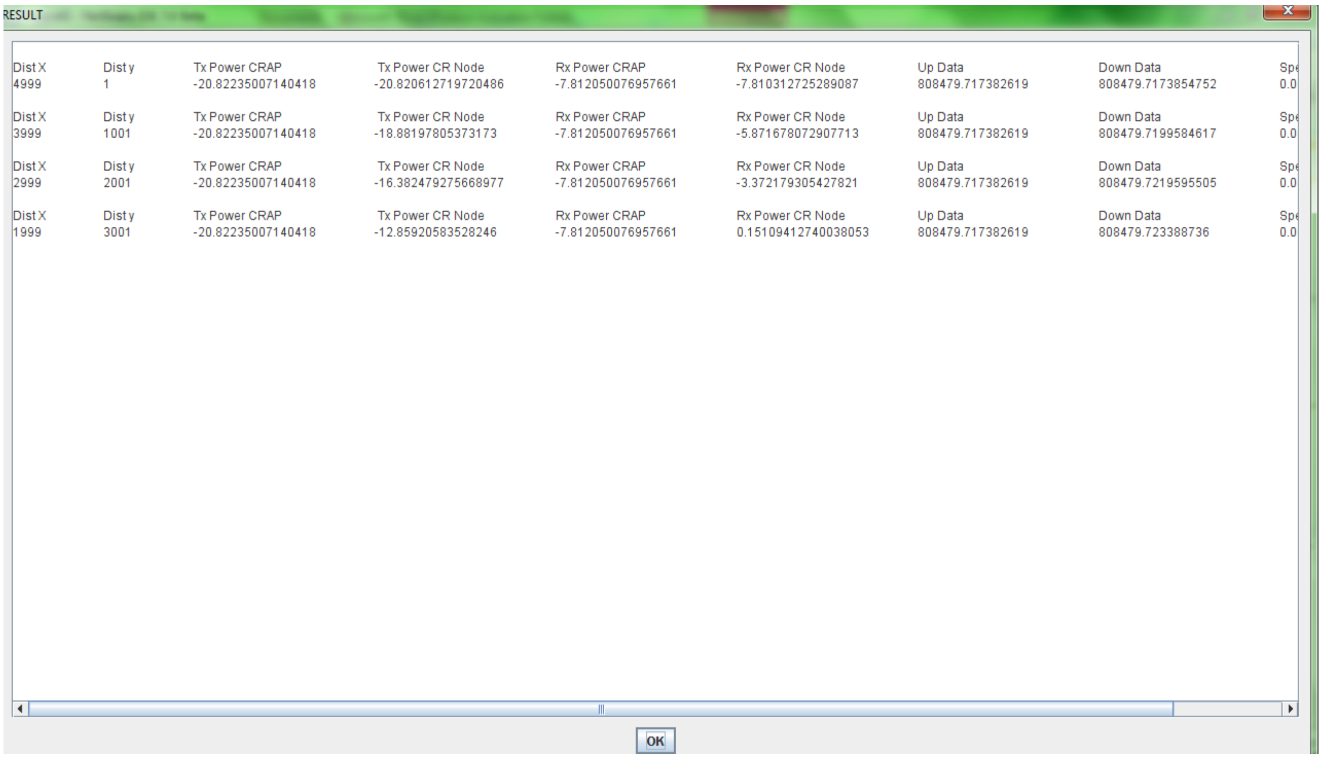


Figure 3.14: Screenshot of the Output for MAFFITM Transmission with High Primary User Transmission Power of 50 KW and 66 MHz Centre Frequency.

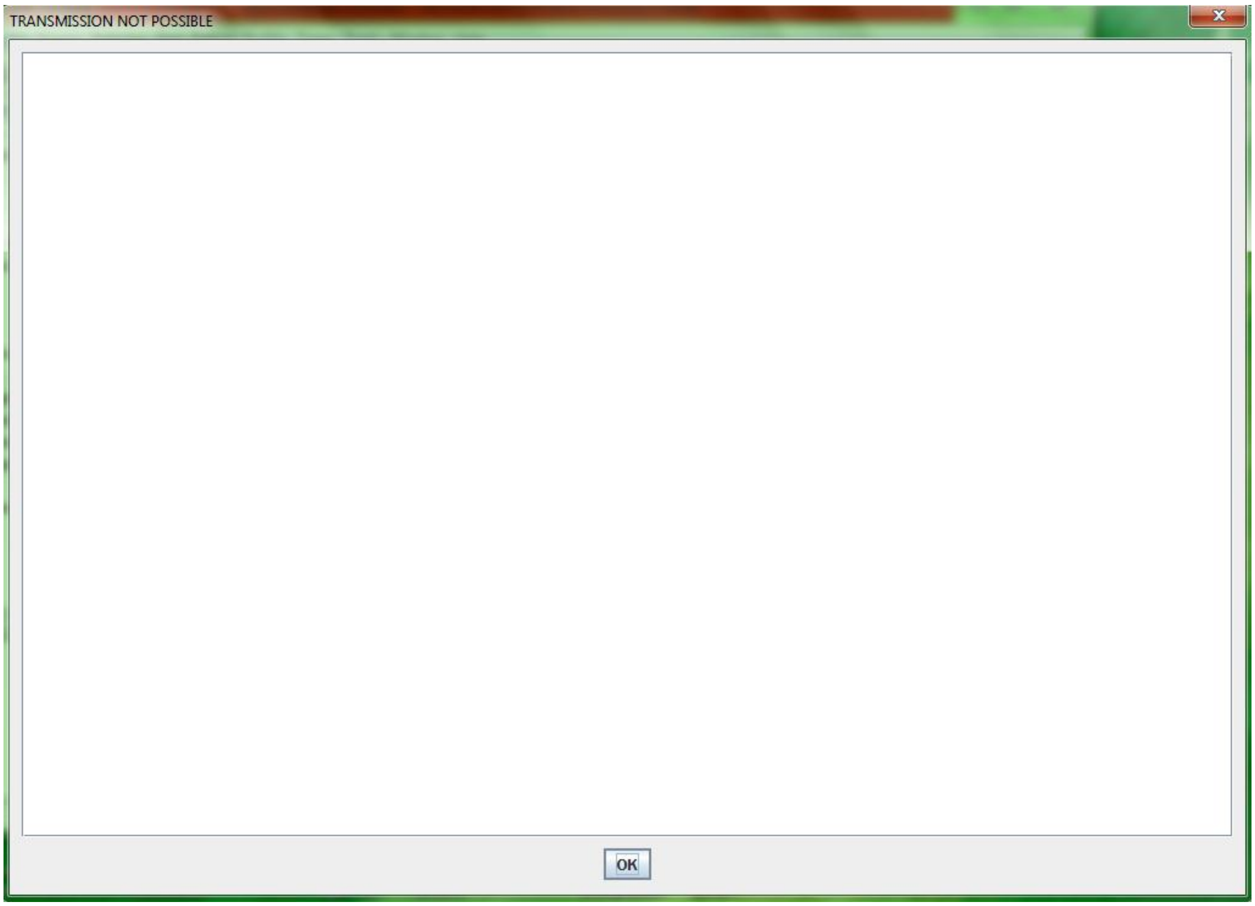


Figure 3.15: Screenshot of the Output for Overlay Transmission in the Presence of Primary User Signal.

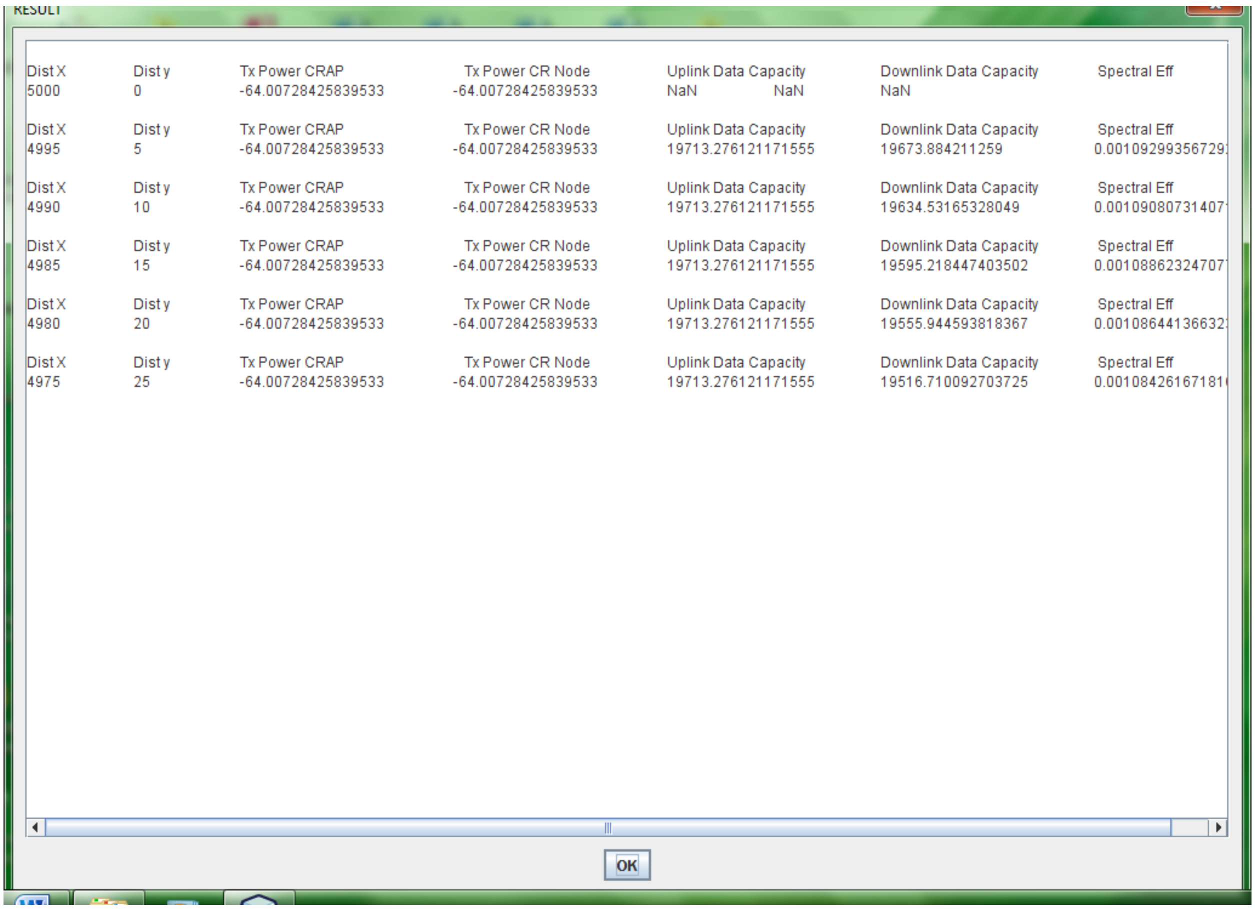
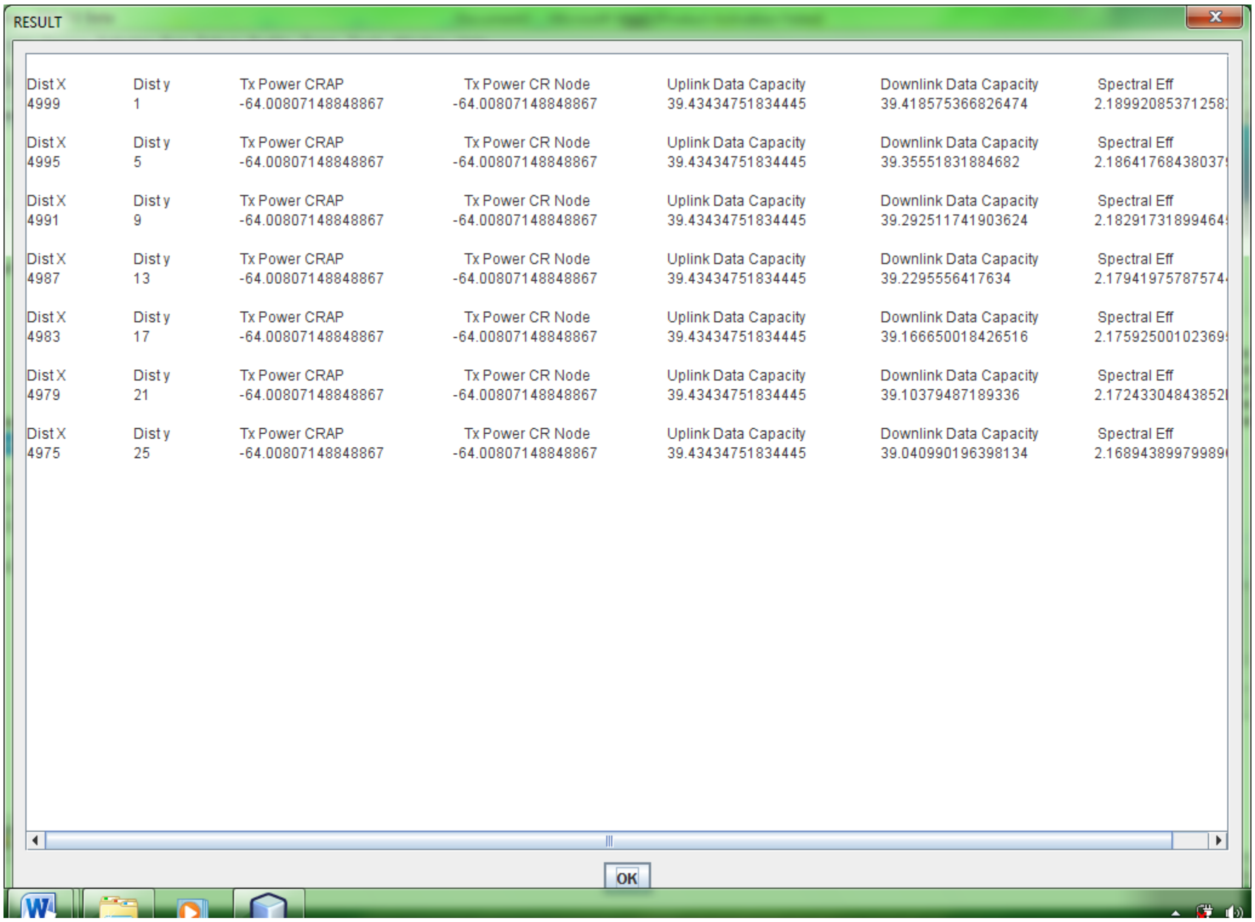


Figure 3.16: Screenshot of the Output for Underlay Transmission with Low Primary User Transmission Power of 100 W and 66 MHz Centre Frequency.



RESULT

Dist X	Dist y	Tx Power CRAP	Tx Power CR Node	Uplink Data Capacity	Downlink Data Capacity	Spectral Eff
4999	1	-64.00807148848867	-64.00807148848867	39.43434751834445	39.418575366826474	2.18992085371258
4995	5	-64.00807148848867	-64.00807148848867	39.43434751834445	39.35551831884682	2.18641768438037
4991	9	-64.00807148848867	-64.00807148848867	39.43434751834445	39.292511741903624	2.18291731899464
4987	13	-64.00807148848867	-64.00807148848867	39.43434751834445	39.2295556417634	2.17941975787574
4983	17	-64.00807148848867	-64.00807148848867	39.43434751834445	39.166650018426516	2.17592500102369
4979	21	-64.00807148848867	-64.00807148848867	39.43434751834445	39.10379487189336	2.17243304843852
4975	25	-64.00807148848867	-64.00807148848867	39.43434751834445	39.040990196398134	2.16894389979989

OK

Figure 3.17: Screenshot of the Output for Underlay Transmission with High Primary User Transmission Power of 50 KW and 66 MHz Centre Frequency.

CHAPTER FOUR

RESULT ANALYSIS AND DISCUSSIONS

This chapter discusses the implementation of the three models using Java programming language. The observations and results of the simulation performed on the three models of cognitive radio transmission are also presented and discussed under the performance metrics of distance covered, achieved capacity, spectral efficiency and margin of carrier to interference ratio. The models are tested based on no primary user signal, lower primary user signal and higher signal primary user scenarios.

4.1 Coverage Area

This is the distance covered by the CR in different models. The performance of the three models is discussed below.

4.1.1 Coverage Area in the MAFITM Model

In the MAFITM model, in the absence of primary user signal, cognitive radio transmits maximally but in the presence of primary user signal, cognitive radio will determine the right transmission parameters to use for its transmission to avoid causing interference to the PU signal. In the absence of PU signal, IEEE 802.22 specifies 4W (36 dBm) transmitter power output and this gives service coverage of about 100 km in all the TV channel range of operation that is 54 to 862 MHz.

The distance between CR_{AP} and PU transmitter is constant which means that the PU signal at CR_{AP} and the transmission power of CR_{AP} remains constant. However, the transmission power of CR node is not constant because it increases as it moves closer to the PU transmitter because the signal strength of PU signal increases. This will cause the CR node to raise its transmission power to maintain the 5% transmission power of PU signal. The CR output power is at maximum around PU transmitter area and starts to decrease as it moves away from it.

Considering a lower PU signal at a CR node, say 100W EIRP of PU transmitter operating at 66MHz centre frequency at 5km away from CR_{AP}, the PU signal power at CR_{AP} is constant while it increases at CR node as the distance between the CR node and the PU transmitter reduces. The transmission Power of CR_{AP} is also constant while that of CR node increases as it moves towards PU transmitter as seen in Table 4.1. When the distance between CR node and CR_{AP} is about 200m, the received signal power by CR from CR_{AP} is below the minimum detectable signal hence, transmission is not possible at this distance.

At a higher signal scenario say 10,000W EIRP of PU transmitter at 5 km away from CR_{AP}, the PU signal power at CR_{AP} increases to a constant value of -14.80 dBm. At CR node, as the distance between the CR node and the PU transmitter reduces the PU signal increases. Also, the coverage distance increases to about 1.5 km as shown in Table 4.2. This shows that the stronger the PU signal at the CR_{AP} or CR node, the longer the distance covered by the CR signal. When the distance between CR node and CR_{AP} is about 1.8 km, the received signal power by CR from CR_{AP} is below the minimum detectable signal hence, transmission is not possible at this distance.

If another higher signal of 50,000 W EIRP is considered, a further increase in distance covered is achieved as shown in Table 4.3. When the distance between CR node and CR_{AP} is about 4 km, the received signal power by CR from CR_{AP} is below the minimum detectable signal hence, transmission is not possible at this distance.

At higher frequency, the PU signal is reduced resulting to a reduction in distance covered. Table 4.4 shows the reduction in PU signal strength as centre frequency increases and the maximum transmission distance between CR_{AP} and CR node at each centre frequency when the primary user transmitter is operating at 100 W EIRP at 5 km away from CR_{AP}.

From the table above, at a centre frequency above 196 MHz, transmission is not possible because the possible transmission power of CR node is below the minimum required transmission power of CR which is -64 dBm.

At a higher PU signal strength, the distance covered increases. Table 4.5 shows the increase in coverage at 10,000 W EIRP as compared to 100 W EIRP of Table 4.3.

If another higher signal of 50,000 W EIRP is considered, a further increase in distance covered is achieved as shown in Table 4.6. Figure 4.1 shows this comparison as well as the decrease in distance covered with increase in centre frequency. Thus in an environment of strong PU signal, there will be a wider coverage of CR_{AP} signal.

Table 4.1: Transmission Power of CR_{AP} and CR at 66 MHz centre frequency, 100W EIRP and Maximum Distance Covered in MAFITM Model

Distance of CR from PU Transmitter (m)	Distance of CR from CR_{AP} (m)	Transmission Power of CR_{AP} (dBm)	Transmission Power of CR Node (dBm)	Primary Signal Power at CRAP(dBm)	Primary Signal Power at CR Node(dBm)
4999	1	-47.81	-47.81	-34.80	-34.80
4949	51	-47.81	-47.72	-34.80	-34.71
4899	101	-47.81	-47.63	-34.80	-34.62
4849	151	-47.81	-47.54	-34.80	-34.53
4799	201	Transmission not possible	Transmission not possible	-34.80	-34.44

Table 4.2: Transmission Power of CRAP and CR at 66 MHz centre frequency, 10,000W EIRP and Maximum Distance Covered in MAFITM Model

Distance from PU Transmitter x (m)	Distance from CR_{AP} Transmitter y (m)	Transmission Power of CR_{AP} (dBm)	Transmission Power of CR Node (dBm)	Primary Signal Power at CR_{AP} (dBm)	Primary Signal Power at CR Node (dBm)
4999	1	-27.81	-27.81	-14.80	-14.80
4499	501	-27.81	-26.89	-14.80	-13.88
3999	1001	-27.81	-25.87	-14.80	-12.86
3499	1501	-27.81	-24.71	-14.80	-11.70
3099	1801	Transmission not possible	Transmission not possible	-14.80	-10.92

Table 4.3: Transmission Power of CRAP and CR at 66 MHz centre frequency, 50,000W EIRP and Maximum Distance Covered in MAFITM Model

Distance from PU Transmitter x (m)	Distance of CR Node from CR_{AP} y (m)	Transmission Power of CR_{AP} (dBm)	Transmission Power of CR Node (dBm)	Primary Signal Power at CR_{AP} (dBm)	Primary Signal Power at CR Node (dBm)
4999	1	-20.82	-20.82	-7.81	-7.81
3999	1001	-20.82	-18.88	-7.81	-5.87
2999	2001	-20.82	-16.38	-7.81	-3.37
1999	3001	-20.82	-12.85	-7.81	0.15
999	4001	Transmission not possible	Transmission not possible	-7.81	6.17

Table 4.4: PU Signal Strength and CR Transmission Coverage at 100W EIRP in MAFITM Model

Frequency	Primary Signal Power at CR_{AP} at (dBm)	Possible Transmission Power of CR_{AP} (dBm)	Maximum distance covered (m)
66 MHz	-34.80	-47.81	150
82 MHz	-36.68	-49.69	100
196 MHz	-44.25	-57.26	10
470 MHz	-51.85	-64.86	No Transmission
830 MHz	-56.79	-69.80	No Transmission

Table 4.5: PU Signal Strength and CR Transmission Coverage at 10000W EIRP

Frequency	Primary Signal Power at CR_{AP} at (dBm)	Possible Transmission Power of CR_{AP} (dBm)	Maximum distance covered (m)
66 MHz	-14.80	-27.81	1500
82 MHz	-16.68	-29.69	1100
196 MHz	-24.25	-37.26	150
470 MHz	-31.85	-44.86	30
830 MHz	-36.79	-49.80	10

Table 4.6: PU Signal Strength and CR Transmission Coverage at 50000W EIRP

Frequency	Primary Signal Power at CR_{AP} at (dBm)	Possible Transmission Power of CR_{AP} (dBm)	Maximum distance covered (m)
66 MHz	-7.81	-20.82	3500
82 MHz	-9.69	-22.70	2500
196 MHz	-17.26	-30.27	400
470 MHz	-24.86	-37.87	70
830 MHz	-29.80	-42.81	20

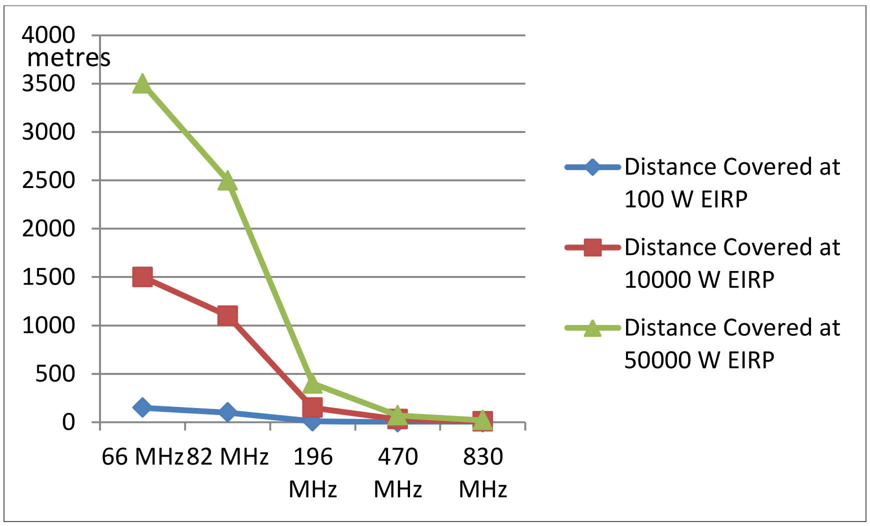


Figure 4.1: Distance Covered in Different Frequency for MAFITM Model

4.1.2 Coverage Area in Overlay Model

In the Overlay model, there is no transmission when the PU signal is detected at both lower and higher level to avoid causing interference to the PU signal. If the PU signal is not detected, then the CR will transmit maximally. In the absence of PU signal, IEEE 802.22 specifies 4 W (36 dBm) transmitter power output and this gives service coverage of about 100 km in all the TV channel range of operation, which is 54 to 862 MHz. Table 4.7 shows the transmission power of CR_{AP} which is constant at all distance because of the absence of the PU signal and Table 4.8 shows that there is no transmission in the presence of PU signal because the distance covered is 0 m. This is illustrated in Figure 4.2.

4.1.3 Coverage Area in Underlay Model

In the presence of PU signal whether at lower or higher level and in the absence of PU signal, the transmission power remain the same at all frequency and distance. The operation of this model depends on the selected interference temperature limit (T_L). In order to ensure CR transmits with the minimum required transmission power of -64 dBm, $1.6 \text{ X } 10^6$ K is selected as the interference limit. Table 4.9 shows the distance covered under different conditions of PU signal.

It is clear from Table 4.9 that the distance covered is not dependent on the PU signal strength as the transmission power of CR_{AP} is fixed at -64 dBm. However, as centre frequency increases, the distance covered reduces. For instance, with a centre frequency of 66 MHz, the maximum distance covered is about 25m, while under the same condition, the distance covered is reduced to 10m with a centre frequency of 196 MHz and to 2m with a centre frequency of 830 MHz. This is illustrated in Figure 4.3.

Table 4.7: Transmission Power of CR_{AP} and CR in Overlay Transmission

Distance from PU Transmitter x (m)	Distance from CR_{AP} Transmitter y (m)	Transmission Power of CR_{AP} (dBm)	Transmission Power of CR Node (dBm)	Primary Signal Power at CR_{AP}	Primary Signal Power at CR Node
4999	1	36.02	36.02	0.0	0.0
95000	100000	36.02	36.02	0.0	0.0

Table 4.8: Distance Covered in Different Frequency for Overlay Transmission

	Distance covered under No PU Signal (m)	Distance Covered at 100 W EIRP (m)	Distance Covered at 10000 W EIRP (m)	Distance Covered at 50000 W EIRP (m)
66 MHz	100000	0	0	0
82 MHz	100000	0	0	0
196 MHz	100000	0	0	0
470 MHz	100000	0	0	0
830 MHz	100000	0	0	0

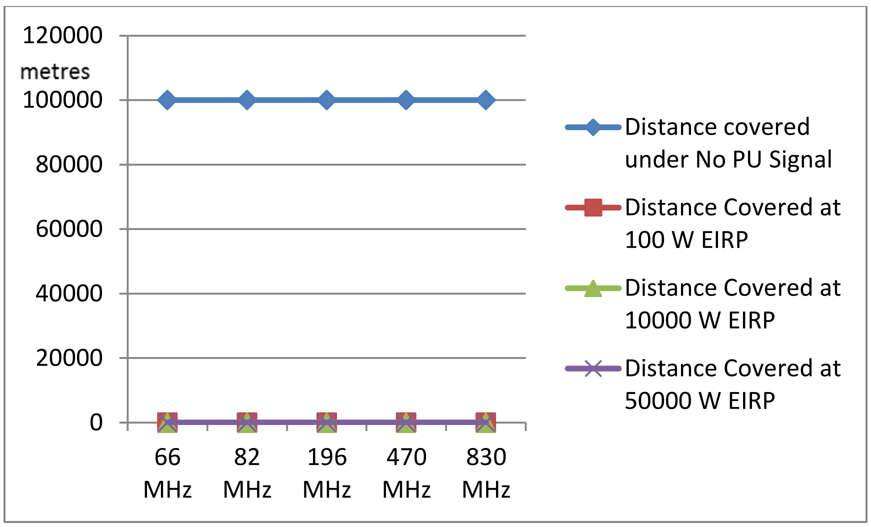


Figure 4.2: Distance Covered in Different Frequency for Overlay Transmission

Table 4.9: Distance Covered in Underlay Transmission

Frequency	Distance covered under No PU Signal (m)	Distance covered under 100 W EIRP (m)	Distance covered under 10000 W EIRP (m)	Distance covered under 50000 W EIRP (m)
66 MHz	25	25	25	25
82 MHz	20	20	20	20
196 MHz	10	10	10	10
470 MHz	3	3	3	3
830 MHz	2	2	2	2

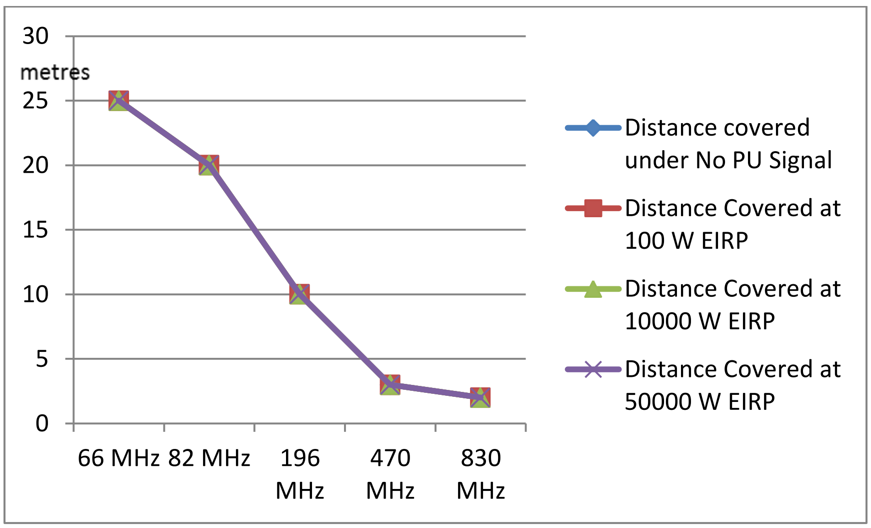


Figure 4.3: Distance Covered in Different Frequency for Underlay Transmission

4.2 Data Rates

This is the achieved capacity of the CR in different models. The performance of the three models is discussed below.

4.2.1 Data Rates in MAFITM Model

In the presence of PU signal, MAFITM model is able to achieve a capacity of up to 789 kb/s (808,470 b/s) in both the downlink and uplink direction. This value is constant over the distance covered in different centre frequencies and PU signal levels as shown in Tables 4.10a, b and c. The reason for this constant value is that as the distance between the PU transmitter and the CR node decreases, the CR node raises its transmission power but there is also a corresponding increase in the PU signal that constitute interference to the CR signal.

Because the transmission power of CR_{AP} is a fixed percentage of PU signal, the capacity remains fairly constant over achievable distance and centre frequency as shown in the Tables 4.10a, b and c. Also, the achieved data rate of CR_{AP} is independent of the PU signal strength as the values remain practically constant at different PU signal strength.

4.2.2 Data Rates in Overlay Model

When PU signal is absent, CR_{AP} transmits at the maximum permissible transmission power of 36 dBm with no PU signal to impair the CR_{AP} data rates. As shown in Table 4.11, as centre frequency increases, the capacity reduces because of the effect of path loss which is more pronounced at higher frequency. At higher frequency, the received signal power is reduced at a specified distance and with a reduced signal; there will be a reduced capacity.

4.2.3 Data Rates in Underlay Model

At restricted transmission parameters where the Underlay transmission power is fixed, the capacity of CR_{AP} increases as centre frequency increases but at lower distance coverage. At higher PU signal the capacity in Underlay transmission drastically reduced because of the PU signal interference. Table 4.12 shows the capacity of Underlay transmission when PU signal is at 0 W, 100 W, 10000 W and 50000 W EIRP when PU transmitter is at about 5 Km away from CR_{AP}.

Table 4.10a: Data Rate at 100W EIRP of PU Transmitter in MAFITM Model

Centre Frequency (MHz)	Downlink Data Capacity (b/s)	Uplink Data Capacity (b/s)	Maximum Distance of CR Node from CR_{AP} y (m)
66	808475	808476	150
82	808474	808474	100
196	808448	808448	10
470	0	0	No Transmission
830	0	0	No Transmission

Table 4.10b: Data Rate at 10,000W EIRP of PU Transmitter in MAFITM Model

Centre Frequency (MHz)	Downlink Data Capacity (b/s)	Uplink Data Capacity (b/s)	Maximum Distance of CR Node from CR_{AP} y (m)
66	808479	808479	1500
82	808479	808479	1100
196	808479	808479	150
470	808477	808477	30
830	808474	808474	10

Table 4.10c: Data Rate at 50,000W EIRP of PU Transmitter in MAFITM Model

Centre Frequency (MHz)	Downlink Data Capacity (b/s)	Uplink Data Capacity (b/s)	Maximum Distance of CR Node from CR_{AP} y (m)
66	808479	808479	3500
82	808479	808479	2500
196	808479	808479	400
470	808479	808479	70
830	808478	808478	20

Table 4.11: Overlay Data Rates

Frequency	Achieved Capacity (Downlink and Uplink) (Mb/s)
66 MHz	163
82 MHz	159
196 MHz	109
470 MHz	70
830 MHz	42

Table 4.12: Underlay Data Rates at Maximum Distance

Frequency	Achieved Capacity at EIRP=0W (Mb/s)	Achieved Capacity at EIRP=100W (Mb/s)	Achieved Capacity at EIRP=10000W (Mb/s)	Achieved Capacity at EIRP=50000W (Mb/s)
66 MHz at 25m	19.93000	0.02000	0.00019	0.00004
82 MHz at 20m	20.10000	0.03000	0.00029	0.00006
196 MHz at 10m	21.38000	0.17000	0.00166	0.00033
470 MHz at 3m	24.62000	0.94000	0.00953	0.00191
830 MHz at 2m	44.76000	2.81000	0.02972	0.00595

4.3 Spectral Efficiency

This is the amount of information transferred per bandwidth of the CR in different models. The spectral efficiency of the three models is discussed below.

4.3.1 Spectral Efficiency of MAFITM Model

A time factor T_{ON} is used to express a time 't' where there is intermittent ON and OFF of the PU signal. T_{ON} = 1 means that for the entire time 't' under consideration, the PU signal is present. T_{ON} = 0 implies that for the entire time 't' under consideration, the PU signal is absent. The percentage of time for which PU signal is either ON or OFF is expressed as a fractional value between 1 and 0. As shown in Table 4.13, when the PU signal is present for the entire time under consideration i.e. T_{ON} =1, the MAFITM transmission has a constant spectral efficiency of about 0.045 b/s/Hz. When there is absence of PU signal as shown in Table 4.14, the spectral efficiency measured at a distance of about 100 km ranges from 9.537 b/s/Hz at 66 MHz to 2.483 b/s/Hz at 830 MHz.

4.3.2 Spectral Efficiency of Overlay Model

Overlay transmission occurs only when there is no PU signal and as a result of this, spectral efficiency at T_{ON} =1 is 0 b/s/Hz. This is illustrated in Table 4.13. Table 4.14 shows the spectral efficiency of Overlay transmission at a distance of about 100 km at different centre frequencies.

4.3.3 Spectral Efficiency of Underlay Model

For underlay transmission as shown in Table 4.13, in the presence of primary user signal, the spectral efficiency increases as the frequency of transmission increases. This is because with higher frequency more data is transmitted in a given time. However, there is much reduction in the transmission distance.

In the absence of primary user signal, the spectral efficiency is constant at about 12.429 b/s/Hz at all frequencies. This is attributed to the fixed transmission power of Underlay transmission and also there is no primary user signal that interferes with the signal.

Table 4.13: Comparison of Spectral Efficiency in the Presence of Primary User signal (T_{ON} =1)

Frequency	MAFITM	OVERLAY	UNDERLAY
66 MHz	0.045	0.000	0.001
82 MHz	0.045	0.000	0.002
196 MHz	0.045	0.000	0.008
470 MHz	0.045	0.000	0.050
830 MHz	0.045	0.000	0.156

Table 4.14: Comparison of Spectral Efficiency in the Absence of Primary User signal (T_{ON} =0)

Frequency	MAFITM At a Distance of 100 km	OVERLAY At a Distance of 100 km	UNDERLAY At a Distance Ranging from 25 m to 2 m
66 MHz	9.537	9.537	12.429
82 MHz	8.910	8.910	12.429
196 MHz	6.381	6.381	12.429
470 MHz	3.937	3.937	12.429
830 MHz	2.483	2.483	12.429

4.4 Margin of Carrier to Interference Ratio

The margin of the carrier to interference ratio is used for interference assessment and states the likelihood of the CR signal being a harmful signal or not. If the margin is negative, there is potential of harmful interference but if it is positive or zero, there is no harmful interference.

4.4.1 Margin of Carrier to Interference Ratio in the MAFITM Model

The margin of carrier to interference ratio in the developed model at different frequencies and PU signal is shown in Table 4.15.

The table shows constant positive margins at different centre frequencies at maximum distance covered and primary signal power. Therefore, there is no harmful interference in the MAFITM model. The margin is constant at both CR_{AP} and CR node because the transmission powers of CR_{AP} and CR node are fixed at a percentage of the PU signal. When the power of PU signal increases, the powers of CR_{AP} and CR node increase accordingly by a fixed 5% value of the PU signal. When the power of PU signal decreases, the powers of CR_{AP} and CR node decrease in the like manner.

4.4.2 Margin of Carrier to Interference Ratio in Overlay Model

There is no transmission when the presence of PU signal is seen therefore; there is no possibility of having any harmful interference assuming that the CR vacates the channel as soon as PU signal appears.

4.4.3 Margin of Carrier to Interference Ratio in Underlay Model

In the Underlay model, when the PU signal is high enough, there is no harmful interference but at a lower PU signal there is likelihood of harmful interference. Table 4.16 shows the margins of carrier to interference ratio at different PU signal at CR_{AP} and CR node.

Table 4.15: Margin of Carrier to Interference Ratio in MAFITM Model

Frequency at Maximum Distance	Primary Signal Power at CR_{AP}	Primary Signal Power at CR Node	Margin at CR_{AP}	Margin at CR Node
66 MHz at 1.5Km	-14.80	-14.80	0.81	0.81
82 MHz at 1.1 Km	-16.68	-16.68	0.81	0.81
196 MHz at 150m	-24.25	-24.25	0.81	0.81
470 MHz at 30m	-31.85	-31.85	0.81	0.81
830 MHz at 10	-36.79	-36.79	0.81	0.81

Table 4.16: Margin of Carrier to Interference Ratio in Underlay Model

Frequency at Maximum Distance	Primary Signal Power at CR_{AP} (dBm)	Primary Signal Power at CR Nod e (dBm)	Margin at CR_{AP}	Margin at CR Node
66 MHz at 25 m	-34.80	-34.75	17.05	17.00
82 MHz at 20 m	-36.68	-36.65	15.15	15.12
196 MHz at 10 m	-44.25	-44.24	7.56	7.55
470 MHz at 3 m	-51.85	--51.84	-0.04	-0.04
830 MHz at 2	-56.79	-56.78	-4.98	-4.98

4.5 Comparison of Models

After the discussion of results of the different models in the above sections, the comparison of these models is now done in this section based upon the performance metrics discussed.

4.5.1 Comparison of Distance Covered

In a no PU signal environment, MAFITM model and Overlay transmission perform better with their maximum coverage of 100 km while Underlay transmission could only achieve a distance of 25m at 66 MHz, 20m at 82 MHz, 10m at 196 MHz, 3m at 470 MHz, and 2m at 830 MHz. With the presence of a lower PU signal of about 100 W, MAFITM transmission achieved a distance of about 150m while in a stronger PU signal of 10,000W the distance covered increased to about 1.5 km and about 3.5 Km with 50,000 W EIRP of PU signal. The MAFITM transmission therefore performs better in an environment of stronger PU signal. The Underlay transmission coverage area remains the same at different frequencies as when there is absence of PU signal. The distance covered in this transmission is therefore not affected by the strength of the PU signal. Transmission in Overlay is not allowed when the PU signal is detected, so the coverage area is zero. At higher frequencies say 196 MHz, the distance covered is still maximum under no PU signal condition for both MAFITM and Overlay transmissions but it is reduced in the Underlay transmission to about 10 metres. In the lower PU signal condition of -34.80 dBm, the distance covered in MAFITM transmission is reduced to a maximum of 10 m while that of Overlay transmission becomes zero and that of Underlay remain constant at 10 m. At a high PU signal condition of -14.80 dBm, the distance covered in MAFITM transmission increased to 150 metres while those of Overlay and Underlay transmissions remains 0 and 10 metres respectively. At a higher PU signal of -7.81 dBm, the distance covered in MAFITM transmission increased to 400 m, Overlay remain zero and Underlay remain 10 m. This is illustrated in Table 4.17 and Figures 4.4 and 4.5

Table 4.17: Comparison of Distance Covered at 66 MHz and 196 MHz

	MAFITM Distance Covered (m)		OVERLAY Distance Covered (m)		UNDERLAY Distance Covered (m)	
	66 MHz	196 MHz	66 MHz	196 MHz	66 MHz	196 MHz
LOW PU SIGNAL (100 W EIRP)	150	10	0	0	25	10
HIGH PU SIGNAL (10000 W EIRP)	1500	150	0	0	25	10
HIGHER PU SIGNAL (50000 W EIRP)	3500	400	0	0	25	10

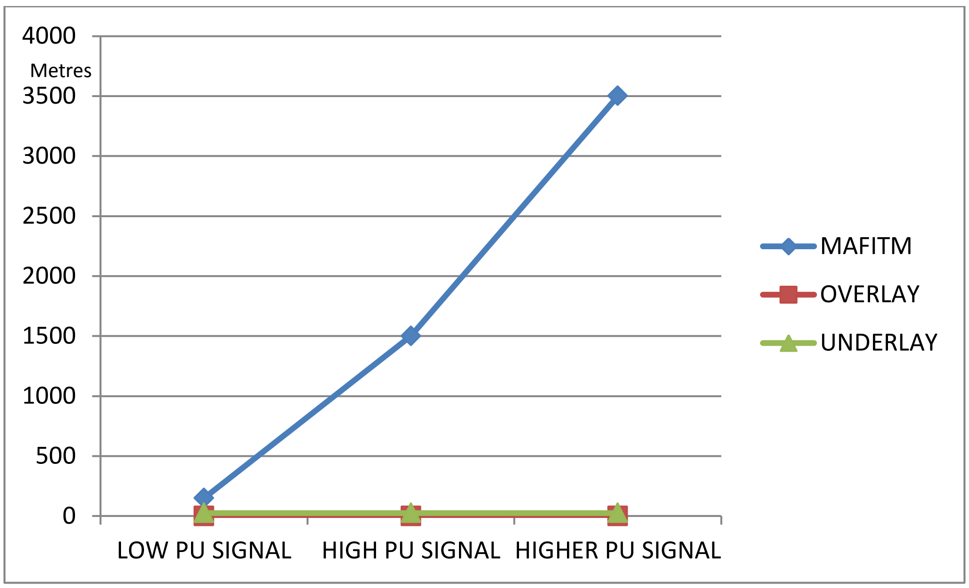


Figure 4.4: Comparison of Distance Covered by the Models at 66 MHz

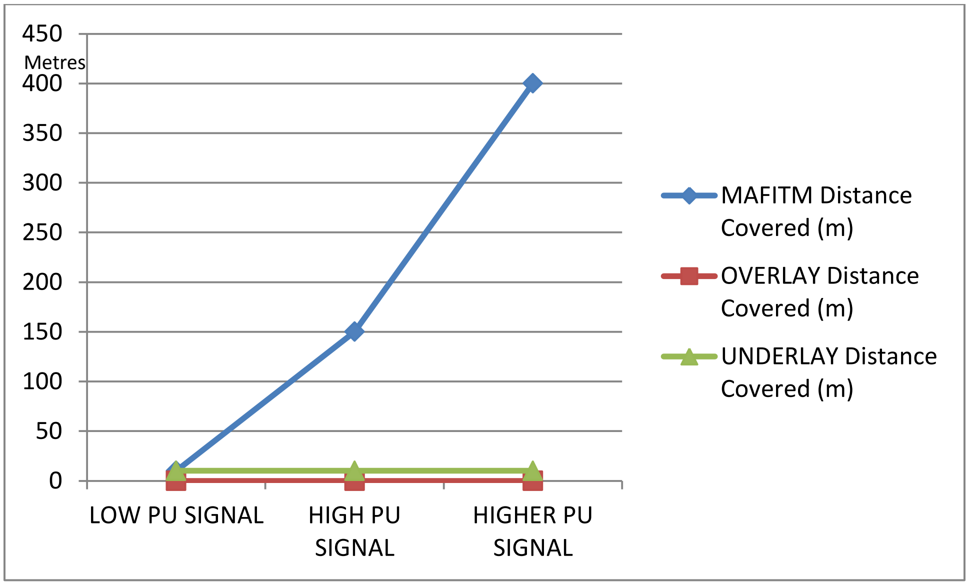


Figure 4.5: Comparison of Distance Covered by the Models at 196 MHz

4.5.2 Comparison of Achieved Capacity

The capacities of the models are compared at maximum distance covered. At no PU signal, Table 4.18 and Figure 4.6 show that both MAFITM and Overlay transmissions have a capacity of about 163 Mb/s in the uplink and downlink transmission while Underlay has a capacity of about 19.93Mb/s in the uplink and downlink transmission. Considering a lower PU signal from a transmitter of 100 W EIRP at 5 km from CR_{AP}, the capacities for each model are stated in Table 4.19.

The MAFITM transmission achieved a capacity of about 789 Kb/s. This value is constant over the possible transmission distance of the model. The capacity in Overlay is zero as there will be no transmission. The Underlay achieved a capacity of 19.24 kb/s in the 66 MHz centre frequency while a capacity of about 2.81 Mb/s is achieved in the 830 MHz centre frequency. This is illustrated in Figure 4.7. The reason for this increase as frequency increases in the Underlay is due to the fact that the transmitting power which constitutes the signal power is constant whereas the interference caused by the primary user signal reduces as the frequency increases. This leads to higher signal to noise ratio that implies higher capacity.

At a higher PU signal from a transmitter of 50000 W EIRP at 5 km from CR_{AP} while the capacity of MAFITM remain the same and the capacity of Overlay still zero, the Underlay capacity drastically reduced to 0.03 Kb/s and 6.09 kb/s in the 66 MHz and 830 MHz centre frequencies respectively. This is illustrated in Table 4.20 and Figure 4.8.

From the above findings, in the presence of PU signal, MAFITM transmission performs better in terms of constant data rates and longer distance coverage when the signal is higher while the Underlay performs better in a lower PU signal detection and higher frequency but this is achieved at lower distance coverage.

Table 4.18: Achieved capacity under No PU Signal at Maximum distance

MAFITM	OVERLAY	UNDERLAY
Achieved Capacity at 100 Km (Mb/s)	Achieved Capacity at 100 Km (Mb/s)	Achieved Capacity at 25 m (Mb/s)
163	163	19.93

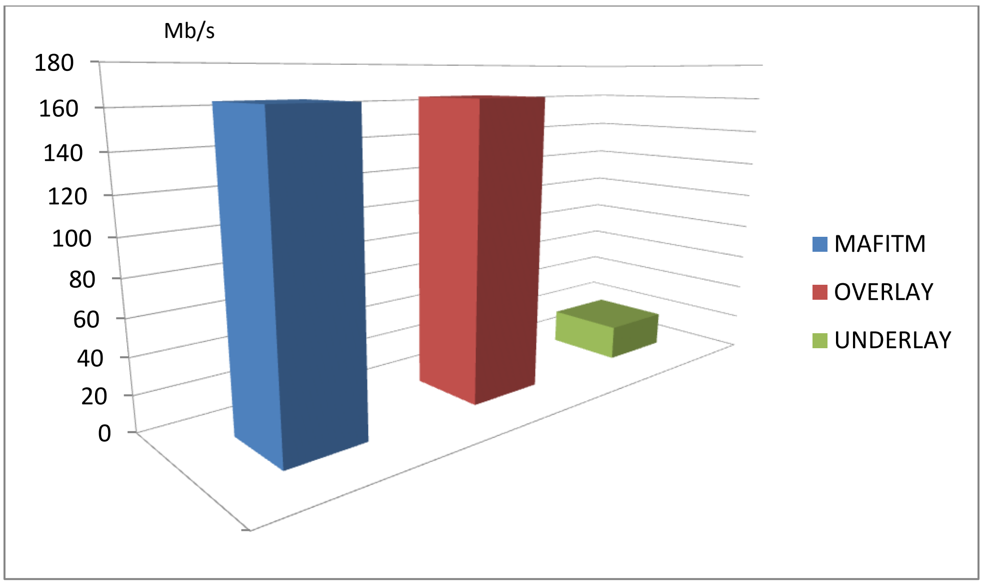


Figure 4.6: Comparison of Achieved Capacity of the Models at Maximum Distance without PU Signal

Table 4.19: Comparison of Achieved Capacity at 100 W EIRP

	MAFITM	OVERLAY	UNDERLAY
	Achieved Capacity (Kb/s)	Achieved Capacity (Kb/s)	Achieved Capacity (Kb/s)
66 MHz	789	0	19.24
82 MHz	789	0	29.70
196 MHz	789	0	169.24
470 MHz	0	0	958.12
830 MHz	0	0	2875.72

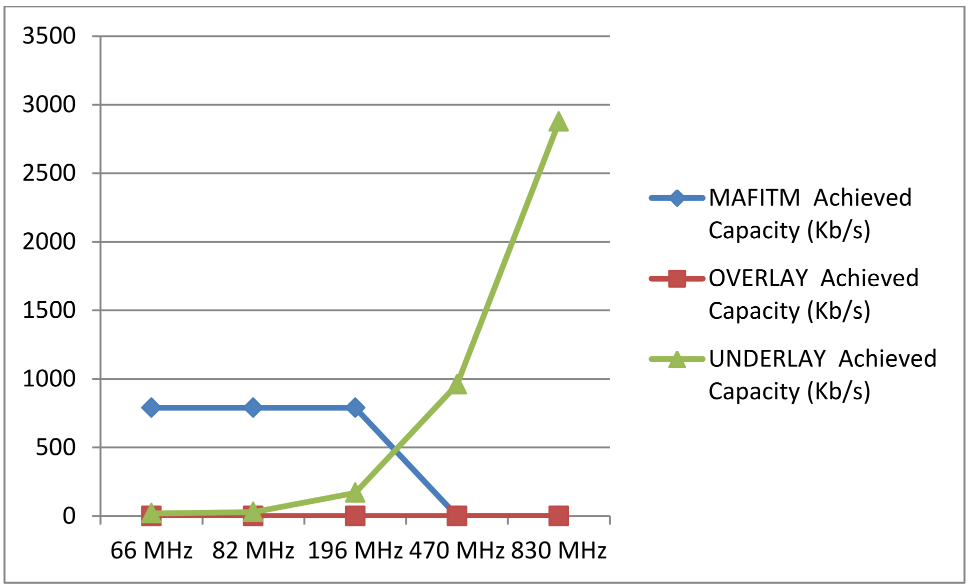


Figure 4.7 Comparison of Achieved Capacity of the Models at Low PU Signal

Table 4.20: Comparison of Achieved Capacity at 50000 W EIRP

	MAFITM Achieved Capacity (Kb/s)	OVERLAY Achieved Capacity (Kb/s)	UNDERLAY Achieved Capacity (Kb/s)
66 MHz	789	0	0.03
82 MHz	789	0	0.06
196 MHz	789	0	0.34
470 MHz	789	0	1.95
830 MHz	789	0	6.09

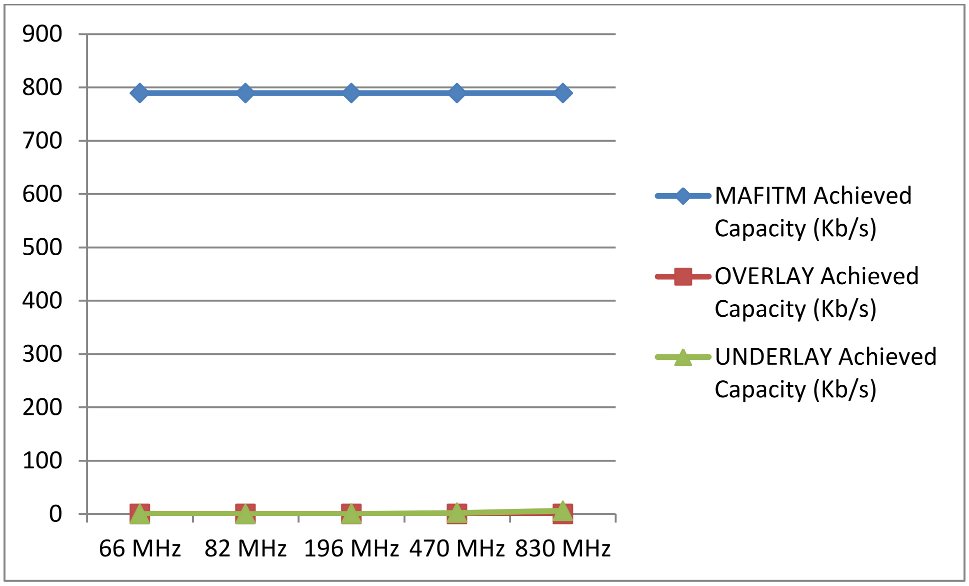


Figure 4.8: Comparison of Achieved Capacity of the Models at Higher PU Signal

4.5.3 Comparison of Spectral Efficiency

In the absence of PU signal, the spectral efficiency of MAFITM and Overlay transmission is 9.537 b/s/Hz while that of Underlay is 12.16 b/s/Hz. This is illustrated in Figure 4.9.

With the presence of PU signal of 100 W EIRP at a centre frequency of 66 MHz, the spectral efficiency of MAFITM is 0.045 b/s/Hz while that of Underlay is about 0.001 b/s/Hz. For Overlay, spectral efficiency is zero as there will be no transmission. This is illustrated in Figure 4.10.

At a higher signal of 10000 W EIRP and centre frequency of 66 MHz, the spectral efficiency of MAFITM is still 0.045 b/s/Hz while that of Underlay reduces to 0.0001 b/s/Hz and Overlay is zero because transmission is not possible. This is illustrated in Figure 4.11.

The comparison of spectral efficiencies of the model is summarised in Table 4.21.

MAFITM performs better out of the three models in the presence of PU signal. Also, its spectral efficiency remains unchanged under different PU signal strength. In the absence of PU signal both MAFITM and Overlay have the same spectral efficiency.

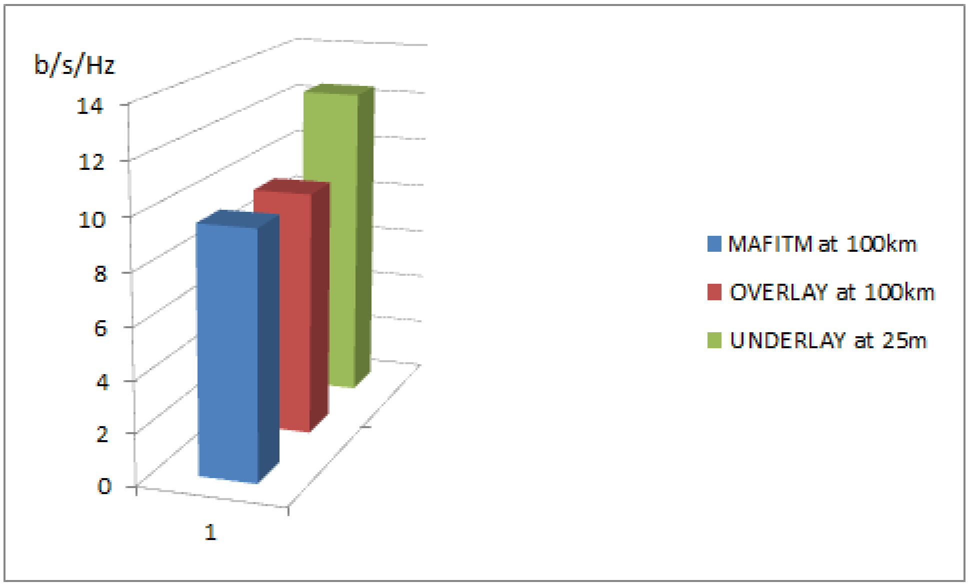


Figure 4.9: Comparison of Spectral Efficiency in the Absence of PU Signal

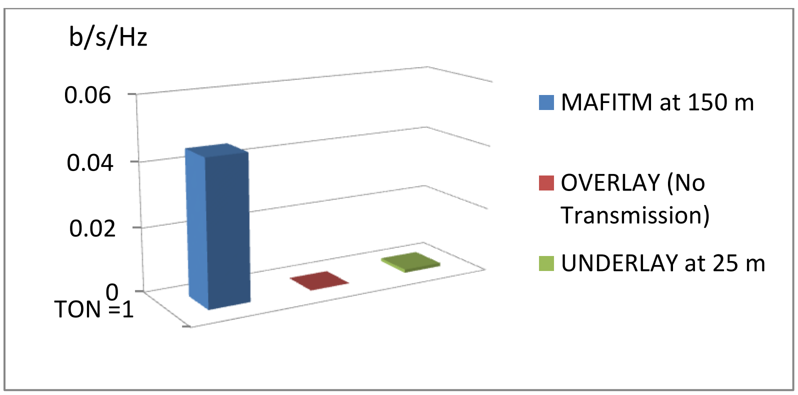


Figure 4.10: Comparison of Spectral Efficiency in the Presence of a Low PU Signal (100W at 66 MHz)

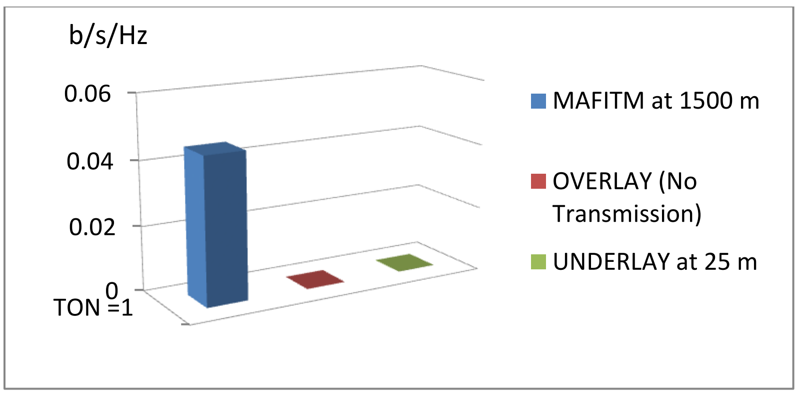


Figure 4.11: Spectral Efficiency in a stronger PU Signal strength (10,000W at 66 MHz)

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Table 4.21: Comparison of Spectral Efficiency at 66 MHz

	MAFITM Spectral Efficiency (b/s/Hz)	OVERLAY Spectral Efficiency (b/s/Hz)	UNDERLAY Distance Spectral Efficiency (b/s/Hz)
No PU Signal	9.537	9.537	12.429
LOW PU SIGNAL (100 W EIRP)	0.045	0.000	0.001
HIGH PU SIGNAL (10000 W EIRP)	0.045	0.000	0.000
HIGHER PU SIGNAL (50000 W EIRP)	0.045	0.000	0.000

4.5.4 Comparison of Margin of Carrier to Interference Ratio

There is positive margin in MAFITM which means that there is no likelihood of harmful interference. In Overlay model, there is no transmission when the presence of PU signal is observed while there is likelihood of harmful interference at a lower PU signal in Underlay but may not produce harmful interference if the PU signal is high enough.

4.6 Comparison of MAFITM with the of IEEE 802.22 Benchmark

IEEE 802.22 standard is based on Overlay method whereby cognitive radio uses the vacant frequency bands only when the licensed user is not detected. According to Cordeiro *et al.* (2006), the benchmark is stated at a range of service coverage from 30 km to 100 km which gives a spectral efficiency of 0.5 b/s/Hz to 15 b/s/Hz and minimum service capacity of 18 Mbps. Table 4.22 compares this benchmark with the results obtained in MAFITM in the absence of primary user signal.

In the presence of primary user signal, the standard prevents transmission by the cognitive radio. However, MAFITM could compute the appropriate transmission parameters that will not interfere significantly with the primary user signal and then test the possibility of transmission. Table 4.23 compares the benchmark with the results obtained in MAFITM in the presence of primary user signal.

Table 4.22: Comparison between IEEE 802.22 Benchmark and MAFITM in the Absence of Primary User Signal

Metric	IEEE 802.22 Benchmark	MAFITM
Service Coverage	30 km to 100 km	Up to 100 km
Service Capacity	≥ 18 Mbps	42 Mbps to 163 Mbps
Spectral Efficiency	0.5 b/s/Hz to 15 b/s/Hz	2.483b/s/Hz to 9.537 b/s/Hz

Table 4.23: Comparison between IEEE 802.22 Benchmark and MAFITM in the Presence of Primary User Signal

Metric	IEEE 802.22 Benchmark	MAFITM
Service Coverage	0 metres	2 m to 3.5 km
Service Capacity	0 bps	789 Kbps
Spectral Efficiency	0 b/s/Hz	0.045 b/s/Hz

CHAPTER FIVE

SUMMARY, CONCLUSION AND RECOMMENDATIONS

This chapter discusses the summary of the research work together with the conclusion and recommendations arising thereof.

5.1 Summary

Software defined radios have been found to be helpful in the management of supposedly scarce spectrum especially in the DTV band. Cognitive radios are classes of software defined radios that intelligently and opportunistically use two broad methods of Overlay and Underlay to access licensed spectrum.

A novel dynamic spectrum access method called MAFITM was developed in this research. The method was implemented by simulation using Java programming language. The simulation was carried out using different primary user signal of zero, lower signal of -34.80 dBm, high signal of -14.80 dBm and higher signal of -7.80 dBm. Centre frequencies of 66 MHz in band I, 82 MHz in band II, 196 MHz in band III, 470 MHz in band IV and 830 MHz in band V of the TV band were selected as the transmission frequencies. Also 1.6 x 10^6 K was selected as the interference temperature limit to give the minimum transmission power of -64 dBm for cognitive radios. The existing methods and MAFITM were compared using performance metrics of covered distance, data rates, spectrum efficiency, and margin of interference.

In terms of coverage area, at no primary user signal environment, MAFITM and Overlay transmission perform better with their maximum coverage of 100 km while Underlay transmission could only achieve a distance of 25 m at 66 MHz, 20 m at 82 MHz, 10 m at 196 MHz, 3 m at 470 MHz and 2 m at 830 MHz. With the detection of primary signal, no transmission is achieved in the Overlay; MAFITM transmission achieved a maximum distance of about 150 m at 66 MHz while in a stronger PU signal of -14.80 dBm and -7.81 dBm the distance covered increased to about 1.5 km and 3.5 km respectively. Underlay transmission coverage remains constant at every signal levels for a particular centre frequency.

In terms of achieved capacity, at no primary signal, MAFITM and Overlay have the same capacity of about 163 Mb/s at 66 MHz and 42 Mb/s at 830 MHz, the Underlay has a capacity of 20 Mb/s at 66 MHz and 44 Mb/s at 830 MHz but at lower distance of 25 m and 2 m respectively. At lower PU signal, MAFITM achieved a capacity of about 789 Kb/s, the Overlay is zero and the Underlay depends on the centre frequency; 19.24 kb/s in the 66 MHz and 2.81 Mb/s is achieved in the 830 MHz. At a higher primary signal, the capacity of MAFITM remain the same at all PU signal level while that of Overlay remains zero, and that of Underlay drastically reduced to 0.19 Kb/s and 30 kb/s in the 66 MHz and 830 MHz centre frequencies respectively.

In terms of spectral efficiency, at no primary signal the spectral efficiencies of MAFITM and Overlay range from 9.537 b/s/Hz at 66 MHz centre frequency to 2.483 b/s/Hz at 830 MHz centre frequency and at a distance of about 100 km. For Underlay, it is about 12.429 b/s/Hz, at all frequencies but shorter distance of 25 m. With lower primary signal, the spectral efficiency of the developed technique is 0.045 b/s/Hz that of Underlay is about 0.001 b/s/Hz and for Overlay it is zero. With higher primary signal the spectral efficiency of MAFITM remains 0.045 b/s/Hz, for Underlay it is about 0.00001 b/s/Hz, and for Overlay it is zero.

Considering margin of interference, there is positive margin of interference of 0.81 in MAFITM at all PU signal level. In Overlay model, there is no transmission when licensed signal is present. For Underlay model, there is a negative margin of interference when the signal is very low, for example there is -0.04 margin of interference when the primary signal is as low as -51.84 dBm; but a positive margin of interference of 7.55 when the primary signal is as high as -44.24 dBm.

5.2 Conclusion

At no primary user signal environment, Overlay and MAFITM models equally performed better in terms of distance covered, data rates, spectral efficiency and margin of interference compared with Underlay transmission. The performance of Underlay is limited due to interference temperature limit

At low primary user signal environment, Underlay performs better in a low primary signal environment in terms of data rates but at lower distance an also with a likelihood of harmful interference. There is no transmission in Overlay at this condition while transmission in the developed model is only possible if the primary signal is high enough to give a transmission power of at least -64 dBm.

The developed technique performs better in an environment of stronger primary signal in terms of data rates, distance covered, and spectral efficiency. The Underlay has the best margin of interference at high primary signal but the data rates at this condition are insignificant and this makes it inappropriate. There is no transmission in Overlay in this environment.

5.3 Recommendations

In line with the aim and objectives, findings and conclusion of this research, the following recommendations are hereby proposed:

1. both the Overlay and MAFITM are appropriate in rural areas where there is a higher chance of the absence of PU signal,
2. MAFITM could be used in urban areas where there is likelihood of high PU signal,
3. with MAFITM, the DTV frequency bands I, II, and III give appreciable range of transmission and could be used when larger distance coverage is desirable while bands IV and V could be used when large range of transmission is not needed but frequency reuse is desirable,

4. this spectrum utilisation technique i.e. MAFITM could be incorporated into computer devices for usage where Wi-Fi spectrum is not available or is ineffective.

5.4 Contributions to Knowledge

With the completion of this research, the following are the main contributions to knowledge:

i. the development of a simulator for the simulation of cognitive radio networks,
ii. the development of a new approach to dynamic spectrum access of cognitive radio that gives improved utilisation of the digital television band especially in urban areas where there is higher usage of the limited spectrum.

5.5 Future Works

This research focused on the development of an improved dynamic spectrum access in the television frequency band where matched filtering technique is used to detect the presence of licensed television signal using a simulator. In future works, the implementation of the developed algorithm in a programmable processor of the cognitive radio platform through microprogramming could be done to test the radio in real life conditions. Also, the licensed frequency bands to be utilised by cognitive radios could be increased beyond television signal. This will however implies higher complexities that have to be addressed by harmonising different numbers of matched filters for the detection of respective licensed signals.

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APPENDIX A

TV bands in Nigeria National Frequency Allocation Table 2014

SEGMENT 2: 30 - 300 MHz				
FREQUENCY BANDS (MHZ)	**ITU REGION 1 ALLOCATIONS**	**NIGERIAN ALLOCATIONS**	**NIGERIAN UTILIZATION**	**REMARKS**
47 – 68	BROADCASTING 5.162A 5.163 5.164 5.165 5.169 5.171	BROADCASTING LAND MOBILE 5.164	LAND MOBILE	Cordless systems
68.00 – 74.80	FIXED MOBILE except aeronautical 5.149 5.174 5.175 5.177 5.179	FIXED MOBILE except aeronautical mobile 5.149	FIXED MOBILE except aeronautical mobile	Cordless systems
74.8 - 75.2	AERONAUTICAL RADIONAVIGATION 5.180 5.181	AERONAUTICAL RADIONAVIGATION 5.180		Marker beacons(phased out nationwide)
75.2 – 87.5	FIXED MOBILE except aeronautical mobile 5.175 5.179 5.187	FIXED MOBILE except aeronautical mobile	FIXED MOBILE except aeronautical mobile	Cordless systems
87.5 - 100.0	BROADCASTING 5.190	BROADCASTING	BROADCASTING	FM radio broadcasting
100 - 108	BROADCASTING 5.192 5.194	BROADCASTING	BROADCASTING	FM radio broadcasting
108.000 - 117.975	AERONAUTICAL RADIONAVIGATION 5.197	AERONAUTICAL RADIONAVIGATION 5.197 5.197A	AERONAUTICAL RADIONAVIGATION	VOR/ILS localizer

National Frequency Allocation Table
Post 2012

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SEGMENT 2: 30 - 300 MHz				
FREQUENCY BANDS (MHZ)	**ITU REGION 1 ALLOCATIONS**	**NIGERIAN ALLOCATIONS**	**NIGERIAN UTILIZATION**	**REMARKS**
162.0375 - 174	FIXED MOBILE except aeronautical mobile 5.226 5.229	FIXED MOBILE except aeronautical mobile 5.226	FIXED MOBILE except aeronautical mobile	Two- way radio (PMR)
174 – 223	BROADCASTING 5.235 5.237 5.243	BROADCASTING	BROADCASTING	TV broadcasting on VHF
223 – 230	BROADCASTING Fixed Mobile 5.243 5.246 5.247	BROADCASTING Fixed Mobile	BROADCASTING	TV broadcasting on VHF
230 – 235	FIXED MOBILE 5.247 5.251 5.252	FIXED MOBILE AERONAUTICAL RADIONAVIGATION 5.251		
235 – 267	FIXED MOBILE 5.111 5.199 5.252 5.254 5.256 5.256A	FIXED MOBILE 5.111 5.254 5.256	FIXED	EPIRB on 243

SEGMENT 3: 300 MHz – 3 000 MHz				
FREQUENCY BANDS (MHz)	**ITU REGION 1 ALLOCATIONS**	**NIGERIAN ALLOCATIONS**	**NIGERIAN UTILIZATION**	**REMARKS**
460 – 470	FIXED MOBILE Meteorological-satellite (space-to-Earth) 5.287 5.288 5.289 5.290	FIXED MOBILE Meteorological-satellite (s-E) 5.287 5.289	FIXED MOBILE	STL; Private CDMA networks
470 – 790	BROADCASTING 5.149 5.291A 5.294 5.296 5.300 5.304 5.306 5.311A 5.312 5.312A	BROADCASTING 5.149 5.304 5.311A	BROADCASTING	Analog TV: 470-854; DTT: 474-698 (GE6 agreement & DVB-T channel arrangement apply)
790 – 862	FIXED MOBILE except aeronautical mobile 5.316B 5.317A BROADCASTING 5.312 5.314 5.315 5.316 5.316A 5.319	FIXED MOBILE except aeronautical mobile 5.316B 5.317A BROADCASTING 5.316A	FIXED MOBILE BROADCASTING	STL; 811-821/852-862: TDD-CDMA; 824-849: FDD- CDMA reverse link; TV broadcasting
862 – 890	FIXED MOBILE except aeronautical mobile 5.317A BROADCASTING 5.322 5.319 5.323	FIXED MOBILE except Aeronautical mobile 5.317A 5.322	MOBILE	869-890: FDD-CDMA forward link

APPENDIX B

TABLE 2

Single entry interference (SEI) protection criteria for FSS carriers

FSS carrier	ITU-R Recommendations for SEI	Type of interference	SEI protection criteria	
			API before 1987	API after 1987
FDM-FM CFDM-FM	Rec. ITU-R S.466	Any	600 pW0p	800 pW0p
TV-FM	Rec. ITU-R S.483	Noise-like	$C/N + 14$ (dB)	$C/N + 14$ (dB)
Digital	Rec. ITU-R S.523	Noise-like	$C/N + 14$ (dB)	$C/N + 12.2$ (dB)
SCPC-FM	(1)	Noise-like	$C/N + 14$ (dB)	$C/N + 12.2$ (dB)
SCPC-FM	Rec. ITU-R S.671	Slowly-swept	$13.5 + 2 \log(\delta) - 3 \log(i/10)$ (dB)	
Digital narrow-band:				
– with coding	Rec. ITU-R S.671	Slowly-swept	$C/N + 9.4 + 3.5 \log(\delta) - 6 \log(i/10)$ (dB)	
– without coding	Rec. ITU-R S.671	Slowly-swept	$C/N + 6.4 + 3 \log(\delta) - 8 \log(i/10)$ (dB)	

APPENDIX C

Publications from this work

i. Olanrewaju, B.S. and Osunade, O. 2012. Proposed Interference Temperature Model for Improved Spectrum Efficiency in Cognitive Radios. In the proceedings of EIE's 2ND International Conference on Computing, Energy, Networking, Robotics and Telecommunications, November 21-23, 2012. Covenant University, Nigeria. Pp.72-80
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iv. Olanrewaju, B.S. and Osunade, O. 2018. Design of a Mathematical Model for Spectrum Utilisation in Cognitive Radio. *International Journal of Computer Application (0975 – 8887). Volume 180 – No.19, pp.27-32 February 2018*.

APPENDIX D

SIMULATION CODE

D1: SIMULATOR

```
package Radio;
import java.awt.Color;
import javax.swing.JFrame;
import javax.swing.*;
import java.lang.Object;

/**
 * @author OLANREWAJU
 */
public class Simulator extends javax.swing.JFrame {

    /**
     * Creates new form SIMULATOR
     */
    public Simulator() {
        initComponents();
    }
    /**
     * This method is called from within the constructor to initialize the form.
     * WARNING: Do NOT modify this code. The content of this method is always
     * regenerated by the Form Editor.
```

```
 */
@SuppressWarnings("unchecked")
// <editor-fold defaultstate="collapsed" desc="Generated Code">
private void initComponents() {

    jLabel1 = new javax.swing.JLabel();
    jComboBox1 = new JComboBox();
    jLabel2 = new javax.swing.JLabel();
    jComboBox2 = new JComboBox();
    jLabel3 = new javax.swing.JLabel();
    jTextField1 = new javax.swing.JTextField();
    jButton1 = new javax.swing.JButton();
    jLabel4 = new javax.swing.JLabel();
    jComboBox3 = new JComboBox();

    setDefaultCloseOperation(javax.swing.WindowConstants.EXIT_ON_CLOSE);
    setBackground(new java.awt.Color(0, 4, 51));

    jLabel1.setForeground(new java.awt.Color(117, 236, 83));
    jLabel1.setText("Select Primary Signal Transmitting Power(Watts)");

    jComboBox1.setModel(new javax.swing.DefaultComboBoxModel<>(new String[]
{ "5000", "10000", "20000", "30000" }));
    jLabel2.setForeground(new java.awt.Color(117, 236, 83));
    jLabel2.setText("Select The Centre Frequency Of Transmission F(10^6)");
```

```
        jComboBox2.setModel(new javax.swing.DefaultComboBoxModel<>(new String[]
{ "63", "82", "180", "600" }));

        jLabel3.setForeground(new java.awt.Color(117, 236, 83));

        jLabel3.setText("Enter The Distance Of Cognitive Radio From CR To PT ");

        jTextField1.setText("jTextField1");

        jButton1.setText("SIMULATE");

        jButton1.addActionListener(new java.awt.event.ActionListener() {

            public void actionPerformed(java.awt.event.ActionEvent evt) {

                jButton1ActionPerformed(evt);

            }

        });

        jLabel4.setForeground(new java.awt.Color(117, 236, 83));

        jLabel4.setText("Select the number of Cognitive radio nodes");

        jComboBox3.setModel(new javax.swing.DefaultComboBoxModel<>(new String[]
{ "1", "2", "3", "4", "5", "6", "7", "8", "9", "10", "11", "12" }));

        javax.swing.GroupLayout layout = new
javax.swing.GroupLayout(getContentPane());

        getContentPane().setLayout(layout);

        layout.setHorizontalGroup(

            layout.createParallelGroup(javax.swing.GroupLayout.Alignment.LEADING)

            .addGroup(layout.createSequentialGroup()

                .addContainerGap()

.addGroup(layout.createParallelGroup(javax.swing.GroupLayout.Alignment.LEADING)

addGroup(layout.createParallelGroup(javax.swing.GroupLayout.Alignment.LEADING,
false)
```

```
                    .addComponent(jLabel1, javax.swing.GroupLayout.DEFAULT_SIZE,
javax.swing.GroupLayout.DEFAULT_SIZE, Short.MAX_VALUE)
                    .addComponent(jComboBox1, 0,
javax.swing.GroupLayout.DEFAULT_SIZE, Short.MAX_VALUE)
                    .addComponent(jLabel2, javax.swing.GroupLayout.DEFAULT_SIZE,
javax.swing.GroupLayout.DEFAULT_SIZE, Short.MAX_VALUE)
                    .addComponent(jComboBox2, 0,
javax.swing.GroupLayout.DEFAULT_SIZE, Short.MAX_VALUE)
                    .addComponent(jLabel3, javax.swing.GroupLayout.DEFAULT_SIZE,
javax.swing.GroupLayout.DEFAULT_SIZE, Short.MAX_VALUE)
                    .addComponent(jTextField1)
                    .addComponent(jButton1, javax.swing.GroupLayout.DEFAULT_SIZE,
javax.swing.GroupLayout.DEFAULT_SIZE, Short.MAX_VALUE)
                    .addComponent(jLabel4, javax.swing.GroupLayout.DEFAULT_SIZE,
javax.swing.GroupLayout.DEFAULT_SIZE, Short.MAX_VALUE))
                  .addComponent(jComboBox3,
javax.swing.GroupLayout.PREFERRED_SIZE,
javax.swing.GroupLayout.DEFAULT_SIZE,
javax.swing.GroupLayout.PREFERRED_SIZE))
                .addContainerGap(128, Short.MAX_VALUE))
        );
        layout.setVerticalGroup(
            layout.createParallelGroup(javax.swing.GroupLayout.Alignment.LEADING)
            .addGroup(layout.createSequentialGroup()
                .addContainerGap()
                .addComponent(jLabel1)
                .addPreferredGap(javax.swing.LayoutStyle.ComponentPlacement.RELATED)
                .addComponent(jComboBox1, javax.swing.GroupLayout.PREFERRED_SIZE,
javax.swing.GroupLayout.DEFAULT_SIZE,
javax.swing.GroupLayout.PREFERRED_SIZE)
```

```
                .addGap(18, 18, 18)
                .addComponent(jLabel2)
                .addPreferredGap(javax.swing.LayoutStyle.ComponentPlacement.RELATED)
                .addComponent(jComboBox2, javax.swing.GroupLayout.PREFERRED_SIZE,
javax.swing.GroupLayout.DEFAULT_SIZE,
javax.swing.GroupLayout.PREFERRED_SIZE)
                .addGap(18, 18, 18)
                .addComponent(jLabel3)
                .addPreferredGap(javax.swing.LayoutStyle.ComponentPlacement.RELATED)
                .addComponent(jTextField1, javax.swing.GroupLayout.PREFERRED_SIZE,
javax.swing.GroupLayout.DEFAULT_SIZE,
javax.swing.GroupLayout.PREFERRED_SIZE)
                .addGap(18, 18, 18)
                .addComponent(jLabel4)
                .addPreferredGap(javax.swing.LayoutStyle.ComponentPlacement.RELATED)
                .addComponent(jComboBox3, javax.swing.GroupLayout.PREFERRED_SIZE,
javax.swing.GroupLayout.DEFAULT_SIZE,
javax.swing.GroupLayout.PREFERRED_SIZE)
                .addPreferredGap(javax.swing.LayoutStyle.ComponentPlacement.RELATED,
23, Short.MAX_VALUE)
                .addComponent(jButton1)
                .addGap(29, 29, 29))
        );
        pack();
    }// </editor-fold>
    private void jButton1ActionPerformed(java.awt.event.ActionEvent evt) {
```

```
//*********************************************************************
**

        //ONCE YOU PRESS THE BUTTON:

        this.setVisible(false);

        //Create a new JFrame ...an Object of resultFrame

        ResultFrame t = new ResultFrame();

        t.setVisible(true);// Now make it visible

        t.setDefaultCloseOperation(JFrame.EXIT_ON_CLOSE);

        t.setSize(1370,700);

        t.setTitle("******RESULT******");

        t.setResizable(false);

        t.setLocationRelativeTo(null);

        t.getContentPane().setBackground(new Color(0,4,51));


        //Connect the two Frames together ... let the second frame take several values from
the first frame.

        //t.figureArea1.setText(getTextFromTextField());

       }

    double getTextFromTextField(){

        return Double.parseDouble(jTextField1.getText());

    }

        public static void main(String args[]) {

          Simulator a = new Simulator();

        a.setDefaultCloseOperation(JFrame.EXIT_ON_CLOSE);

        a.setSize(334,380);
```

```
        a.setTitle("SIMULATOR");
        a.setVisible(true);
        a.setResizable(false);
        a.setLocationRelativeTo(null);
        a.getContentPane().setBackground(new Color(0,4,51));
        }
    // Variables declaration - do not modify
    private javax.swing.JButton jButton1;
    private javax.swing.JComboBox<String> jComboBox1;
    private javax.swing.JComboBox<String> jComboBox2;
    private javax.swing.JComboBox<String> jComboBox3;
    private javax.swing.JLabel jLabel1;
    private javax.swing.JLabel jLabel2;
    private javax.swing.JLabel jLabel3;
    private javax.swing.JLabel jLabel4;
    private javax.swing.JTextField jTextField1;
    // End of variables declaration
}
```

D2: RESULTS FRAME

```
package ;
import java.awt.BorderLayout;
import java.awt.Color;
import java.awt.Font;
import java.awt.GridLayout;
import javax.swing.JFrame;
import javax.swing.JLabel;
import javax.swing.JOptionPane;
import javax.swing.JPanel;
import javax.swing.JTextArea;
import javax.swing.border.Border;
import javax.swing.border.LineBorder;
import javax.swing.text.html.CSS;

/**
 *
 * @author OLANREWAJU B.S
 */
class ResultFrame extends JFrame {

    //HEADERS LABELS
     JLabel l1 = new JLabel("Distance From PU TX");
     JLabel l2 = new JLabel("Distance From Cognitive Radio AP");
     JLabel l3 = new JLabel("Transmitting Power Of CR AP");
```

```
   JLabel l4 = new JLabel("Transmitting Power of Cognitive radio in Watt PCIR");
   JLabel l5 = new JLabel("Transmit");
   JLabel l6 = new JLabel("CAPCRAP");
   JLabel l7 = new JLabel("CAPCR");
   JLabel l8 = new JLabel("SUE");

   //Labels that display the figure LABELS
   JTextArea figureArea1 = new JTextArea();
   JPanel p1 = new JPanel();
   JPanel p2 = new JPanel();
   JPanel p3 = new JPanel();
   JPanel p4 = new JPanel();
   JPanel p5 = new JPanel();
   JPanel p6 = new JPanel();
   JPanel p7 = new JPanel();
   JPanel p8 = new JPanel();
   //BORDERS FOR FANCY
   Border greenBorder = new LineBorder(new Color(117,236,83));
   Border lightBlueBorder = new LineBorder(new Color(120,129,209));
ResultFrame(){
   l1.setForeground(Color.WHITE);
   l2.setForeground(Color.WHITE);
   l3.setForeground(Color.WHITE);
   l4.setForeground(Color.WHITE);
   l5.setForeground(Color.WHITE);
```

```
l6.setForeground(Color.WHITE);
l7.setForeground(Color.WHITE);
l8.setForeground(Color.WHITE);

l1.setFont(new Font("",Font.BOLD,14));
l2.setFont(new Font("",Font.BOLD,14));
l3.setFont(new Font("",Font.BOLD,14));
l4.setFont(new Font("",Font.BOLD,14));
l5.setFont(new Font("",Font.BOLD,14));
l6.setFont(new Font("",Font.BOLD,14));
l7.setFont(new Font("",Font.BOLD,14));
l8.setFont(new Font("",Font.BOLD,14));

l1.setBorder(lightBlueBorder);
l2.setBorder(lightBlueBorder);
l3.setBorder(lightBlueBorder);
l4.setBorder(lightBlueBorder);
l5.setBorder(lightBlueBorder);
l6.setBorder(lightBlueBorder);
l7.setBorder(lightBlueBorder);
l8.setBorder(lightBlueBorder);

l1.setToolTipText("Distance From PU TX");
l2.setToolTipText("Distance From Cognitive Radio AP");
l3.setToolTipText("Transmitting Power Of CR AP");
```

```
l4.setToolTipText("Transmitting Power of Cognitive radio in Watt PCIR");

figureArea1.setForeground(new Color(131,231,210));
figureArea1.setBackground(new Color(0,4,51));
//figureArea1.setEditable(false);
figureArea1.setLineWrap(true);

p1.setLayout(new BorderLayout(5,5));
p1.add(l1,BorderLayout.NORTH);
p1.add(figureArea1,BorderLayout.CENTER);
p1.setBackground(new Color(0,4,51));
p1.setBorder(greenBorder);

p2.setLayout(new BorderLayout(5,5));
p2.add(l2,BorderLayout.NORTH);
p2.setBackground(new Color(0,4,51));
p2.setBorder(greenBorder);

p3.setLayout(new BorderLayout(5,5));
p3.add(l3,BorderLayout.NORTH);
p3.setBackground(new Color(0,4,51));
p3.setBorder(greenBorder);

p4.setLayout(new BorderLayout(5,5));
p4.add(l4,BorderLayout.NORTH);
```

```
p4.setBackground(new Color(0,4,51));
p4.setBorder(greenBorder);

p5.setLayout(new BorderLayout(5,5));
p5.add(l5,BorderLayout.NORTH);
p5.setBackground(new Color(0,4,51));
p5.setBorder(greenBorder);

p6.setLayout(new BorderLayout(5,5));
p6.add(l6,BorderLayout.NORTH);
p6.setBackground(new Color(0,4,51));
p6.setBorder(greenBorder);

p7.setLayout(new BorderLayout(5,5));
p7.add(l7,BorderLayout.NORTH);
p7.setBackground(new Color(0,4,51));
p7.setBorder(greenBorder);

p8.setLayout(new BorderLayout(5,5));
p8.add(l8,BorderLayout.NORTH);
p8.setBackground(new Color(0,4,51));
p8.setBorder(greenBorder);
```

```
        setLayout(new GridLayout(1,8,0,0));
        add(p1);
        add(p2);
        add(p3);
        add(p4);
        add(p5);
        add(p6);
        add(p7);
        add(p8);
    }

}
```

D3: MAFITM MODEL

```
import javax.swing.*;
import javax.swing.JScrollPane;
import java.util.*;
import java.text.DecimalFormat;
class HybridG {

                public static void main(String[] args){
        // DECLARATION AND INITIALIZATIONS


double c = 3 * Math.pow(10, 8);                // Speed of light in m/s

double k = 1.38 * Math.pow(10, -23);         //Boltzmann constant in J/K

double EPAP = 0; //Energy of primary signal as received by  cognitive radio Access Point

double EPCR = 0; // Energy of primary signal as received by cognitive radio

double ELCR = 0; //The limit of the energy of interference signal at CR

double ELAP = 0; // The limit of the energy of interference signal at CR AP

double ECRIMAX;  //Maximum signal of Cognitive radio Access

double ECRI;           //Energy due to the signal of cognitive radio node at cognitive radio AP

double ECRAP;       //Energy due to the signal of cognitive radio AP at a cognitive radio location

double ECRAPMAX;

double ECRIMDS = 7.94 * Math.pow(10, -14) ;//Minimum detectable signal of cognitive radio in
                                                                   // Watts

double PCRI =0 ; //Transmitting Power of Cognitive radio node in Watt

double PCRAP =0; //Transmitting Power of Cognitive radio access point in Watt

double PCRIMAX = 4;//Transmitting Power of Cognitive radio in W

double PCRAPMAX =4;

String frequency;     // Frequency of Transmission

String PTPower;       // Primary Signal Transmitting Power

String dy;

String dz;

String Period;     //The ON-OFF Period of Primary Signal

double ton;    //Time Factor for the ON Period of Primary Signal
```

```
double toff;  //Time Factor for the OFF Period of Primary Signal

double capacityCR;    //Summed data Capacity of Cognitive radio Node for the ON Period of
                      //Primary Signal

double maxcapacityCR; //Summed data Capacity of Cognitive radio Node for the OFF Period of
                      //Primary Signal

double capacityAP; //Summed data Capacity of Cognitive radio Access Point for the ON Period
                   //of Primary Signal

double maxcapacityAP; //Summed data Capacity of Cognitive radio AP for the OFF Period of
                      //Primary Signal

String result =" "; // INITIALIZATION OF  OUTPUT

double EIRP;

int F = 0;            // Centre frequency

int B = 18000000;            // Bandwidth

double PUTRE = 2.5 * Math.pow(10, -15);  //Received Primary signal threshold in watt

                                          // (-116 dBm)

double TLAP;            // Interference limit at CR AP

double TLCR;            // Interference limit at CR

double TI = 290;    // Interference temperature floor in kelvin

double TAP;  //Interference temperature due to cognitive radio Access Point signal

double TCRI;  //Interference temperature due to CR signal

double TTOT;       // Total interference temperature

int x =0;   //Distance of cognitive radio from Primary Transmitter in metres

int y ;    //Distance of cognitive radio from Cognitive Radio Access Point in metres

int z ;   //Distance of Primary Transmitter from Cognitive Radio Access Point in metres

double YTAP=0;  //Output of match filter of CR Access Point

double YTCR=0;      //Output of match filter of cognitive radio

double N = 3.162277; //Additive white gaussian noise Power (5dB)

String Transmit = "";

double SCR;

double SCRMAX;
```

```
double EFF=0;

double RSE=0;

double SUE=0;

double SE=0;

double SSUE=0;

double CAPCR = 0;

double CAPCRMAX=0;

double SCRAP;

double SCRAPMAX;

double CAPCRAP = 0;

double CAPCRAPMAX =0;

DecimalFormat twoDigits = new DecimalFormat("0.00");

JTextArea output = new JTextArea(40,90);

JScrollPane scrollbar = new JScrollPane(output);

PTPower = JOptionPane.showInputDialog ("Enter Primary Signal Transmitting Power in
                                                                                          Watts");

EIRP = Double.parseDouble(PTPower);

frequency = JOptionPane.showInputDialog

 ("Enter the Centre Frequency of Transmission in Hz");

F = Integer.parseInt(frequency);

dz= JOptionPane.showInputDialog ("Enter the distance of Primary Transmitter from CR AP");

 z= Integer.parseInt(dz);

Period= JOptionPane.showInputDialog ("Enter the Time Factor for the ON Period of Primary
                                                                                          Signal");

ton= Double.parseDouble(Period);

toff = 1- ton;

            for (y = 1; y< 100001 ;y=y+100 )

                  {

            double M = 1-(y/100000);  //Attenuation Factor between CR
```

```
//Access Point and Cognitive Radio Node
        if (z >= y)
    { x = z - y;
    } // End if
      if (y > z)
        { x = y - z;
        } // End if
EPAP = (EIRP)/Math.pow((4*Math.PI*z*F/c),2);//Calculate Signal Power of  Primary
                                              Transmitter as received by CR AP

EPCR = (EIRP)/Math.pow((4*Math.PI*x*F/c),2);//Calculate Signal Power of Primary
                                      //Transmitter as received by Cognitive Radio Node

YTAP = 2*EPAP/N;      // Calculate Match Filter Output of CRAP

YTCR = 2*EPCR/N;     // Calculate Match Filter Output of CR

     if ((YTAP >= PUTRE) & (YTCR >= PUTRE))  //Testing  the presence of primary signal
                                                 //At CRAP and CR

              {

ELAP = 0.05*YTAP;

ELCR = 0.05*YTCR;

TLAP = (ELAP)/(B*k);  //Interference Temperature limit at CRAP

TLCR = (ELCR)/(B*k);  // Interference Temperature limit at CR

TLAP = TLAP - TI; //Maximum Permissible Interference Temperature produced by a Cognitive
               radio AP

TLCR = TLCR - TI ;  //Maximum Permissible Interference Temperature produced by a Cognitive
                    radio

 PCRAP  = TLAP*B*k;   // Allowable Transmitting Power of CRAP

PCRI  = TLCR*B*k;   // Allowable Transmitting Power of CR

ECRAP = (PCRAP)/(Math.pow((4*Math.PI*y*F/c),2)); //Signal power

                    //of CRAP as received by CR

ECRI = (PCRI)/(Math.pow((4*Math.PI*y*F/c),2)); //Signal power of CR as received by CRAP

YTAP = (10* Math.log10(YTAP))+30;//MFilter output at CRAP in dBm

YTCR = (10* Math.log10(YTCR))+30;//MFilter output at CRN in dBm
```

```
if (( ECRI > ECRIMDS) & (ECRAP > ECRIMDS))
      { Transmit = "Yes" ;
    SCRAP = 1+ ((M*PCRAP)/((k*TI*B)+ EPAP));// SNR of CRAP
    CAPCRAP =B*(Math.log10(SCRAP)/Math.log10(2));//Capacity of CRAP
    SCR = 1+ ((M*PCRI)/((k*TI*B)+EPCR));// SNR of CR
    CAPCR = B*(Math.log10(SCR)/Math.log10(2)); //Capacity of CR
    PCRAP =(10* Math.log10(PCRAP))+ 30;//CRAP Transmit power in dBm
    PCRI = (10* Math.log10(PCRI))+30;  // CR Transmit power in dBm
    ECRAPMAX = (PCRAPMAX)/Math.pow((4*Math.PI*y*F/c),2);   //Maximum
                    //Signal power of CRAP as received by CR
  ECRIMAX = (PCRIMAX)/Math.pow((4*Math.PI*y*F/c),2);
        //Maximum Signal power CR as received by CRAP
    SCRAPMAX = 1+((ECRAPMAX)/(k*TI*B));
    CAPCRAPMAX = B*(Math.log10(SCRAPMAX)/Math.log10(2));
  SCRMAX = 1+((ECRIMAX)/(k*TI*B));  // Calculate data capacity
    CAPCRMAX = B*(Math.log10(SCRMAX)/Math.log10(2));//Calculate Cap
    SSUE = CAPCRMAX/(B*(Math.PI)*y*y) ;
    capacityCR = CAPCR*ton;//capacity of CR when primary user is ON
    maxcapacityCR = CAPCRMAX*toff;
          //capacity of CR when primary user is OFF
    CAPCR = capacityCR + maxcapacityCR;
  // total capacity of CR node throughout a period of time t
    capacityAP = CAPCRAP*ton;
          // capacity of AP when primary user is ON
    maxcapacityAP = CAPCRAPMAX*toff;
          // capacity of AP when primary user is OFF
    CAPCRAP = capacityAP + maxcapacityAP;
  // total capacity of AP node throughout a period of time t
        if (CAPCR < CAPCRAP)
```

```
                {
                 EFF = (CAPCR/CAPCRMAX)* 100;
           SUE = CAPCR/(B*(Math.PI)*y*y) ;
                 SE = CAPCR/(B) ;
                 RSE = (SUE/SSUE)* 100;
                }
                 EFF = (CAPCRAP/CAPCRMAX)* 100;
                 SUE = CAPCRAP/(B*(Math.PI)*y*y) ;
                 SE = CAPCRAP/(B) ;
                 RSE = (SUE/SSUE)* 100;
         result +="\nDistance From PU TX\tDistance From Cognitive Radio AP"
      +"\tTransmitting Power of CR AP\tTransmitting Power of CR Node"
      +"\tUplink Data Capacity\tDownlnk Data Capacity\tEfficiency"  ;

     result +="\n"+ x +"\t"+ y +"\t"+ PCRAP +"\t"+ PCRI +"\t"+YTAP+"\t"+YTCR
      +"\t"+CAPCRAP +"\t"+ CAPCR+"\t"+ EFF +"\t"+ SUE +"\t"+ SE
      +"\t" +SSUE+"\t"+ RSE +"\n";

           // SET OUTPUT TO NON-EDITABLE
      output.setEditable(false);
      output.setText(result);
      JOptionPane.showMessageDialog
       (null,scrollbar, "RESULT" ,JOptionPane.PLAIN_MESSAGE);
            } // End if statement
     else      { Transmit = "No";
result +="\nPrimary Signal Power at CRAP\tPrimary Signal Power at CR Node\t";
result +="\n"+YTAP+"\t"+YTCR+"\n";
           output.setEditable(false);
      output.setText(result);
```

```
JOptionPane.showMessageDialog
     (null,scrollbar, "TRANSMISSION NOT POSSIBLE" ,JOptionPane.PLAIN_MESSAGE);
                    System.exit(0);
               }   // end else statement
                 } // End if statement
       else {    Transmit = "Yes" ;
       ECRAPMAX = (PCRAPMAX)/Math.pow((4*Math.PI*y*F/c),2);
                 // Maximum Signal power of CRAP as received by CR
       ECRIMAX = (PCRIMAX)/Math.pow((4*Math.PI*y*F/c),2);
     // Maximum Signal power CR as received by CR AP
     SCRAPMAX = 1+((ECRAPMAX)/(k*TI*B));
       CAPCRAPMAX = B*(Math.log10(SCRAPMAX)/Math.log10(2));
       SCRMAX = 1+((ECRIMAX)/(k*TI*B));     // Calculate capacity
       CAPCRMAX = B*(Math.log10(SCRMAX)/Math.log10(2));//Calculate capacity
       capacityAP =  CAPCRAPMAX * toff ;
       capacityCR = CAPCRMAX*toff;
       SSUE = CAPCRMAX/(B*(Math.PI)*y*y) ;
       SE = capacityCR/B;
     EFF = (capacityCR/CAPCRMAX)* 100;
       SUE = capacityCR/(B*(Math.PI)*y*y) ;
       RSE = (SUE/SSUE)* 100;
 result +="\nDistance From PU TX\tDistance From Cognitive Radio AP"
     + "\tTransmitting Power of CR AP\tTransmitting Power of CR Node"
     + "\tUplink Data Capacity\tDownlnk Data Capacity\tEfficiency"  ;

result +="\n"+ x +"\t"+ y +"\t"+ PCRAPMAX +"\t"+ PCRIMAX +"\t"+YTAP+"\t"
     +YTCR+"\t"+capacityAP +"\t"+ capacityCR+"\t"+ EFF +"\t"+ SUE +"\t"
     + SE +"\t" +SSUE+"\t"+ RSE +"\n";
  // SET OUTPUT TO NON-EDITABLE
```

```
  output.setEditable(false);
  output.setText(result);
  JOptionPane.showMessageDialog
   (null,scrollbar, "RESULT" ,JOptionPane.PLAIN_MESSAGE);
  }       // end else statement
           } // end for loop
System.exit(0);
         }  // END MAIN
}  //END CLASS
```

D4: OVERLAY MODEL

```
import javax.swing.*;
import javax.swing.JScrollPane;
import java.util.*;
import java.text.DecimalFormat;
class OverlayA {


            public static void main(String[] args){

      // DECLARATION AND INITIALIZATIONS

double c = 3 * Math.pow(10, 8);            // Speed of light in m/s

double k = 1.38 * Math.pow(10, -23);       //Boltzmann constant in J/K

double EPAP = 0; //Energy of primary signal as received by  cognitive radio Access Point

double EPCR = 0; // Energy of primary signal as received by cognitive radio

double ELCR = 0; //The limit of the energy of interference signal at CR

double ELAP = 0; // The limit of the energy of interference signal at CR AP

double ECRIMAX;  //Maximum signal of Cognitive radio Access

double ECRI;        //Energy due to the signal of cognitive radio nodeat cognitive radio AP

double ECRAP;      //Energy due to the signal of cognitive radio AP at a cognitive radio location

double ECRAPMAX;

double ECRIMDS = 7.94 * Math.pow(10, -14) ;//Minimum detectable signal of cognitive radio in
                                           // Watts

double PCRI =0 ; //Transmitting Power of Cognitive radio node in Watt

double PCRAP =0; //Transmitting Power of Cognitive radio access point in Watt

double PCRIMAX = 4;//Transmitting Power of Cognitive radio in W

double PCRAPMAX =4;

String frequency;    // Frequency of Transmission

String PTPower;      // Primary Signal Transmitting Power

String dy;

String dz;

String Period;    //The ON-OFF Period of Primary Signal
```

```
double ton;    //Time Factor for the ON Period of Primary Sigal

double toff;  //Time Factor for the OFF Period of Primary Sigal

double capacityCR;    //Summed data Capacity of Cognitive radio Node for the ON Period of
                      //Primary Signal

double maxcapacityCR; //Summed data Capacity of Cognitive radio Node for the OFF Period of
                      //Primary Signal

double capacityAP; //Summed data Capacity of Cognitive radio Access Point for the ON Period
                   //of Primary Signal

double maxcapacityAP; //Summed data Capacity of Cognitive radio AP for the OFF Period of
                      //Primary Signal

String result =" "; // INITIALIZATION OF  OUTPUT

double EIRP;

int F = 0;            // Centre frequency

int B = 18000000;            // Bandwidth

double PUTRE = 2.5 * Math.pow(10, -15);  //Received Primary signal threshold in watt

                                          // (-116 dBm)

double TLAP;            // Interference limit at CR AP

double TLCR;            // Interference limit at CR

double TI = 290;    // Interference temperature floor in kelvin

double TAP;  //Interference temperature due to cognitive radio Access Point signal

double TCRI;  //Interference temperature due to CR signal

double TTOT;       // Total interference temperature

int x =0;   //Distance of cognitive radio from Primary Transmitter in metres

int y ;    //Distance of cognitive radio from Cognitive Radio Access Point in metres

int z ;   //Distance of Primary Transmitter from Cognitive Radio Access Point in metres

double YTAP=0;  //Output of match filter of CR Access Point

double YTCR=0;      //Output of match filter of cognitive radio

double N = 3.162277; //Additive white gaussian noise Power (5dB)

String Transmit = "";

double SCR;
```

```
double SCRMAX;

double EFF=0;

double RSE=0;

double SUE=0;

double SE=0;

double SSUE=0;

double CAPCR = 0;

double CAPCRMAX=0;

double SCRAP;

double SCRAPMAX;

double CAPCRAP = 0;

double CAPCRAPMAX =0;

DecimalFormat twoDigits = new DecimalFormat("0.00");

JTextArea output = new JTextArea(40,90);

JScrollPane scrollbar = new JScrollPane(output);

PTPower = JOptionPane.showInputDialog ("Enter Primary Signal Transmitting Power in
                                                                                Watts");

EIRP = Double.parseDouble(PTPower);

frequency = JOptionPane.showInputDialog

 ("Enter the Centre Frequency of Transmission in Hz");

F = Integer.parseInt(frequency);

dz= JOptionPane.showInputDialog ("Enter the distance of Primary Transmitter from CR AP");

 z= Integer.parseInt(dz);

Period= JOptionPane.showInputDialog ("Enter the Time Factor for the ON Period of Primary
                                                                                Signal");

ton= Double.parseDouble(Period);

toff = 1- ton;

      for (y = 0; y< 10000001 ;y=y+1000 )

                  {
```

```
if (z > y)
{ x = z - y;
} // End if
if (y > z)
{ x = y - z;
} // End if
double M = 1-(y/100000);  // Attenuation Factor between Cognitive Radio Access Point and Cognitive Radio Node
EPAP = (EIRP)/Math.pow((4*Math.PI*z*F/c),2);
EPCR = (EIRP)/Math.pow((4*Math.PI*x*F/c),2);
YTAP = 2*EPAP/N;
YTCR = 2*EPCR/N;
if ((YTAP > PUTRE) & (YTCR > PUTRE))        // Testing  the presence of primary signal
{
Transmit = "No";
JOptionPane.showMessageDialog (null,scrollbar, "TRANSMISSION NOT POSSIBLE" ,JOptionPane.PLAIN_MESSAGE);
System.exit(0);
} // End if statement
PCRAP = 4;
PCRI = 4;
ECRAP = (PCRAP)/Math.pow((4*Math.PI*y*F/c),2); // Signal power received from cognitive radio AP
ECRI = (PCRI)/Math.pow((4*Math.PI*y*F/c),2); // Signal power received from cognitive radio AP
if (( ECRI > ECRIMDS) & (ECRAP > ECRIMDS))
{
```

```
Transmit = "Yes" ;

 // ECRI = 10* Math.log(ECRI);  // Cognitive radio AP Signal power in dBm

SCRAP = 1+ ((M*PCRAP)/((k*TI*B)+ EPAP));   // Signal To Noise Ratio of CRAP

CAPCRAP = B*(Math.log10(SCRAP)/Math.log10(2)); // Data Capacity of CRAP

SCR = 1+ ((M*PCRI)/((k*TI*B)+EPCR));       // Signal To Noise Ratio of CR

CAPCR = B*(Math.log10(SCR)/Math.log10(2)); // Data Capacity of CR

ECRAPMAX = (PCRAPMAX)/Math.pow((4*Math.PI*y*F/c),2); // Maximum Signal power of
                                                     CRAP as received by CR

ECRIMAX = (PCRIMAX)/Math.pow((4*Math.PI*y*F/c),2); // Maximum Signal power CR as
                                                   received by CR AP
SCRAPMAX = 1+((ECRAPMAX)/(k*TI*B));

CAPCRAPMAX = B*(Math.log10(SCRAPMAX)/Math.log10(2));

capacityAP =  CAPCRAPMAX * toff ;

SCRMAX = 1+((ECRIMAX)/(k*TI*B));       // Calculate data capacity

CAPCRMAX = B*(Math.log10(SCRMAX)/Math.log10(2)); // Calculate data capacity

capacityCR = CAPCRMAX*toff;

SSUE = CAPCRMAX/(B*(Math.PI)*y*y) ;

SUE = capacityCR/(B*(Math.PI)*y*y) ;

SE = capacityCR/B;

RSE = (SUE/SSUE)* 100;

EFF = (capacityCR/CAPCRMAX)* 100;

 // PRESENTING THE RESULT TO THE USER

 result +="\nDistance From PU TX\tDistance From Cognitive Radio AP\tTransmitting Power of
CR AP\tTransmitting Power of CR Node\tUplink Data Capacity\tDownlnk Data
Capacity\tEfficiency"  ;


result +="\n"+ x +"\t"+ y +"\t"+ PCRAP +"\t"+ PCRI +"\t"+ capacityAP +"\t"+ capacityCR+"\t"+
EFF +"\t"+ SUE +"\t"+ SE +"\t"+ SSUE +"\t"+ RSE + "\n";

}
```

```
                                }

 // SET OUTPUT TO NON-EDITABLE

   output.setEditable(false);

   output.setText(result);

   JOptionPane.showMessageDialog (null,scrollbar, "RESULT"
,JOptionPane.PLAIN_MESSAGE);

  System.exit(0);

            }  // END MAIN

}  //END CLASS
```

D5: UNDERLAY MODEL

```
import javax.swing.*;
import javax.swing.JScrollPane;
import java.util.*;
import java.text.DecimalFormat;
class UnderlayB {

            public static void main(String[] args){

      // DECLARATION AND INITIALIZATIONS

double c = 3 * Math.pow(10, 8); // Speed of light in m/s

double k = 1.38 * Math.pow(10, -23) ;     // Boltzmann constant in J/K

double EPAP = 0;        // Energy of primary signal as received by cognitive radio Access Point

double EPCR = 0;        // Energy of primary signal as received by cognitive radio

double ELCR = 0;        // The limit of the energy of interference signal at CR

double ELAP = 0;        // The limit of the energy of interference signal at CR AP

double ECRIMAX;      // Maximum signal of Cognitive radio Access

double ECRAPMAX;  // Signal power received from cognitive radio AP

double SCRAPMAX ;

double CAPCRAPMAX ;

double SCRMAX ;         // Calculate data capacity

double CAPCRMAX;

int PCRAPMAX =4;

int PCRIMAX =4;

double maxcapacityCR;  // Summed data Capacity of Cognitive radio for the OFF Period of
                       //Primary Signal

double maxcapacityAP;  // Summed data Capacity of Cognitive radio for the OFF Period of
                      //Primary Signal

double capacityCR;  // Summed data Capacity of Cognitive radio for the OFF Period of Primary
                      //Signal

double capacityAP;  // Summed data Capacity of Cognitive radio for the OFF Period of Primary
                      //Signal
```

```
double ECRI =0;        // Energy due to the signal of cognitive radio at cognitive radio AP

double ECRAP =0;        // Energy due to the signal of cognitive radio AP at a cognitive radio
                        //location

double ECRIMDS = 2.4 * Math.pow(10, -17) ;      // Minimum detectable signal of cognitive
                                                //radio in Watts

double PCRI =0 ;    // Transmitting Power of Cognitive radio in Watt

double PCRAP =0;

String frequency;    // Frequency of Transmission

String PTPower;      // Primary Signal Transmitting Power

String distance;

String Period;

String dz;

String dy;

String Interference;

String result =" "; // INITIALIZATION OF  OUTPUT

double EIRP;

int F = 0;          // Centre frequency

int B = 18000000;          // Bandwidth

double PUTRE = 2.5 * Math.pow(10, -15);   // Received Primary signal threshold in watt (-116
                                          dBm)

double TL ;          // Interference limit at CR AP

double TLCR;          // Interference limit at CR

double TI = 290;      // Interference temperature floor in kelvin

double TAP;          // Interference temperature due to cognitive radio AP signal

double TCRI;          // Interference temperature due to cognitive radio signal

double ton;       // Time Factor for the ON Period of Primary Sigal

double toff;      // Time Factor for the OFF Period of Primary Sigal

double TTOT;        // Total interference temperature
```

```
int x = 0;          // Distance of cognitive radio from Primary Transmitter in metres
int y ;          // Distance of cognitive radio from Cognitive Radio Access Point in metres
int z;
double YTAP;        // Output of match filter of cognitive radio Access Point
double YTCR;        // Output of match filter of cognitive radio
double N = N = 3.16227766;        // Additive white gaussian noise Power (5 dB)
String Transmit = "";
double SCR;
double EFF=0;
double RSE;
double SUE;
double SE;
double SSUE;
double CAPCR = 0;
double SCRAP;
double CAPCRAP = 0;
DecimalFormat twoDigits = new DecimalFormat("0.00");
JTextArea output = new JTextArea(40,90);
JScrollPane scrollbar = new JScrollPane(output);
Interference = JOptionPane.showInputDialog("Enter The Interference Temperature Limit");
TL = Double.parseDouble(Interference);
PTPower = JOptionPane.showInputDialog("Enter Primary Signal Transmitting Power in Watts");
EIRP = Double.parseDouble(PTPower);
frequency = JOptionPane.showInputDialog("Enter the Centre Frequency of Transmission in
                                                                    Hz");
F = Integer.parseInt(frequency);
```

```
dz= JOptionPane.showInputDialog("Enter the distance of Primary Transmitter from CR Access
                                                                                    Point");
z= Integer.parseInt(dz);

Period= JOptionPane.showInputDialog("Enter the Time Factor for the ON Period of Primary
                                                                              Signal");

 ton= Double.parseDouble(Period);

toff = 1- ton;

                    for (y = 1; y< 100002 ;y=y+10000 )

                              {

double M = 1-(y/100000);  // Attenuation Factor between Cognitive Radio Access Point and
                                                                      //Cognitive Radio Node

                    if (z >= y)

             { x = z - y;

             } // End if

                    if (y > z)

                    { x = y - z;

                    } // End if


EPAP = (EIRP)/Math.pow((4*Math.PI*z*F/c),2);   // Calculate Signal Power of Primary
                                        //Transmitter as received by Cognitive Radio Access Point

EPCR = (EIRP)/Math.pow((4*Math.PI*x*F/c),2);   // Calculate Signal Power of Primary
Transmitter as received by Cognitive Radio Node

YTAP = 2*EPAP/N;                         // Calculate Match Filter Output of CRAP

YTCR = 2*EPCR/N;                          // Calculate Match Filter Output of CR

  PCRAP = ((TL - TI)*B*k)/M ;   // Transmitting Power of CR AP

  PCRI  = PCRAP;             // Transmitting Power of CR

 ECRAP = (PCRAP)/Math.pow((4*Math.PI*y*F/c),2); // Signal power of CR AP at a cognitive
                                                                              //radio location

 ECRI = (PCRI)/Math.pow((4*Math.PI*y*F/c),2); // Signal power received from cognitive radio
                                                                              at CR AP
```

```
SCRAP = 1+(M*ECRAP/((k*TI*B)+ EPAP));   // Signal To Noise Ratio of CRAP
 CAPCRAP = B*(Math.log10(SCRAP)/Math.log10(2)); // Data Capacity of CRAP
 SCR = 1+(M*ECRI/((k*TI*B)+EPCR));            // Signal To Noise Ratio of CR
 CAPCR = B*(Math.log10(SCR)/Math.log10(2)); // Data Capacity of CR
  capacityCR = CAPCR * ton;
  capacityAP = CAPCRAP *ton;
SCRAPMAX = 1+((M*ECRAP)/(k*TI*B));
CAPCRAPMAX = B*(Math.log10(SCRAPMAX)/Math.log10(2));
SCRMAX = 1+((M*ECRI)/(k*TI*B));            // Calculate data capacity
CAPCRMAX = B*(Math.log10(SCRMAX)/Math.log10(2)); // Calculate data capacity
 maxcapacityCR = CAPCRMAX*toff;  // capacity of CR when primary user is OFF
maxcapacityAP = CAPCRAPMAX*toff;     // capacity of AP when primary user is OFF
CAPCR = capacityCR + maxcapacityCR;  // total capacity of CR node throughout a period of
                                                                              //time t
CAPCRAP = capacityAP + maxcapacityAP;  // total capacity of AP node throughout a period of
time t
PCRAP = (10* Math.log10(PCRAP))+ 30;  // CRAP Transmit power in dBm
PCRI = (10* Math.log10(PCRI))+30;  // CR Transmit power in dBm
YTAP = (10* Math.log10(YTAP))+30;  // Matched Filter output at CRAP in dBm
YTCR = (10* Math.log10(YTCR))+30;  // Matched Filter output at CR node in dBm
                    SSUE = CAPCRMAX/(B*(Math.PI)*y*y);
                    SUE = CAPCR/(B*(Math.PI)*y*y) ;
                    SE = CAPCR/B ;
                    RSE = (SUE/SSUE)* 100;
                    EFF = (CAPCR/CAPCRMAX)* 100;
 result +="\nDistance From PU TX\tDistance From Cognitive Radio AP\tTransmitting Power of
CR AP\tTransmitting Power of CR Node\tUplink Data Capacity\tDownlnk Data
Capacity\tEfficiency"  ;
```

```
 result +="\n"+ x +"\t"+ y +"\t"+ PCRAP +"\t"+ PCRI +"\t"+YTAP+"\t"+YTCR+"\t"+CAPCRAP
+"\t"+ CAPCR+"\t"+ EFF +"\t"+ SUE +"\t"+ SE +"\t" +SSUE+"\t"+ RSE +"\n";


                        // SET OUTPUT TO NON-EDITABLE
output.setEditable(false);
output.setText(result);
JOptionPane.showMessageDialog (null,scrollbar, "RESULT" ,JOptionPane.PLAIN_MESSAGE);
                              }
System.exit(0);
          }  // END MAIN
}  //END CLASS
```