DESIGN OF A VIRTUAL WIRELESS LINK SELECTION ALGORITHM FOR RELIABILITY OF COOPERATIVE COGNITIVE RADIO NETWORKS

Daniel Hailu Tirkasso
EE300-0009/12

Master of Science in Electrical Engineering
(Telecommunication Option)

PAN AFRICAN UNIVERSITY

INSTITUTE FOR BASIC SCIENCES TECHNOLOGY AND INNOVATION

August 2014

DESIGN OF A VIRTUAL WIRELESS LINK SELECTION ALGORITHM FOR RELIABILITY OF COOPERATIVE COGNITIVE RADIO NETWORKS

Daniel Hailu Tirkasso
EE300-0009/12

A thesis submitted to Pan African University, Institute for Basic Sciences Technology and Innovation in partial fulfillment of the requirement for the degree of

Master of Science in Electrical Engineering

(Telecommunication Option)

August 2014

DECLARATION

This thesis is my original work and has not been submitted to any other university for examination.

Signature: ………………… Date: ………………………

Daniel Hailu Tirkasso

This thesis report has been submitted for examination with our approval as university supervisors.

Signature: …………………… Date: ……………………………

Dr. Hillary Tarus (Technical Director at WIOCC, Kenya)

Signature: …………………. Date: …………………………..

Dr. Philip Kibet Langat (Chair of Department at JKUAT and Program Coordinator at PAUISTI)

Acknowledgements

First of all I would like to thank the Almighty God for His Mercy, Love and Blessings upon me.

My way towards this master thesis would not have been possible without the support of various people. So it is my pleasure to take this opportunity to thank them all.
I would like to express my greatest gratitude to my supervisors, Dr. P. K. Langat and Dr. H.Tarus for their guidance, understanding, motivation and excellent support during this study and preparation of this thesis.

I would also like to express my gratitude to the PAUISTI Director, Prof. G.Magoma, Deputy Director Dr. Hunja Waithaka and PAUISTI Staff Isaac, Andrew, Madam Christine and Joyce for their guidance and contributions. I would also like to thank Prof. V.K.Oduol, Dr. S.Kimani, Dr. S.Musyoki, Prof. D.B. O. Konditi and Dr. E.N. Ndungu for the valuable information they provided in their classes.

I would also like to thank the African Union Commission for their support with the scholarship they provided me for two years.

I would like to thank my family in Nairobi, Aydagn, Lemlem, Wakjira, Kalkidan, Meazi, Wudinesh and Gash Girma for their warmest hospitality & for making me to feel at home by devising a comfort zone over the weekend & during holidays.

Further, I would like to thank my fellow pioneer students at PAUISTI who came from thirteen different African countries for their good friendliness and support.

Finally, I am deeply grateful to my wife Tsion Gebre and daughter Yohana Daniel for their infinite understanding, comfort and accompany that make this thesis possible. I am also sincerely grateful to my family, my brothers, and my sisters and especially to my father Hailu Tirkasso for unconditionally supporting and assisting me spiritually throughout my life.

Dedication

Behind this thesis is a strong woman to whom I dedicate this work.
My wife, Tsion Gebre, who is my best friend and companion, gave me the support through her love and understanding.
She is the beacon of my life.

Abstract

Owing to the rapidly increasing number of users in the wireless technology and the renovation of voice-only communications to multimedia applications, increasing efficiency of spectrum usage is an urgent and reliable solution. Cognitive radio is considered as a promising candidate to be employed in such systems as they are aware of their operating environments and can be trained to dynamically and autonomously adjust its radio operating parameters accordingly.

The objective of this research is to design, analyze and simulate a more reliable cooperative cognitive radio network that is able to establish a virtual wireless link before the actual communication starts. A system model for the cognitive radio network is developed and a virtual wireless link selection (VWLS) algorithm for cooperative cognitive radio networks is then developed.

The virtual wireless link is used to carry out the end-to-end data transmission. The VWLS algorithm is then analyzed and computer simulated to show the impact of the virtual link on the performance of the network. To interpret the simulation results and explicate the relation between the number of available free channels and number of virtual links to be established, the idea of probability theory is used.

Performance evaluation shows significant improvements not only in the secondary users blocking and forced termination probabilities but also in the throughput of cognitive users. By demonstrating the performance improvement of the cognitive radio network (CRN) with the help of the newly developed algorithm, it is proved that the reliability is also enhanced.

TABLE OF CONTENTS

LIST OF FIGURES

ABBREVIATIONS

AWGN	Additive White Gaussian Noise
BER	Bit Error Rate
BS	Base Station
CDMA	Code-Division Multiple Access
CFCDB	Central Free Channel DataBase
CMOS	Complementary Metal Oxide Semiconductor
CR	Cognitive Radio
CRN	Cognitive Radio Network
CRS	Cognitive Radio Systems
DTX	Discontinuous Voice Transmission
ECL	Emitter Coupled Logic
ED	Energy Detection
EM	Electromagnetic
FCC	Federal Communications Commission
FDMA	Frequency-Division Multiple Access
FFT	Fast Fourier Transform
GSM	Global System for Mobile Communications
HLR	Home Location Register
IO	Interacting Object
ISI	InterSymbol Interference
LOS	Line of Sight
LTE	Long Term Evolution
MF	Matched Filtering

MPC	Multi Path Component
MS	Mobile Station
NGN	Next Generation Network
OFDM	Orthogonal Frequency Division Multiplexing
PU	Primary User
RAT	Radio Access Technology
RX	Receiver
SNR	Signal-to-Noise Ratio
SU	Secondary User
TDMA	Time-Division Multiple Access
TX	Transmitter
VLR	Visitor Location Register
VWLS	Virtual Wireless Link Selection
WLAN	Wireless Local Area Network
WSS	Wide Sense Stationary

CHAPTER 1: INTRODUCTION

1.1 Background

In the background section, characteristics of the wireless communication system are discussed along with its technical challenges. According to Molisch [1], the most notable technical challenges of wireless communications are multipath propagation, spectrum limitations, spectrum sharing issues, energy limitations and user mobility.

1.1.1 Multipath Propagation

The characteristics of a wireless communication channel between transmitter and receiver controls the performance of the overall system [2]. For wireless communications, the transmission medium is the radio channel between transmitter (TX) and receiver (RX). The signal can get from the TX to the RX via a number of different propagation routes. In some cases, a Line of Sight (LOS) connection might exist between TX and RX. Furthermore, the signal can get from the TX to the RX by being reflected at, scattered or diffracted by different Interacting Objects (IOs) in the environment: houses, mountains (for outdoor environments), windows, walls, etc. The number of these possible propagation paths is very large. Signal components following each of the paths has a distinct amplitude, delay (runtime of the signal), direction of departure from the TX, and direction of arrival at the RX; most importantly, the components have different phase shifts with respect to each other [3]. Multipath can significantly degrade performance of wireless systems, and proposals to alleviate the effects of multipath include equalization, spread spectrum and multicarrier modulation. Among the main effects of multipath propagation are fading and intersymbol interference (ISI).

i. Fading

Rapid phase changes in each multipath component gives rise to constructive and destructive addition of the multipath components comprising the received signal, which in turn causes rapid variation in the received signal strength. This phenomenon is called fading. Communication systems operate in diverse environments, including those susceptible to fading. That is why spectrum sensing must be analyzed in fading environments [2].

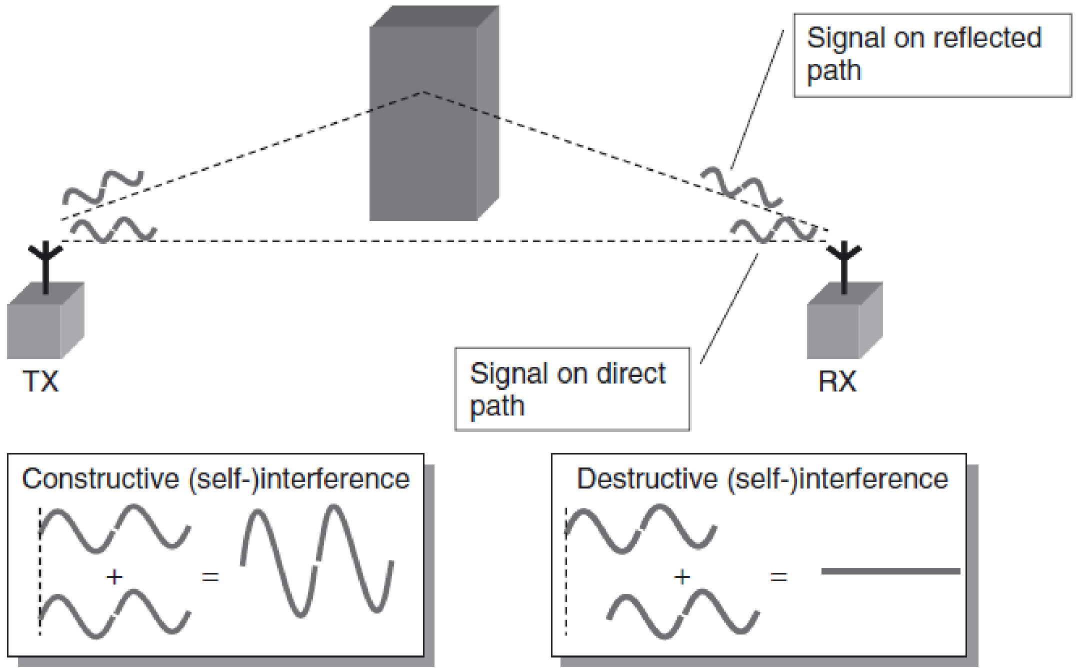

Figure 1.1: Principle of small-scale fading

A simple RX cannot differentiate between the different Multi Path Components (MPCs); it just adds them up, so that they interfere with each other. The interference between them can be constructive or destructive, depending on the phases of the MPCs [1] as shown in Figure 1.1 above.

The phase of the nth time varying MPC is given by the equation:

$$\Phi_n(t) = 2\pi f_c \tau_n(t) - \Phi_{D_n} - \Phi_0 \tag{1.1}$$

where f_c is the carrier frequency, $\tau_n(t)$ is the time varying nth path delay, Φ_{D_n} is the nth path Doppler phase shift and Φ_0 is the random phase offset of the carrier. The phases, in turn, depend mostly on the run length (the path length) of the MPC, and thus on the position of the Mobile Station (MS) and the IOs. For this reason, the interference, and thus the amplitude of the total signal, changes with time if TX, RX, or IOs is moving. This effect – namely, the changing of the total signal amplitude due to interference of the different MPCs – is called small-scale fading which is also shown in Figure 1.1. Furthermore, the amplitudes of each distinct MPC vary with time (or with location).

Obstacles can lead to a shadowing of one or several MPCs. Generally shadowing is caused by obstacles between the TX and RX that attenuate signal power through absorption, reflection, scattering, and diffraction. Since variations due to shadowing occur over relatively large distances, this variation is sometimes referred to as large-scale propagation effect i.e. shadowing gives rise to large-scale fading. Large-scale and small-scale fading overlap, so that the transmission quality (signal strength) is low at the times (or places) with low signal amplitude. This can lead to bad speech quality (for voice telephony), high Bit Error Rate (BER) and low data rate (for data transmission), and if the quality is too low for an extended period of time, this leads to termination of the connection [1]. It is well known from conventional digital communications that for nonfading communication links i.e. Additive White Gaussian Noise (AWGN) channel, the BER decreases approximately exponentially with increasing Signal-to-Noise Ratio (SNR) if no special measures are taken.

However, in a fading channel, the SNR is not constant; rather, the probability that the link is in a fading dip (i.e., location with low SNR) dominates the behaviour of the BER [3]. For this reason, the average BER decreases only linearly with increasing average SNR. Consequently, improving the BER often cannot be achieved by simply increasing the transmit power. Rather, more sophisticated transmission and reception schemes have to be used. Due to fading, it is almost impossible to exactly predict the received signal amplitude at specific locations. For many aspects of system development and deployment, it is considered sufficient to predict the mean amplitude and the statistics of fluctuations around that mean.

ii. Intersymbol Interference

The path lengths as well as the runtimes for distinct MPCs are different. It is already mentioned above that this can lead to different phases of MPCs, which leads to interference in narrowband systems [1]- [3]. In a system with large bandwidth, and thus good resolution in the time domain, the major consequence is signal dispersion or spreading: in other words, the impulse response of the channel is not a single delta pulse but rather a series of pulses (corresponding to different MPCs), each of which has a distinct arrival time in addition to having a different amplitude and phase. This signal dispersion leads to InterSymbol Interference (ISI) at the RX. MPCs with long runtimes, carrying information from bit *k*, and MPCs with short runtimes, carrying contributions from bit *k* + 1 arrive at the RX at the same time, and interfere with each other. Assuming that no special measures are taken, this ISI leads to errors that cannot be eliminated by simply increasing the transmit power, and are therefore often called irreducible errors. The time-varying channel impulse response is given by:

$$c(\tau,t) = \sum_{n=0}^{N(t)} \alpha_n(t) e^{-j\Phi_n(t)} \delta(\tau - \tau_n(t)) \qquad (1.2)$$

where $N(t)$ is the number of resolvable MPCs, $\alpha_n(t)$ is the amplitude of the nth MPC, $\Phi_n(t)$ is the phase of the nth MPC, $\tau_n(t)$ is the delay associated with the nth MPC and δ is the impulse function, n=0 corresponds to the LOS path. The time-invariant channel impulse response for discrete MPCs is then given as:

$$c(\tau) = \sum_{n=0}^{N} \alpha_n e^{-j\Phi_n} \delta(\tau - \tau_n) \qquad (1.3)$$

For continuum MPCs, the time-invariant channel impulse response is:

$$c(\tau) = \alpha(\tau) e^{-j\Phi(\tau)} \qquad (1.4)$$

ISI is essentially determined by the ratio between symbol duration and the duration of the impulse response of the channel according to Goldsmith [3]. This implies that ISI is not only more important for higher data rates but also for multiple access methods that lead to an increase in transmitted peak data rate (e.g., time division multiple access (TDMA)). Eventually, it is also worth mentioning that ISI can even play a role when the duration of the impulse response is shorter (but not much shorter) than bit duration.

1.1.2 Spectrum Limitations

The design of wireless networks differs from wired network design due to the nature of the wireless channel. Firstly, the radio spectrum is a limited resource that must be allocated to different applications and systems efficiently [1]. The exploitable spectrum available for wireless communications services is limited, and regulated by international agreements. For this reason, the spectrum has to be used in a highly efficient manner. Two approaches are used: regulated spectrum usage, where a single network operator has control over the usage of the spectrum, and unregulated spectrum, where each user can transmit without additional control, as long as she/he complies with certain restrictions on the emission power and bandwidth. Spectrum can also be very costly since in many countries spectral licenses are often auctioned to the highest bidder. Hence, the spectrum obtained through these auctions must be used extremely efficiently to get a reasonable return on its investment, and it must also be reused repeatedly in the same geographical area, thus demanding cellular system designs with high capacity and good performance.

The part of the electromagnetic (EM) spectrum that includes radio frequencies (RF) extends from about 9 KHz to 300 GHz, although radio wave propagation is actually possible down to a few kilohertz. It is evident that different frequency ranges are most favourable for different applications [1]. Low carrier frequencies usually propagate more easily, so that a single base station (BS) can cover a large area. On the other hand, absolute bandwidths are smaller, and the frequency reuse is not as efficient as it is at higher frequencies. For this reason, low frequency bands are best for services that require good coverage, but have a small aggregate rate of information that has to be exchanged as a trade-off. Typical cases in point are paging services and television; paging is suitable because the amount of information transmitted to each user is small, while in the latter case, only a single information stream is sent to all users. For cellular systems, low carrier frequencies are ideal for covering large regions with low user density especially in the rural areas. For cellular systems with high user densities, as well as for wireless local area networks (WLANs), higher carrier frequencies are usually more desirable.

Given that spectrum is limited, the same spectrum has to be used for different wireless connections in different locations [2]. For this purpose, the area (a region, a country, or a whole continent) is divided into a number of cells; the available frequency channels are also divided into several groups. The channel groups are now assigned to the cells. The important thing is that channel groups can be used in multiple cells. The only requirement is that cells that use the same frequency group do not interfere with each other significantly. The threshold for significant interference (i.e., the admissible signal-to-interference ratio) is determined by modulation and reception schemes, as well as by propagation conditions.

Figure 1.2 illustrates the concept of cellular frequency reuse, where cells labelled with the same letter use the same group of channels. The frequency reuse plan is overlaid upon a map to indicate where different frequency channels are used. The hexagonal cell shape shown in Figure 1.2 is conceptual and is a simplistic model of the radio coverage for each base station, but it has been universally adopted since the hexagon permits easy and manageable analysis of a cellular system. The actual radio coverage of a cell is known as the footprint and is determined from field measurements or propagation prediction models. Although the real footprint is amorphous in nature, a regular cell shape is needed for systematic system design and adaptation for future growth. While it might seem natural to choose a circle to represent the coverage area of a base station, adjacent circles cannot be overlaid upon a map without leaving gaps or creating overlapping regions. Thus, when considering geometric shapes which cover an entire region without overlap and with equal area, there are three sensible choices—a square, an equilateral triangle, and a hexagon. A cell must be designed to serve the weakest mobiles within the footprint, and these are typically located at the edge of the cell. For a given distance between the centre of a polygon and its farthest perimeter points, the hexagon has the largest area of the three. Thus, by using the hexagon geometry, the fewest number of cells can cover a geographic region, and the hexagon closely approximates a circular radiation pattern which would occur for an omnidirectional base station antenna and free space propagation. Of course, the actual cellular footprint is determined by the contour in which a given transmitter serves the mobiles successfully.

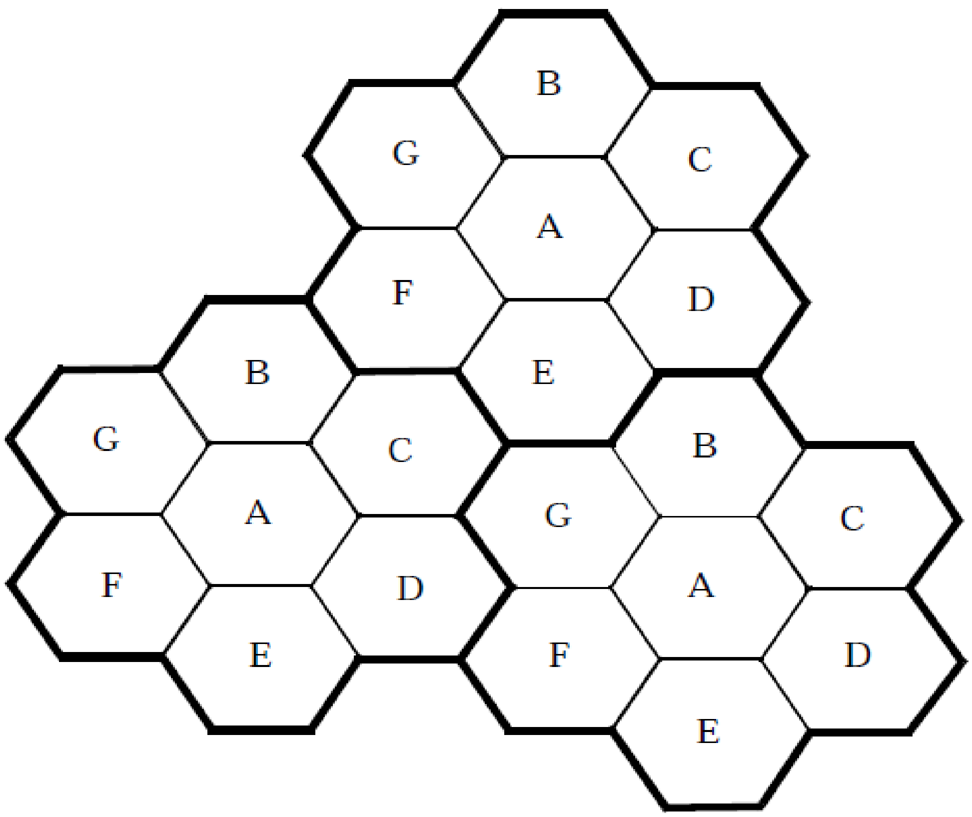

Figure 1.2: Illustration of the cellular frequency reuse concept [2]

1.1.3 Spectrum Sharing Issues

Spectral sharing in communication systems, also called multiple-access, is done by dividing the signalling dimensions along the time, frequency, and/or code space axes [1]- [2]. In frequency-division multiple-access (FDMA) the total system bandwidth is divided into orthogonal frequency channels. In time-division multiple access

(TDMA) time is divided orthogonally and each channel occupies the entire frequency band over its assigned timeslot. TDMA is more difficult to implement than FDMA since the users must be time-synchronized. However, it is easier to accommodate multiple data rates with TDMA since multiple timeslots can be assigned to a given user. Code-division multiple-access (CDMA) is typically implemented using direct-sequence or frequency-hopping spread spectrum with either orthogonal or non-orthogonal codes. In direct-sequence each user modulates its data sequence by a different chip sequence which is much faster than the data sequence. In the frequency domain, the narrowband data signal is convolved with the wideband chip signal, resulting in a signal with a much wider bandwidth than the original data signal [2].

1.1.4 Limited Energy

Truly wireless communications requires not only that the information be sent over the air (not via cables) but also that one-way or rechargeable batteries power the MS [1]. Otherwise, an MS would be tied to the “wire” of the power supply; batteries in turn impose restrictions on the power consumption of the devices. The requirement for small energy consumption results in several technical imperatives as explained below:

- The power amplifiers in the transmitter have to have high efficiency. As power amplifiers account for a considerable fraction of the power consumption in an MS, mainly amplifiers with efficiency above 50% should be used in MSs. Such amplifiers – specifically, class-C or class-F amplifiers – are highly nonlinear. As a consequence, wireless communications tend to use modulation formats that are insensitive to nonlinear distortions. For example, constant envelope signals are preferred.
- Signal processing must be done in an energy-saving manner. This implies that the digital logic should be implemented using power-saving semiconductor technology like Complementary Metal Oxide Semiconductor (CMOS), while the faster but more power-hungry approaches like Emitter Coupled Logic (ECL) do not seem suitable for MSs. This restriction has important

consequences for the algorithms that can be used for interference suppression, combating of ISI, etc.

- The RX (especially at the BS) needs to have high sensitivity. For example, Global System for Mobile Communications (GSM) is specified so that even a received signal power of −100 dBm leads to an acceptable transmission quality. Such a receiver is several orders of magnitude more sensitive than a TV receiver. If the GSM standard had defined −80 dBm instead, then the transmit power would have to be higher by a factor of 100 in order to achieve the same coverage. This in turn would mean that – for identical talk time – the battery would have to be 100 times as large – i.e., 20 kg instead of the current 200 g. But the high requirements on receiver sensitivity have important consequences for the construction of the RX (low-noise amplifiers, sophisticated signal processing to fully exploit the received signal) as well as for network planning.
- Maximum transmit power should be used only when required. In other words, transmit power should be adapted to the channel state, which in turn depends on the distance between TX and RX (power control). If the MS is close to the BS, and thus the channel has only a small attenuation, transmit power should be kept low. Furthermore, for voice transmission, the MS should only transmit if the user at the MS actually talks, which is the case only about 50% of the time (Discontinuous Voice Transmission (DTX)).

Several of the mentioned requirements are contradictory. For example, the requirement to build an RX with high sensitivity (and thus, sophisticated signal processing) is in contrast to the requirement of having energy-saving (and thus slow) signal processing. Engineering tradeoffs are thus called for [1].

1.1.5 User Mobility

Mobility is an inherent feature of most wireless systems, and has important consequences for system design. In addition to fading, a second important effect is particular to mobile users in cellular systems [1]. If there is an incoming call for a certain MS (user), the network has to know in which cell the user is located. The first requirement is that an MS emits a signal at regular intervals, informing nearby BSs that it is "in the neighbourhood." Two databanks then employ this information: the Home Location Register (HLR) and the Visitor Location Register (VLR). The HLR is a central database that keeps track of the location a user is currently at; the VLR is a database associated with a certain BS that notes all the users who are currently within the coverage area of this specific BS.

Figure 1.3 shows the GSM Network Infrastructure. Consider user A, who is registered in Mombasa, but is currently located in Nairobi. It informs the nearest base transceiver station (BTS) in Nairobi that it is now within its coverage area; the BTS enters that information into its VLR. At the same time, the information is forwarded to the central HLR (located, e.g., in Nairobi). If now somebody calls user A, an enquiry is sent to the HLR to find out the current location of the user. After receiving the answer, the call is rerouted to Nairobi. For the Nairobi BTS, user A is just a "regular" user, whose data are all stored in the VLR. If an MS moves across a cell boundary, a different BTS becomes the serving BTS; in other words, the MS is handed over from one BTS to another.

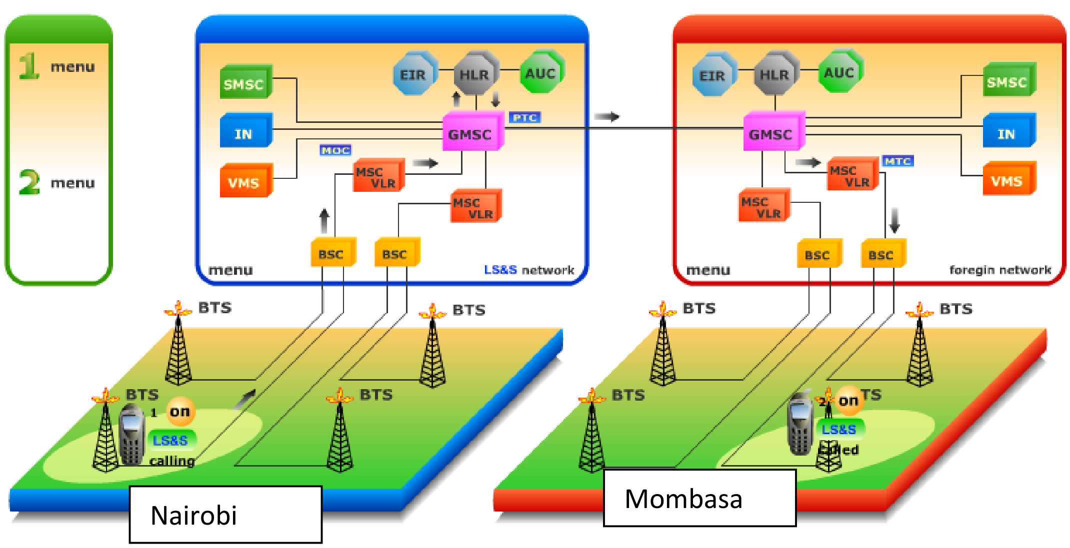

Figure 1.3: GSM Network Infrastructure

The events during a call when a user in Nairobi calls a user in Mombasa are: -> The Mobile Station is requesting connection-> The BTS is sending request data to the BSC-> The BSC is sending request data to the MSC-> The MSC is checking registration and subscribed services of calling MS-> The MSC is checking registration and location of called MS-> The MSC is sending request data to the GMSC-> The GMSC is requesting registration and location data of called MS-> The HLR is checking authentication, validation and location of called MS-> The HLR is sending registration and location data to the GMSC-> The GMSC is sending data to another network-> The GMSC is sending location data to the MSC-> The MSC is sending location data for call set-up to the BSC-> The BSC is paging called MS-> Connection established.

1.2 Statement of the Problem

Radio wave frequency bands in accordance with Article 5 of the ITU Radio regulations range from 9 kHz to 275GHz. EM waves with frequencies less than 9 KHz are not employed due to the following reasons: i) Limited bandwidth resulting in low traffic capacity and ii) Very large antennas because of long wavelengths. In addition, frequency bands higher than 100GHz are not usually employed for the time being due to the following reasons: High free space loss, High atmospheric attenuation and limitations in RF component manufacturing [4]. The fixed spectrum assignment scheme is facing difficulties due to the scarcity of the natural usable radio frequency band we have.

To mitigate the spectrum scarcity problem different techniques have been proposed so far in the literature, among which, the cognitive radio (CR) technology is the main one. CRs allow a Secondary User (SU) to dynamically access portions of radio spectrum that lie fallow at a particular time and location by the license-holder also known as the Primary User (PU) without causing any harmful interference. CR selects the communication parameters (such as carrier frequency, bandwidth and transmission power) to optimize the spectrum usage and adapts its transmission and reception accordingly.

In wireless communication networks, uncertainties in received signal strength arise due to channel fading or shadowing which may wrongly interpret that the primary system is located out of the secondary user's interference range as the primary signal may be experiencing a deep fade or being heavily shadowed by obstacles. Therefore, CRs have to be more sensitive to distinguish a faded or shadowed primary signal from a white space. Any uncertainty in the received power of the primary signal translates into a higher detection sensitivity requirement [5].

Whenever a PU is detected, the cognitive radio devices have to evacuate from the licensed band possessed by the PU, and transmission link failure could occur. At this time if there is no other free channel for transferring the call in the vicinity of the SU, then the communication becomes aborted and the issue of reliability comes into question. Therefore, to improve the reliability of the cognitive radio network (CRN), the CR devices should be ready in advance before any communication starts. If the CR devices could establish a virtual wireless link with their neighbouring CRs in order to report the trueness of the available free channels via the reporting channel to the central free channel database (CFCDB), then whenever a channel is to be accessed by the CR it can be provided.

The virtual point-to-multipoint wireless link between a single CR & many CR devices that are actually separated by an electrical distance (measured in wavelengths) is established before the actual communication starts. That is, through virtualization it is possible to build a virtual wireless network from abstract (logical) resources on top of a physical network constructed from physical resources. The CFCDB continuously communicates with its CR devices to update its database and is in charge of the establishment of the virtual wireless link.

1.3 Research Questions

1. How is it possible to enhance the reliability of Cognitive Radio Networks?
2. How to develop an algorithm for the selection of better quality virtual wireless links between CR devices?
3. How to show and evaluate the performance improvement of the CRN using the newly developed VWLS algorithm?

1.4 Objectives

1.4.1 Main Objective

This thesis mainly focuses on the design and analysis of an algorithm that enhances the reliability of a cognitive radio network through the establishment of a virtual wireless link.

1.4.2 Specific Objectives

1. To design and analyze a more reliable cognitive radio network that is able to establish a virtual wireless link before the actual communication starts.
2. To design and simulate an algorithm that enables the CRs to select the highest Signal-to-Noise Ratio (SNR) channel.
3. To evaluate the system performance of the Cognitive Radio Network.

1.5 Justification

Designing CRNs is considerably challenging. The secondary system should be capable of discovering as many spectrum opportunities as possible whereas strictly preventing interference to the primary transmissions. Thus, spectrum sensing is one of the essential components of CRNs to detect PUs efficiently and accurately. Owing to numerous unpredictable problems, such as noise uncertainty, multi-path fading and shadowing, the performance of spectrum sensing may be significantly degraded. The reliability of the reporting channel has a great impact on sensing performance. Like sensing channels, the reporting channel may be susceptible to multi-path fading.

Eventually, the channel uncertainties may lead to irreducible errors during the communication process. Therefore, it is necessary to ensure the accurateness of all the channels between the CR devices and the reporting channel between the central free channel data base and the CRs. In this way, it is possible to improve the reliability as well as the quality of service in the CRN in addressing the issue of customer satisfaction.

1.6 Scope

The research is focused on the enhancement of the reliability of CRNs and aspects that affect the performance of CRNs. It uses C++ programming platform for coding the algorithm and the computer simulation software OMNET++/MiXiM to show the results. OMNET++ (Objective Modular Network Test bed in C++) is an object-oriented modular discrete network simulator and MiXiM (Mixed Simulator) is a simulation framework for wireless and mobile networks which was developed on top of OMNET++ [6]. The reasons why we select OMNET++/MiXiM are the open source nature of the framework, its well-organized and modular architecture, the existing documentation, and the provided integrated development environment (IDE) [7].

1.7 Organization of the thesis

To point out the root problems for the scarcity of the usable electromagnetic spectrum suitable for radio frequency communication, we discuss the characteristics of the wireless communication system along with its technical challenges in the first chapter of the thesis. Additionally some of the spectrum sensing techniques proposed in the literature for cognitive radio based systems will be explained in the literature review. The methodology is discussed in chapter three and the results in chapter four. Finally the conclusions of the research work and recommendations on future work are discussed in chapter five.

CHAPTER 2: LITERATURE REVIEW

2.1 Introduction

The accessible electromagnetic radio spectrum is a limited natural resource and getting crowded day-after-day due to the increase in wireless devices and applications. According to Yucek and Arslan [8] spectrum is a very valuable resource in wireless communication systems, and it has been a focal point for research and development efforts over the last several decades. It is obvious that the contemporary static frequency allocation schemes cannot accommodate the demands of the rapidly increasing number of higher data rate devices. Consequently, dynamic usage of the radio spectrum in an opportunistic way should be implemented instead of the static frequency allocation in order to ameliorate the spectrum usage efficiency [9].

Cognitive radio, which is one of the efforts to exploit the available radio spectrum more efficiently through opportunistic spectrum usage, has become an exciting and promising technology. One of the important elements of cognitive radio is detecting the available spectrum opportunities [10]. Spectrum sensing is the task of acquiring awareness about the spectrum usage and presence of primary users in a geographical area.

One of the reasons for the under-utilization of the spectrum is the partial occupancy of the licenced bands temporally and spatially by the primary users. This scenario has led to a more sophisticated and structured manner - cognitive radio that is aware of its environmental, internal state, and location, and autonomously adjusts its operating parameters to achieve designed objectives [11]. Otherwise sated, cognitive radio first senses its spectral environment over a wide frequency band, and then adapts the parameters to maximize spectrum efficiency while co-existing with legacy wireless networks as explained by Haykin [12].

The focus of this thesis is on the performance improvement of spectrum sensing methods in cognitive radio technology via ensuring the reliability of the CRN. Since

CRs are secondary users of vacant spectrum, they do not have a priori right to any frequency band [9]. Their communication is strictly conditional on the reliable detection of PU transmissions in their vicinity. As a result, CRs must operate in a much wider frequency bandwidth than conventional radios, which spans multiple PU bands, and CRs must perform frequent measurements of PUs' activity through spectrum sensing. The most autonomous and flexible approach which could be used to check the presence of PU signals, is based on measurements of the actual spectrum occupancy at a given location and time [13].

2.2 Overview of Cognitive Radios

The name Cognitive Radio (CR) was originally invented by Joseph Mitola III in an article published in 1999 [11]. Mitola's objective was to set the foundation for the development of extremely intelligent wireless devices, able to smartly exploit the radio resource, but also to adapt their behaviour to the specific needs of the single user while acting in compliance with the Regulation Authorities [14]. The ideal Cognitive Radio device hypothesized by Mitola would be able to learn from the user and from past experiences and to always provide the highest possible information quality on a user/context basis. Such device embodies what is indicated as Full Cognitive Radio, a wireless device equipped with Cognition.

The term, cognitive radio, can formally be defined as follows [15]: A ''Cognitive Radio'' is a radio that can change its transmitter parameters based on interaction with the environment in which it operates. From this definition, two main characteristics of the CR can be defined:

Cognitive Capability: Cognitive capability refers to the ability of the radio technology to capture or sense the information from its radio environment, such as temporal and spatial variations, and avoid interference to other users. Through this capability, the portions of the spectrum that are unused at a specific time or location can be identified. Consequently, the best spectrum and appropriate operating parameters can be selected.

Reconfigurability: The cognitive capability provides spectrum awareness whereas reconfigurability enables the radio to be dynamically programmed according to the radio environment. More specifically, the CR can be programmed to transmit and receive on a variety of frequencies and to use different transmission access technologies supported by its hardware design [16]. While ideal CR devices process an extremely wide range of information, CR devices consider the radio frequency spectrum as the only significant source of information to be processed in a cognitive way; therefore they can be referred them as Spectrum Sensing Cognitive Radios.

CR techniques provide the capability to use or share the spectrum in an opportunistic manner [17]. Dynamic spectrum access techniques allow the CR to operate in the best available channel. More specifically, the CR technology will enable the users to (1) determine which portions of the spectrum are available and detect the presence of licensed users when a user operates in a licensed band (spectrum sensing), (2) select the best available channel (spectrum management), (3) coordinate access to this channel with other users (spectrum sharing), and (4) vacate the channel when a licensed user is detected (spectrum mobility). Once a CR supports the capability to select the best available channel, the next challenge is to make the network protocols adaptive to the available spectrum. Hence, new functionalities are required in the next generation network (NGN) to support this adaptivity [17].

2.2.1 Cognitive Capability

The cognitive capability of a CR enables real time interaction with its surroundings to determine appropriate communication parameters and adapt to the dynamic radio environment. The tasks required for adaptive operation in open spectrum are shown in Figure 2.1 which is referred to as the cognitive cycle [12]. In this section, an overview of the three main steps of the cognitive cycle: spectrum sensing, spectrum analysis, and spectrum decision, is provided.

The steps of the cognitive cycle as shown in Figure 2.1 are as follows:

i. Spectrum Sensing: A CR monitors the available spectrum bands, captures their information, and then detects the spectrum holes.
ii. Spectrum Analysis: The characteristics of the spectrum holes that are detected through spectrum sensing are estimated.
iii. Spectrum Decision: A CR determines the data rate, the transmission mode, and the bandwidth of the transmission. Then, the appropriate spectrum band is chosen according to the spectrum characteristics and user requirements.

Once the operating spectrum band is determined, the communication can be performed over this band. However, since the radio environment varies temporally and spatially, the cognitive radio should keep track of the changes of the radio environment [17,18].

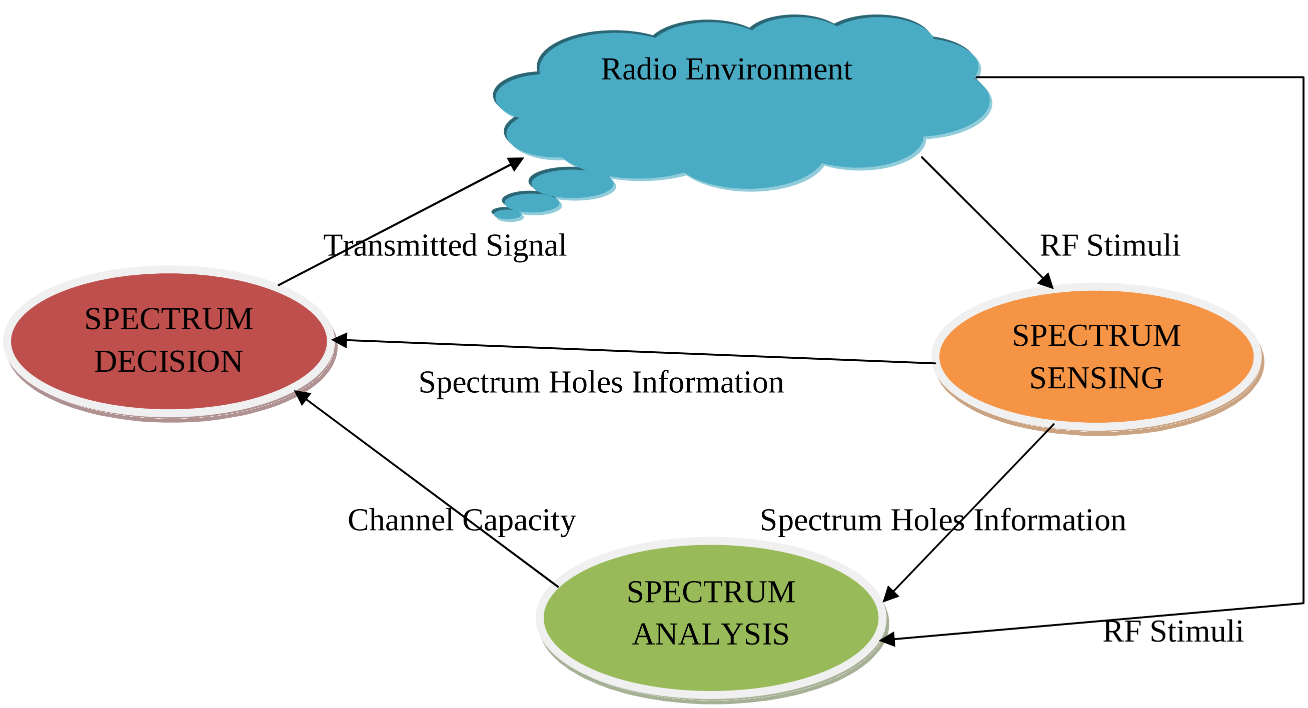

Figure 2.1: The Cognitive Cycle [12]

2.2.2 Reconfigurability

Reconfigurability is the capability of adjusting operating parameters for the transmission on the fly without any modifications on the hardware components. This capability enables the CR to adapt easily to the dynamic radio environment. There are several reconfigurable parameters that can be incorporated into the cognitive radio as explained below [16]:

- Operating Frequency: A cognitive radio is capable of changing the operating frequency. Based on the information about the radio environment, the most suitable operating frequency can be determined and the communication can be dynamically performed on this appropriate operating frequency.
- Modulation: A cognitive radio should reconfigure the modulation scheme adaptive to the user requirements and channel conditions. For example, in the case of delay sensitive applications, the data rate is more important than the error rate. Thus, the modulation scheme that enables the higher spectral efficiency should be selected. Conversely, the loss-sensitive applications focus on the error rate, which necessitate modulation schemes with low bit error rate. For example higher order QAMs are used to increase uplink and downlink bit rates.
- Transmission Power: Transmission power can be reconfigured within the power constraints [e.g. $0 \sim 17dBm$]. Power control enables dynamic transmission power configuration within the permissible power limit. If higher power operation is not necessary, the cognitive radio reduces the transmitter power to a lower level to allow more users to share the spectrum and to decrease the interference.
- Communication Technology: A cognitive radio can also be used to provide interoperability among different communication systems.

To illustrate a practical scenario of the above reconfigurable parameters of a CR, a microwave link configuration shown in Figure 2.2 is used.

The left half of the picture shows the TX side and the right half shows the RX side. It can be seen that the RX is reconfiguring the receiving parameters according to the TX requirements.

The transmission parameters of a cognitive radio can be reconfigured not only at the beginning of a transmission but also during the transmission. According to the spectrum characteristics, these parameters can be reconfigured such that the cognitive radio is switched to a different spectrum band, the transmitter and receiver parameters are reconfigured and the appropriate communication protocol parameters and modulation schemes are used [19]. As shown in Figure 2.2 the TX uses 256QAM modulation, 183Mbit/s data rate, 25767MHz of frequency and 4dBm of power. Likewise the RX reconfigures its receiving parameters as per the TX requirements and it is indicated in the same figure.

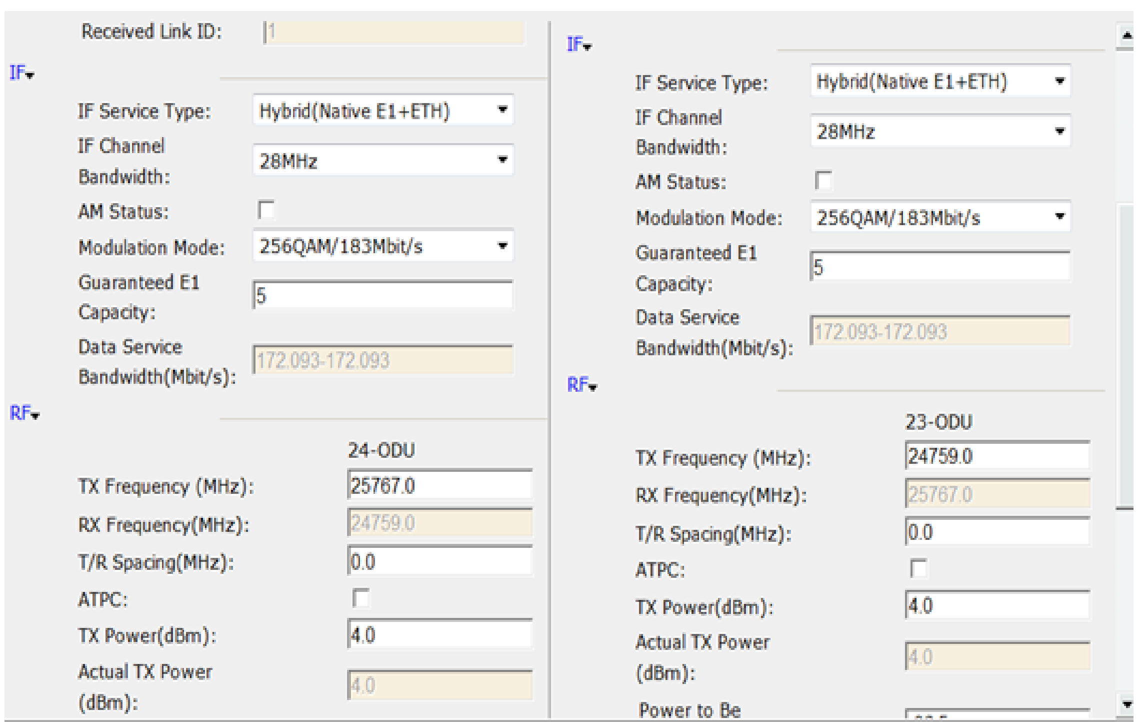

Figure 2.2: Reconfigurability Scenario in Cognitive Radios

2.3 Spectrum Detection Techniques

In band detection theory of CR networks, it is necessary to find out whether the PU is accessing the channel or not [13]. Due to this reason, there will be two hypotheses tests to be stated and the algorithm has to decide which one is most likely true. The signal detection problem is solved by the decision between the two hypotheses:

$$\begin{cases} H_0: Primary\ User\ not\ Present \\ H_1: Primary\ User\ Present \end{cases} \tag{2.1}$$

The signal under each hypothesis takes the form:

$$\begin{cases} H_0: y[n] = w[n] & n = 0,1,\dots,N-1 \\ H_1: y[n] = x[n] + w[n] & n = 0,1,\dots,N-1 \end{cases} \tag{2.2}$$

Where $y[n]$ is the signal received by the cognitive user, $x[n]$ is the noiseless received signal when the PU is present, $w[n]$ is the Additive White Gaussian Noise (AWGN) and N is the number of samples of the received signal used in the spectrum sensing process. The decision on the presence or absence of a signal will be done by evaluating if a certain random variable Θ is above or below a certain threshold T [20]. This variable is defined by the chosen test statistics. Suppose that H_0 is the event that only noise is present and H_1 is the event of existence of the primary user signal. The performance of a detector is evaluated by the probability of false alarm (P_{fa}) and probability of correct detection (P_{cd}) given below by equations (2.3) and (2.4) respectively.

$$P_{fa} = P(\Theta > T | H_0) \tag{2.3}$$

$$P_{cd} = P(\Theta > T | H_1) \tag{2.4}$$

The missed detection probability is $P_{md} = 1 - P_{cd}$. The threshold T is usually set depending on a target false alarm probability. If the cognitive radio network is required to guarantee a reuse probability of the unused spectrum, the probability of false alarm is fixed to a small value (e.g., 5%) and the detection probability should be maximized as much as possible [21]. On the other hand, if the cognitive radio is required to guarantee a non-interference probability to the incumbent systems, the probability of detection should be fixed to a high value (e.g., 95%) and the probability of false alarm should be minimized as much as possible. For example, in IEEE 802.22 P_{fa} and P_{md} must both be lower than 10^{-1} [21].

Generally, there are four spectrum sensing methods proposed in the literature:

1. Matched Filtering Based Signal Detection
2. Energy Detection
3. Covariance Based Signal Detection
4. Cyclostationary Feature Detection

2.3.1 Matched Filtering Based Signal Detection

The optimal way for any signal detection is a matched filter [22]. It is a linear filter, which maximizes the received signal-to-noise ratio (SNR) in the presence of additive stochastic noise. However, a matched filter effectively requires demodulation of a primary user signal. This means that cognitive radio has a priori knowledge of primary user signal x[n], such as modulation scheme, pulse shaping, and packet format. Such information must be pre-stored in CR memory, but the inconvenience part is that for demodulation it has to achieve coherency with primary user signal by performing timing and carrier synchronization, even channel equalization.

When the transmitted signal is known at the receiver, matched filtering (MF) is known as the optimal method for detection of primary users [22] since it maximizes received signal-to-noise ratio (SNR), and the SNR corresponding to equation (2.2) is

$$SNR = \gamma = \frac{|x(n)|^2}{E[w^2(n)]} \qquad (2.5)$$

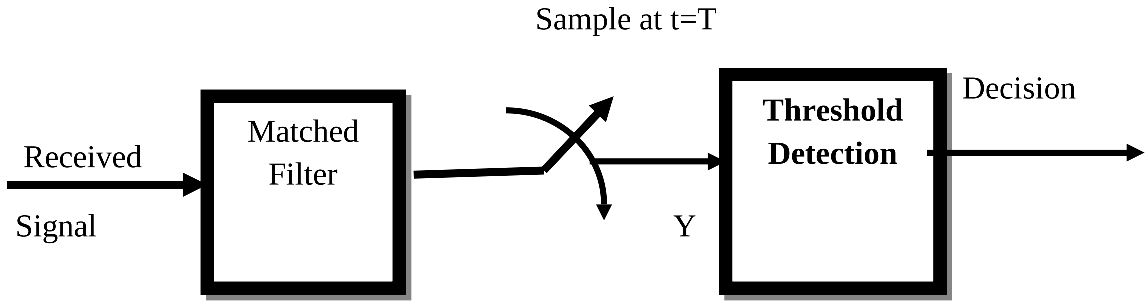

Figure 2.3: Matched Filter for Signal Detection

Simple matched filter based detection can be implemented as shown in Figure 2.3, where threshold is used to estimate the signal. Cabric et al [23] used matched filter-based detection for pilot signal (Xp) where the method assumes that the primary user sends pilot signal along with the data. The process is depicted in Figure 2.4. The matched filter performs best when the signalling features to be received are known at the receiver (which is called coherent detection).

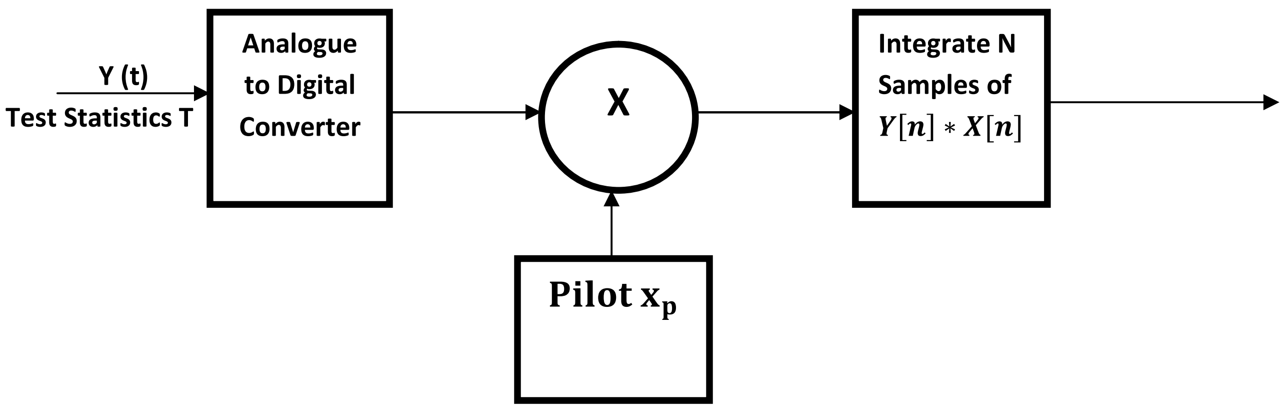

Figure 2.4: Pilot Signal and Matched Filter Based Detection [23]

Despite its best performance, the MF has more disadvantages than its advantages: First, MF requires perfect knowledge of the primary user signalling features (such as modulation type, operating frequency, etc), which is supposed to be detected at cognitive radio. CR is known to use wide band of spectrum wherever it finds the spectrum opportunities. Therefore it is almost impossible to have MF implemented in cognitive radio for all types of signal in wideband regime. Second, MF implementation complexity of detection unit in CR devices is very high because CR system needs receivers for all signal types of wideband regime [23].

Lastly, large power will be consumed to execute such several detection processes as CR device sense the wideband regime. Therefore, the disadvantages outweigh the advantages of MF based detection. It is important to note that MF based technique might not be a good choice for real CR system because of its above-mentioned disadvantages [13].

2.3.2 Covariance Based Signal Detection

This is another method to detect the primary signal by CR users. Zeng and Liang [19] have proposed covariance based signal detection whose main idea is to exploit the covariance of signal and noise since the statistical covariance of signal and noise are usually different. These covariance properties of signal and noise are used to differentiate signal from noise where the sample covariance matrix of the received signal is computed based on the receiving filter. The system model for received signal is considered as in equation (2.2), and the received signal in a vector channel form can be written as [19]

$$\boldsymbol{y} = \boldsymbol{G}\boldsymbol{x} + \boldsymbol{w} \tag{2.6}$$

Where **G** is channel matrix through which the signal travels. The covariances corresponding to the signal and noise can be written as

$$\boldsymbol{R}_y = E[\boldsymbol{y}\boldsymbol{y}^T] \tag{2.7a}$$
$$\boldsymbol{R}_x = E[\boldsymbol{x}\boldsymbol{x}^T] \tag{2.7b}$$
$$\boldsymbol{R}_w = E[\boldsymbol{w}\boldsymbol{w}^T] \tag{2.7c}$$

Where $E[.]$ is the expected value of [.]. If there is no signal ($\mathbf{x} = 0$), then $\boldsymbol{R}_x = 0$ and therefore the off-diagonal elements of $\boldsymbol{R}_y$ are all zeros. If there is signal ($\mathbf{x} \neq 0$) and the signal samples are correlated, and thus $\boldsymbol{R}_x$ is no more a diagonal matrix. Therefore, some of the off-diagonal elements of $\boldsymbol{R}_y$ should not be zeros. Hence, this method detects the presence of signals with the help of covariance matrix of the received signal. That is, if all the off diagonal values of the matrix $\boldsymbol{R}_y$ are zeros, then the primary user is not using the band at that time and location, and otherwise the band is not idle [13].

2.3.3 Energy Detection

One approach to simplify matched filter approach is to perform noncoherent detection through energy detection [22]. Energy Detection (ED) is one of the most basic sensing schemes. It is optimal if both the signal and the noise are Gaussian, and the noise variance is perfectly known. However, its performance degrades rapidly when there is uncertainty in the noise power value and is also incapable to differentiate between signals from different systems and between these signals and noise. Its advantage lies in its simplicity and not requiring prior knowledge of the primary user's signal, making it best suited for fast and coarse spectrum scanning.

In Figure 2.5, a scheme of a simple energy detector where a Fast Fourier Transform (FFT) is used to do the filtering. The energy detection process can be made in time domain or frequency domain through a FFT block. The advantage of the frequency domain testing lies in the flexibility the FFT can provide by trading temporal resolution for frequency resolution [24]. This means that a narrowband signal's bandwidth and central frequency can be estimated without requiring a very flexible pre-filter [25].

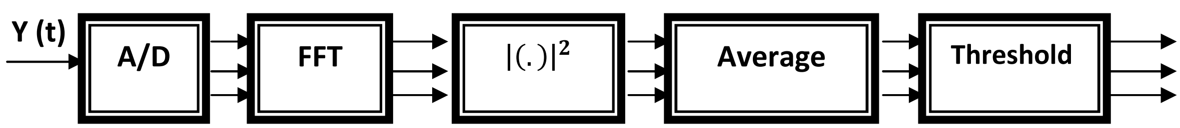

Figure 2.5: Signal Processing in an Energy Detector

2.3.4 Cyclostationary Feature Detection

Primary users' signals include periodical signals like carriers, pulse trains and cyclic prefixes. The autocorrelation of such signals are characterized by a certain periodicity. The idea behind the cyclostationary detection method is to search for a periodicity in the autocorrelation of the received signal. If such periodicity is found, a primary user signal is detected [26]. The modulated PU signals are characterized as cyclostationary signals since their mean and autocorrelation exhibit periodicity. These features are detected by analyzing a spectral correlation function. The main advantage of the spectral correlation function is that it differentiates the noise energy from modulated signal energy, which is a result of the fact that the noise is a wide-sense stationary (WSS) signal with no correlation, while modulated signals are cyclostationary with spectral correlation due to the embedded redundancy of signal periodicity.

A cyclostationary feature detector can perform better than the energy detector in discriminating against noise due to its robustness to the uncertainty in noise power [27]. However, it is computationally complex and requires prior knowledge about the PU signal structure and significantly long observation time.

2.4 Cooperative Sensing in Cognitive Radios

Cooperation is proposed in the literature as a solution to problems that arise in spectrum sensing due to noise uncertainty, fading, and shadowing [28] . In cooperative sensing, multiple sensing nodes perform the task of detection of an incumbent and the detection decision is made based on the fused results of each node. The main motivation behind cooperative sensing is to lighten the burden of sensing that a single sensing node would need to carry by distributing the detection among multiple nodes [29]. When a single node exhibits multipath or shadowing and therefore has higher sensitivity requirements on its sensing algorithm, cooperative sensing can be used to effectively decrease the sensitivity requirements by relying on other nodes which may not exhibit these same unfavourable conditions.

Figure 2.6 illustrates the decrease in sensitivity with cooperative sensing under different fading conditions. As the number of users is increased, the required sensitivity of the sensing devices decreases and approaches the path loss. In a practical system, however, the number of users is limited and only a limited amount of gain can be achieved through cooperative sensing.

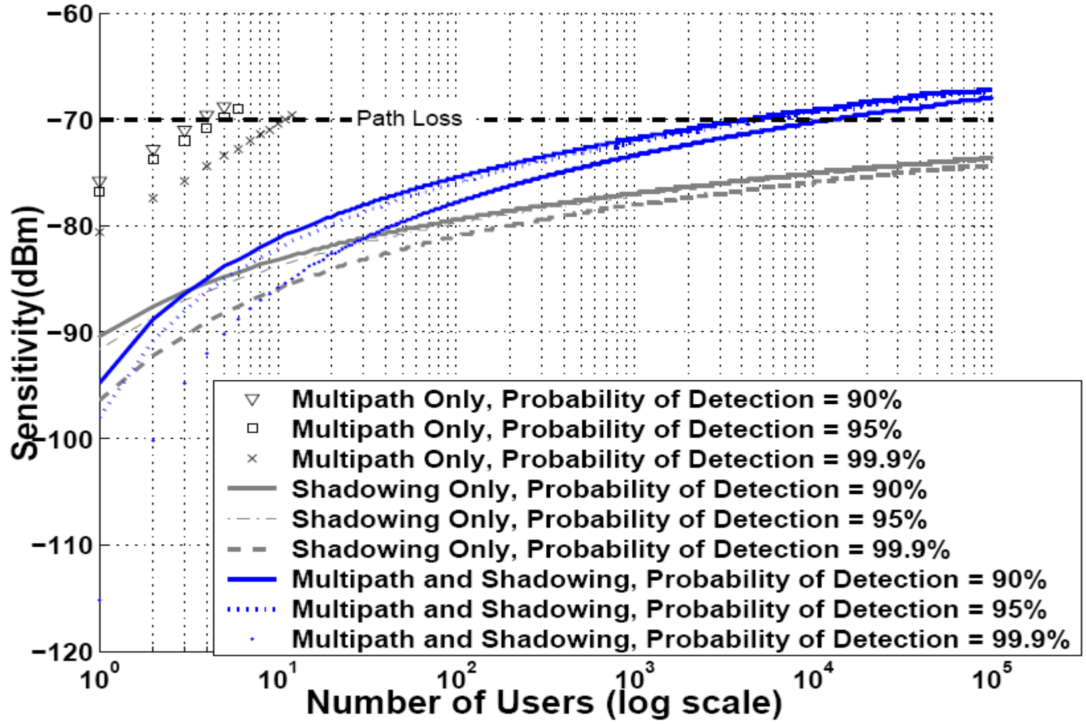

Figure 2.6: Sensitivity Increase with Cooperative Sensing

The cooperative sensing scheme shares sensing information from the independent number of secondary local users. Cooperative sensing decreases the probabilities of misdetection and false alarm considerably. In addition, cooperation can solve hidden primary user problem and it can decrease sensing time. Cooperative spectrum sensing is most effective when local user observes independent fading or shadowing [23]. The performance degradation due to correlated shadowing is investigated in terms of missing the opportunities. It is found that it is more advantageous to have the same amount of users cooperating over a large area than over a small area [28].

CHAPTER 3: METHODOLOGY

3.1 Problem Formulation

One major motivation for this research is to support cognitive radio devices equipped with multiple radio access technologies such that one or more of the RATs may be active at once. There are several benefits to this type of approach. First, techniques such as [30] may be used to send portions of traffic on each link, recombining it at the destination using erasure codes. Second, increasing the number of RATs available for connection improves reliability. If neighbouring infrastructure using one particular RAT experiences problems such as congestion or downtime, another available RAT may be chosen to take on a greater load leading to better connectivity and reliability.

An important feature of cognitive radios is their ability to perform spectrum sensing. A reliable operating frequency channel can therefore be selected based on its interference level (from primary or secondary users) and its attenuation, shadowing and fading characteristics [31]. Increasing the accuracy of the sensing algorithms is thus a primary factor in providing an accurate channel characterization and in improving network reliability.

The under-utilization of the scarce spectrum triggered the need for opportunistic spectrum sharing among mobile radio users recently. The users who own the spectrum usually get higher access privilege while the cognitive users (also known as secondary users) usually look for opportunistic access. The aim of this thesis is to design and simulate a virtual wireless link selection (VWLS) algorithm that enables the cognitive users to access the unused spectrum hole in an opportunistic and reliable way.

The system under consideration is a collection of one or more wireless access networks. In order to quantify the performance improvement gained by the establishment of VWLs in cognitive radio networks, a classical CRN is first described, and then the proposed network system model which uses the newly developed VWLS algorithm is presented.

3.2 The Classic Cognitive Radio Network Model

A cognitive radio network belonging to service provider j possesses wireless resources in the form of A_j channels. Connection-based traffic is considered, where service requirements of each flow or connection C_j is continuous and constant. Flows arrive at the network and request service. Each flow requires the capacity of one channel for the duration of its service in order to fulfil its requirements. If the CRN has available resources, it can accept the flow. If not, then the flow must be blocked – service is refused and the flow ends without being serviced. Once accepted, a flow must have continuous service for the duration of its service time [32]. The single network is depicted in Figure 3.1.

The classical CRN system consists of N classical networks. Each network has its own set of channels, with the total capacity of the system being $M = \sum_{i=1}^{N} A_j$. However, these networks are completely independent of each other, with clients arriving to network j only being serviced on network j. As a result, when a network reaches its capacity, it must start blocking flows, as it has no available channels. Therefore, flows may be blocked even if the overall utilization of the total system (the complete set of N networks) is relatively low.

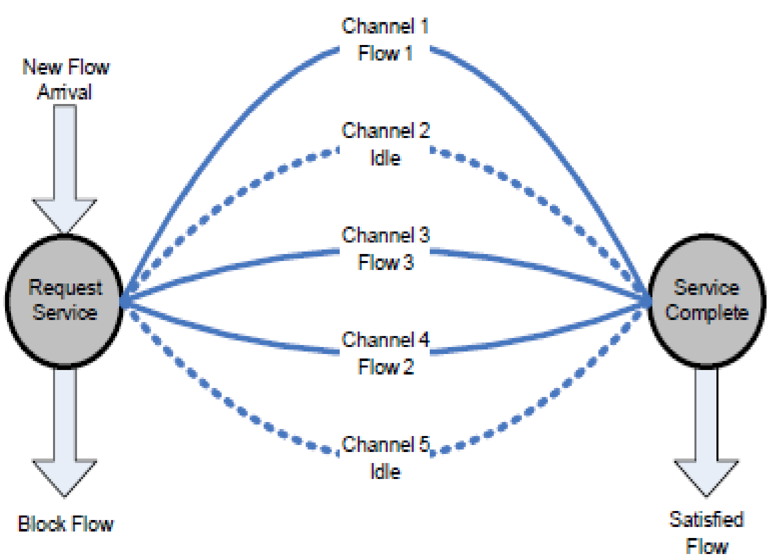

Figure 3.1: A Network with five Channels [5]

3.3 Design of the Proposed Cognitive Radio Network Model

The cognitive radio network system model for the proposed algorithm is depicted in Figure 3.2. The CFCDB is a fixed component in the cognitive radio system and has cognitive radio capabilities. It represents the infrastructure side of the CR system and provides supports (e.g. spectrum holes management, mobility management, security management) to CRs. It provides a gateway for CRs to access the backbone networks (e.g. Internet) via the multi-RAT base station. CFCDB can also form a mesh wireless backbone network by enabling wireless communications between them, and some of them act as gateway routers if they are connected with wired backbone networks.

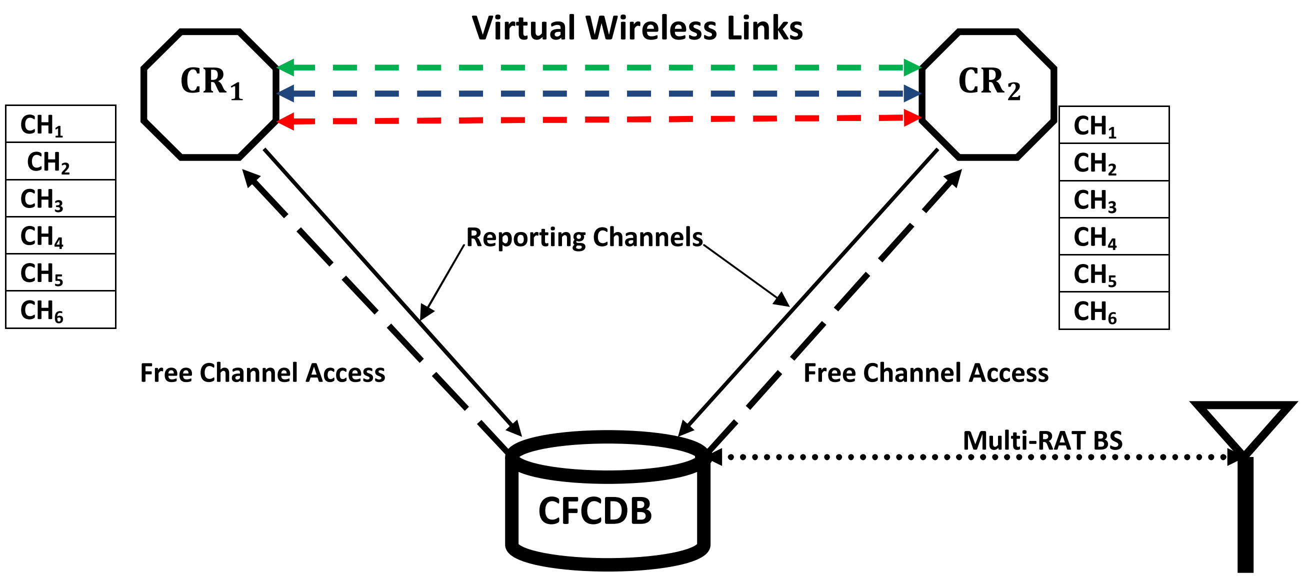

Figure 3.2: Cognitive Radio Network System Model for the Proposed Algorithm

During the virtual wireless link establishment, first the CFCDB collects channel information from all the CRs under its service area and broadcasts that information to the other CRs who do not know the channel information of a given CR. For example in our case we have only two CRs, the CFCDB informs the channel information of CR_1 to CR_2 & the channel information of CR_2 to CR_1. Then CR_1 &CR_2 establish a virtual link between them based on the a priori knowledge of channel information as indicated in Figure 3.2.

While enabling direct wireless links between CR and CFCDB, they can form a mesh virtual wireless backbone network. Because of their cognitive radio capability, they can dynamically choose operating frequency band and communicate with each other. Since the CR→CFCDB links may have much more air interfaces, the link capacity between CR_1 → CFCDB and CR_2→CFCDB may be large. Another benefit of this kind of virtual link is the reduced cost in placing the CR→CFCDBs. This is because that setting up a CR→CFCDB in some environment with a physical wired link is not feasible.

3.3.1 Virtual Wireless Link Establishment

In this subsection we use a two dimensional vector space to show how the virtual wireless link is established and how the selection will be done between two CR devices. Whenever the CR is allowed to transmit in a given band, it should select one free channel and adjust its transmission parameters with those in the PU band for efficient transmission. Each cognitive radio device sorts its free channels as: $CH_1, CH_2, CH_3, \dots, CH_n$ based on their signal quality or received signal to noise ratio (SNR), $CH_1 > CH_2 > CH_3 > \cdots > CH_n$ if there are n free channels in the vicinity of a given CR. Then the virtual wireless link will be established by selecting an element from the following link matrix.

$$L = \begin{bmatrix} CH_{11} & CH_{12} & \cdots & CH_{1n} \\ \vdots & & \ddots & \vdots \\ CH_{n1} & CH_{n2} & \cdots & CH_{nn} \end{bmatrix} \tag{3.1}$$

Where $L \in C^{NxN}$, C^{NxN} denotes the space of complex NxN matrices, N is the number of free channels on one CR and CH_{ij} indicates the virtual wireless link between the two CR devices.

For the specific case of only two CR devices and each listing only the first best three channels, the link matrix having nine links becomes:

$$L^* = \begin{bmatrix} CH_{11} & CH_{12} & CH_{13} \\ CH_{21} & CH_{22} & CH_{23} \\ CH_{31} & CH_{32} & CH_{33} \end{bmatrix} \tag{3.2}$$

*Note that each CH_{ij} may belong to any communication technology, it could be from GSM or UMTS or LTE or etc. The multi-RAT base station is adopted for the purpose of interoperability between the different RATs.

If we assume that there are only two secondary users (SUs), CR_1 and CR_2, each listing only the best three of their free channels, and the channels are collected from different RATs: for CR_1, CH_1 is from GSM, CH_2 is from UMTS, CH_3 is from LTE & for CR_2, CH_1 is from LTE, CH_2 is from GSM and CH_3 is from UMTS. Then the link matrix becomes:

$$L = \begin{bmatrix} GSM - LTE & GSM - GSM & GSM - UMTS \\ UMTS - LTE & UMTS - GSM & UMTS - UMTS \\ LTE - LTE & LTE - GSM & LTE - UMTS \end{bmatrix} \tag{3.3}$$

And the visualization of the links is represented in the following diagram.

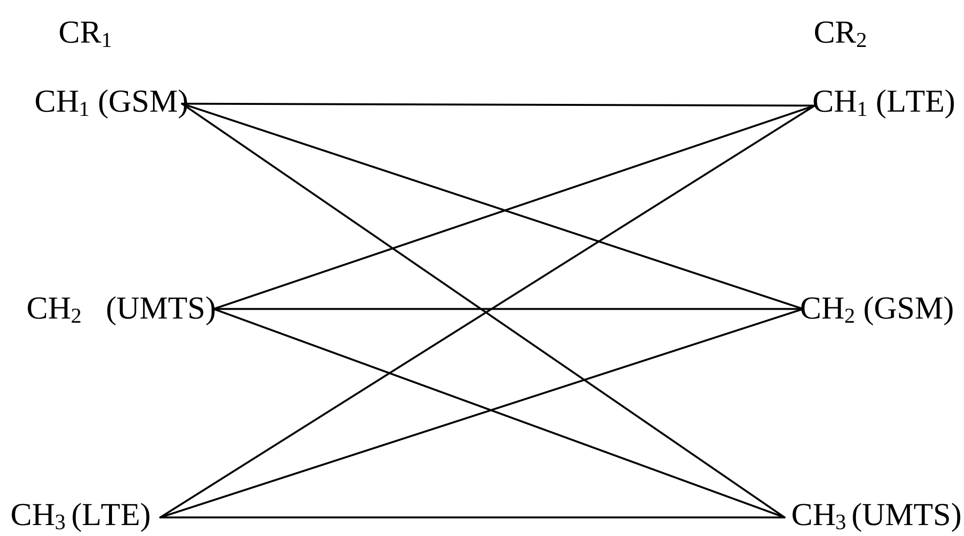

Figure 3.3: Visualization of the virtual wireless link between two CR devices

3.4 Design of the Proposed Algorithm

For the development of the algorithm we assume that there are only three bands available in the given local area.

The steps to be executed in the VWLS algorithm are:

i. Sense the available frequency bands in the local area (like GSM, UMTS or LTE) & keep them in the database.
ii. Calculate the probability of false alarm $\left(P_{fa}\right)$ and the probability of correct detection (P_{cd}) . If $P_{fa} < 0.1 \; and \; P_{cd} > 0.9$ then go to step four, else if $P_{fa} \geq 0.1 \; or \; P_{cd} \leq 0.9$, then go to step two.
iii. Measure the radio transmission parameters of the PU like power, modulation, coding, and frequency.
iv. Check for the availability of free channels & sort the free channels based on their signal strength (SNR).
v. Report to the central free channel database via the reporting channel.
vi. Cooperate with neighbouring CRs & with the CFCDB to establish a virtual wireless link on the free channels.
vii. Reconfigure its own radio parameters to match with that specific band for efficient transmission.
viii. Select the channel with the strongest signal or highest SNR and start transmission of voice or data. While transmitting, if the current channel is wanted by the PU, handover to another free channel. If there is no free channel for handovering, then the call is dropped.
ix. If either the call is ended or dropped, then go to step two.

The parameters to be considered in the VWLS algorithm are:

a. The available frequency bands.
b. Band Occupancy in percentage $= \frac{\text{Number of active users}}{\text{Total number of available channels}} * 100\%$

$$\eta = \frac{N \; of \; ActivePU}{N \; of \; total \; channels} \times 100 \qquad (3.4)$$

c. Transmission parameters such as the channel coding type and rate, the signaling rate and the modulation and operating frequency.

3.4.1 Coding of the Algorithm

The next step is to code the VWLS algorithm using C++ programming language on the OMNET++/MiXiM platforms, where OMNET++ (Objective Modular Network Test bed in C++) is an object-oriented modular discrete network simulator and MiXiM (MiXed siMulator) is a simulation framework for wireless and mobile networks which was developed on top of OMNET++ [33]. A partial definition of module configuration is depicted in the Figure 3.4 below.

```
simple CRBasePhyLayer like CRWirelessPhy
{
    parameters:
        double sensingtime @unit(s);
        bool coreDebug   = default(false);
        bool recordStats = default(false);
        int headerLength = default(0) @unit(bit);
        bool usePropagationDelay;
        double thermalNoise @unit(dBm);
        bool useThermalNoise;
        xml analogueModels;
        xml decider;
        double sensitivity @unit(dBm);
        double maxTXPower @unit(mW);
        //# switch times [s]:
        double timeRXToTX       = default(0) @unit(s);
        double timeRXToSleep    = default(0) @unit(s);
        double timeTXToRX       = default(0) @unit(s);
        double timeTXToSleep    = default(0) @unit(s);
        double timeSleepToRX    = default(0) @unit(s);
        double timeSleepToTX    = default(0) @unit(s);
        int initialRadioState   = default(0);
        double radioMinAtt = default(1.0);
        double radioMaxAtt = default(0.0);
        int nbRadioChannels = default(1);
        int initialRadioChannel = default(0);
```

Figure 3.4: Partial example of a module definition (Basic Physical Layer Module)

3.4.2 Configuration of Primary and Secondary Users

We configure both the cognitive users & primary users with the necessary transmission & reception parameters defined at the physical layer module. Figure 3.5

illustrates the partial configuration we did for the first primary user (PU1). As indicated in the figure the sensing time is set to 5s, the sensitivity of the receiver is set to -80dBm, the maximum transmit power is set to 100mW, the time to switch from receive state to transmit state is set to 0.00021s, the time from the receive state to sleep state is set to 0.000031s and the physical layer considers thermal noise and propagation delay.

```
**.PU1[*].nic.phy.sensingtime = 5s
**.PU1[*].nic.phy.usePropagationDelay = true
**.PU1[*].nic.phy.thermalNoise = -100dBm
**.PU1[*].nic.phy.useThermalNoise = true
**.PU1[*].nic.phy.analogueModels = xmldoc("config-template.xml")
**.PU1[*].nic.phy.decider = xmldoc("deciderConfig.xml")
**.PU1[*].nic.phy.sensitivity = -80dBm
**.PU1[*].nic.phy.maxTXPower = 100.0mW
**.PU1[*].nic.phy.initialRadioState = 0
**.PU1[*].nic.phy.timeRXToTX = 0.00021s
**.PU1[*].nic.phy.timeRXToSleep = 0.000031s
```

Figure: 3.5 Configuration of a primary user

3.4.3 The Simulation Diagram

After the entire configuration for all the radios is done, the simulation is carried out and the appearance of the network after coding looks like the one given in Figure 3.6.

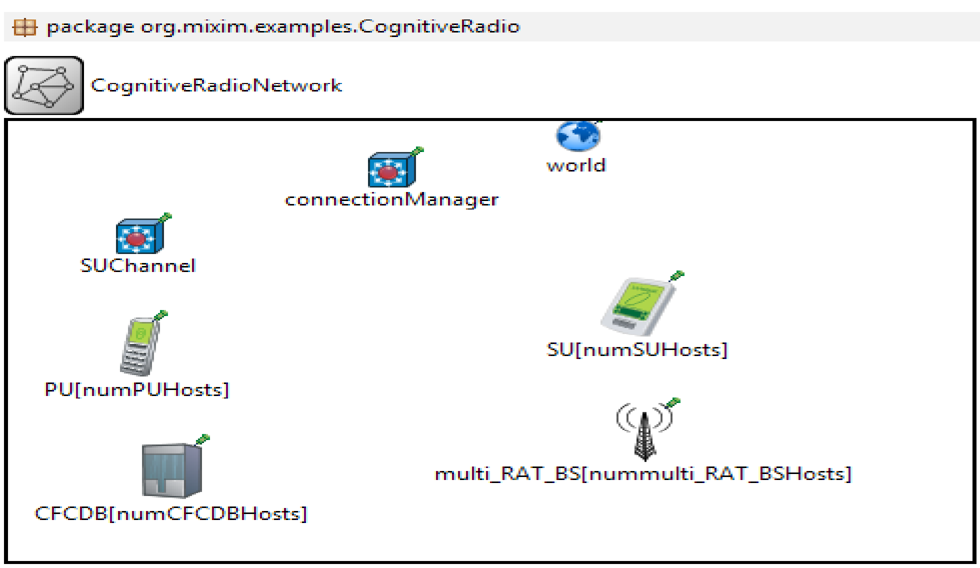

Figure 3.6: Simple cognitive radio network design on OMNET++ Simulator

In Figure 3.6, PU indicates the primary users and SU indicates the secondary users; CFCDB is the central free channel database, connectionManager is the entity responsible for managing the communication between the nodes and the multi_RAT_BS is the multi radio access technology base station capable of handling different communication technologies. The SUChannel is the central module that coordinates the connections between all nodes, and handles dynamic gate creation. ConnectionManager therefore periodically communicates with the mobility module and ChannelAccess.

3.4.4 Coding of the Engine Module

The framework includes a base CR engine which is implemented as a simple module in each host. The main function of this module is to enable the CR medium access control protocol to select a channel. It can be configured, through the configuration file, to return the first channel or a random channel from a set of channels which are considered available, and to try to preserve the previously selected channel. The provided base CR engine also includes a method which enables the CR medium access control module to report its experience in accessing the selected channels (i.e., successful or unsuccessful access). The current implementation of this method performs no operations upon the reception of an access report. More advanced selection schemes can be implemented by overriding it (e.g., in order to collect and maintain statistics about past history), as well as other methods which are related to channel selection.

Finally, it can also be noted that the provided CR Engine can be configured in order to have a perfect knowledge about which channels are sensed free of PU activity at a given moment. This is not a realistic assumption, but might be useful for some simulation experiments (e.g., for establishing a comparison base).

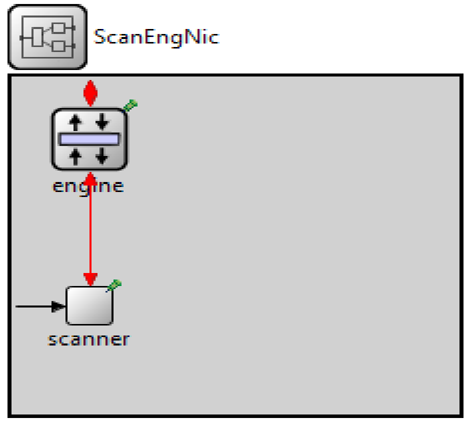

Figure 3.7: Scanner and Engine Modules of the Cognitive Radio

```
void EngineLayer::initialize(int stage)
{
    EngineBaseLayer::initialize(stage);

    if (stage == 0) {

        queueLength = hasPar("queueLength")      ? par("queueLength").longValue()      : 10;
        //busyRSSI = hasPar("busyRSSI")              ? par("busyRSSI").doubleValue()        : -90;
        slotDuration = hasPar("slotDuration")   ? par("slotDuration").doubleValue()  : 0.1;
        difs = hasPar("difs")                   ? par("difs").doubleValue()          : 0.001;
        maxTxAttempts = hasPar("maxTxAttempts") ? par("maxTxAttempts").longValue()   : 7;
        bitrate = hasPar("bitrate")             ? par("bitrate").doubleValue()       : 10000;
        txPower = hasPar("txPower")             ? par("txPower").doubleValue()       : 50;
        initialCW = hasPar("contentionWindow")  ? par("contentionWindow").longValue(): 31;

        macState = RX;

        //droppedPacket.setReason(DroppedPacket::NONE);

        //nicId = getParentModule()->getId();

        // initialize the timer
        backoffTimer = new cMessage("backoff");
        minorMsg = new cMessage("minClear");

        nbBackoffs = 0;
        backoffValues = 0;
        nbTxFrames = 0;

        txAttempts = 0;
    }
    else if(stage == 1) {
        BaseConnectionManager* cc = getConnectionManager();

        if(cc->hasPar("pMax") && txPower > cc->par("pMax").doubleValue())
            opp_error("TranmitterPower can't be bigger than pMax in ConnectionManager! "
                      "Please adjust your omnetpp.ini file accordingly.");
```

Figure 3.8: Coding of the Engine Module

3.4.5 Coding of the Scanner Module

The base scanner module in Figure 3.7 is implemented as a simple module which is connected to the CR Engine, and has a dual role in the context of the simulation framework. Firstly, it can act as the scanner entity. In this case, scanning requests are made by the CR Engine through the sending of messages which identify the targeted frequency band. Then, when scanning is over, results are asynchronously sent back through messages. The Base CR engine keeps the conclusions of these sensing requests in an internal data structure. Therefore, CR engines which are based on extensions of the base CR engine can take advantage of these facilities (i.e., scanning requests and the internal data structure). Time to scan a channel is defined in the configuration file. The scanner module can also be extended in order to model less ideal scanners (e.g., with missed detection and false alarm probabilities).

The base scanner module is also a utility module. It keeps track of primary user activity changes (i.e., active to inactive, and vice-versa). If the SU it belongs to is in the interference area of the PU which has changed its activity state, an update message is sent to the corresponding CR engine. The interference area is determined based on the coverage areas of the SUs and PUs, which are modeled as perfect circles, and on their positions in the simulation playground. The radii of the coverage areas of the provided base PUs are fixed and defined in the configuration file. In terms of the SUs, the coverage areas are calculated based on the transmission power and on the analog models in usage.

The base scanner module can naturally be extended in order to consider other propagation models. The update messages which are sent include the activity status of the corresponding PU, its frequency band, and if the SU is in its coverage range, i.e., if it can detect it through local sensing. This information is primarily intended to be used by the CR engine to collect statistics about interferences to PUs and missed detections. This enables the user of the CR framework to analyze the effectiveness of its CR proposals in terms of PU protection. The scanner layer of the cognitive radio is coded in order to perform its scanning function as shown in Figure 3.9.

```
template int ScannerPhyLayer::readPar<int>(const char* parName, const int) const;
template double ScannerPhyLayer::readPar<double>(const char* parName, const double) const;
template<> simtime_t ScannerPhyLayer::readPar<simtime_t>(const char* parName, const simtime_t defaultValue) const {
    if(hasPar(parName))
        return simtime_t( par(parName).doubleValue() );
    return defaultValue;
}
template bool ScannerPhyLayer::readPar<bool>(const char* parName, const bool) const;

void ScannerPhyLayer::initialize(int stage) {

    ConnectionManagerAccess::initialize(stage);

    if (stage == 0) {
        // if using sendDirect, make sure that messages arrive without delay
        gate("radioIn")->setDeliverOnReceptionStart(true);

        //get gate ids
        upperLayerIn = findGate("upperLayerIn");
        upperLayerOut = findGate("upperLayerOut");
        upperControlOut = findGate("upperControlOut");
        upperControlIn = findGate("upperControlIn");

        //read simple ned-parameters
        //  - initialize basic parameters
        if(par("useThermalNoise").boolValue()) {
            double thermalNoiseVal = FWMath::dBm2mW(par("thermalNoise").doubleValue());
            thermalNoise = new ConstantSimpleConstMapping(DimensionSet::timeDomain,
                                                          thermalNoiseVal);
        } else {
            thermalNoise = 0;
        }
        headerLength = par("headerLength").longValue();
        sensitivity = par("sensitivity").doubleValue();
        if (!isFiniteNumber(sensitivity) || sensitivity <= -999999)
            sensitivity = 0; // disabled
```

Figure 3.9: Partial view of the coding for the scanner layer

CHAPTER 4: RESULTS AND DISCUSSIONS

4.1 Simulation Results

The Physical Layer Decider of the CR device has the following tasks in MiXiM:

- Classify signal as noise if it is below a certain sensitivity threshold.
- Decide whether a signal header was received correctly by checking its SINR against a certain threshold.
- Decide whether the whole signal was received correctly by checking its SINR against a certain threshold.
- Decide whether the channel is busy or idle at a time point or during a time interval (channel sensing).

After the coding is done, the code is debugged and the resulting output is shown below.

```
[Host 0] - PhyLayer(Decider): Processing AirFrame with ID 7...
[Host 0] - PhyLayer(Decider): ... AirFrame processing as NewSignal...
[Host 0] - PhyLayer(Decider): Signal is too weak (6.51465e-009 < 1e-008) -> do not receive.
PU[0]::PhyLayer: Handed AirFrame with ID 7 to Decider. Next handling in 0.00625s.
** Event #121  T=4.530784382616  CognitiveRadioNetwork.multi_RAT_BS[0].nic.phy (PhyLayer, id=35), on selfmsg `{transmission over}' (cMessage, id=21)
** Event #122  T=4.530784382616  CognitiveRadioNetwork.multi_RAT_BS[0].nic.mac (CSMAMacLayer, id=34), on `{Transmission over}' (cMessage, id=99)
** Event #123  T=4.530784827958  CognitiveRadioNetwork.PU[0].nic.phy (PhyLayer, id=15), on selfmsg `BROADCAST_MESSAGE' (MiximAirFrame, id=98)
PU[0]::PhyLayer: End of Airframe with ID 7.
** Event #124  T=4.530904382616  CognitiveRadioNetwork.multi_RAT_BS[0].nic.phy (PhyLayer, id=35), on selfmsg `{radio switching over}' (cMessage, id=20)
** Event #125  T=4.530904382616  CognitiveRadioNetwork.multi_RAT_BS[0].nic.mac (CSMAMacLayer, id=34), on `{Radio switching over}' (cMessage, id=100)
** Event #126  T=5.495507189494  CognitiveRadioNetwork.PU[0].nic.mac (CSMAMacLayer, id=14), on selfmsg `backoff' (cMessage, id=1)
[Host 0] - PhyLayer(Decider): Creating RSSI map for range [5.495507189494,5.495507189494]
** Event #127  T=5.496007189494  CognitiveRadioNetwork.PU[0].nic.mac (CSMAMacLayer, id=14), on selfmsg `minClear' (cMessage, id=2)
[Host 0] - PhyLayer(Decider): Creating RSSI map for range [5.496007189494,5.496007189494]
** Event #128  T=5.496217189494  CognitiveRadioNetwork.PU[0].nic.phy (PhyLayer, id=15), on selfmsg `{radio switching over}' (cMessage, id=3)
** Event #129  T=5.496217189494  CognitiveRadioNetwork.PU[0].nic.mac (CSMAMacLayer, id=14), on `{Radio switching over}' (cMessage, id=101)
PU[0]::CSMAMacLayer: CInfo removed, mac addr=FF-FF-FF-FF-FF-FF
PU[0]::CSMAMacLayer: pkt encapsulated
** Event #130  T=5.496217189494  CognitiveRadioNetwork.PU[0].nic.phy (PhyLayer, id=15), on `BROADCAST_MESSAGE' (MacPkt, id=102)
PU[0]::PhyLayer: AirFrame encapsulated, length: 96
PU[0]::PhyLayer: sendToChannel: sending to gates
going forward. x = 230 y = 220 z = 100
```

Figure 4.1: The simulation output of the Physical Layer Decider

The results of the simulation indicated that there is a decrease in the total number of blocked calls (back offs) in the secondary users due to the presence of the virtual wireless link as illustrated in Figure 4.2.

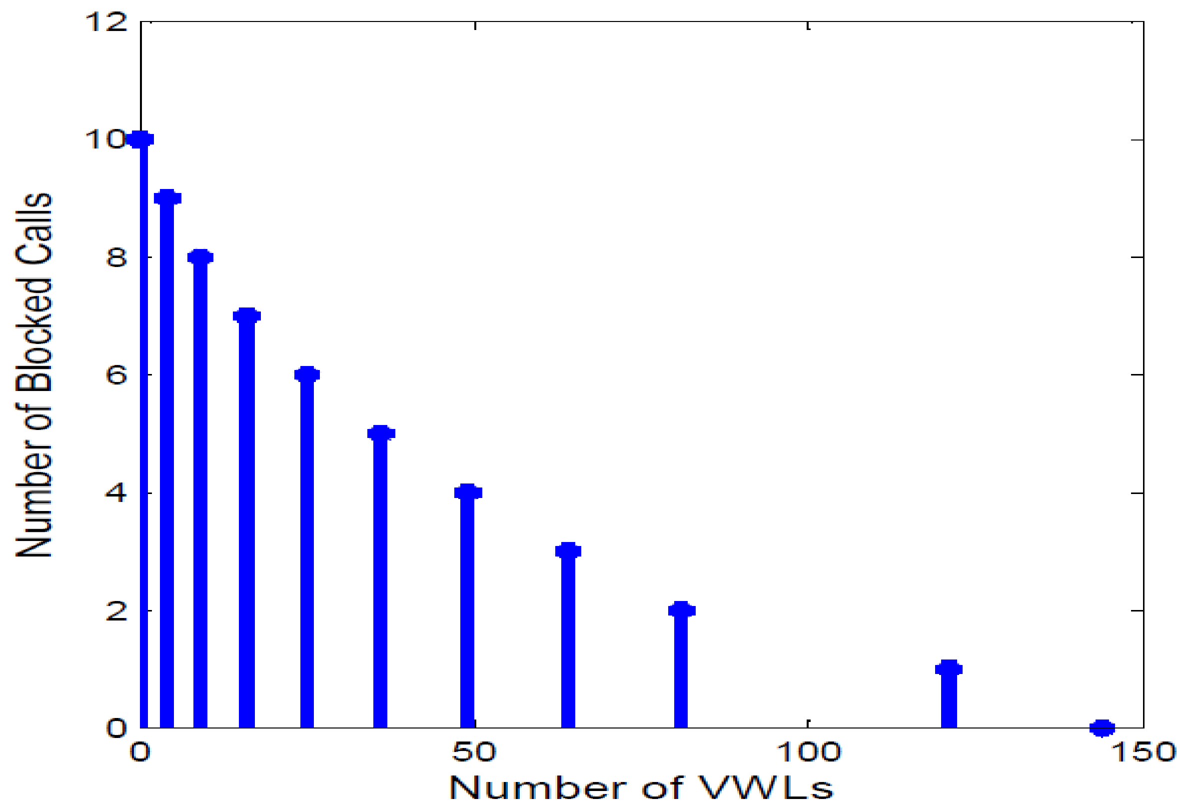

Figure 4.2: Number of blocked calls versus number of virtual wireless links

When a CR has a packet to transmit, it waits for a random backoff time before transmitting a request-to-send (RTS) packet to a desired receiver. The RTS contains the list of idle channels at the sender in the order of preference. The backoff value is selected within the interval [0, CW], where CW denotes the CR's current contention window (CW) size. The CW is initially set to cw_0 (minimum CW) and is doubled with every retransmission up to cw_{max}. A receiver of an RTS, combines the preference list of the sender with its own, and replies with a clear-to-send (CTS) message that reserves the channel with the least number of reservations. CRs around the receiver overhearing the CTS update their channel preference list by degrading the priority of the selected channel [34]. The CR user monitors the spectrum band to detect when there is no transmission from the other CR users and transmits after backoff duration to prevent simultaneous transmissions. The backoff counter indicates the number of slots that the station has to wait before the transmission. As the number of VWLs increases, the backoff duration and the probability of blocking decrease approximately exponentially as illustrated in Figure 4.3 and Figure 4.4 respectively.

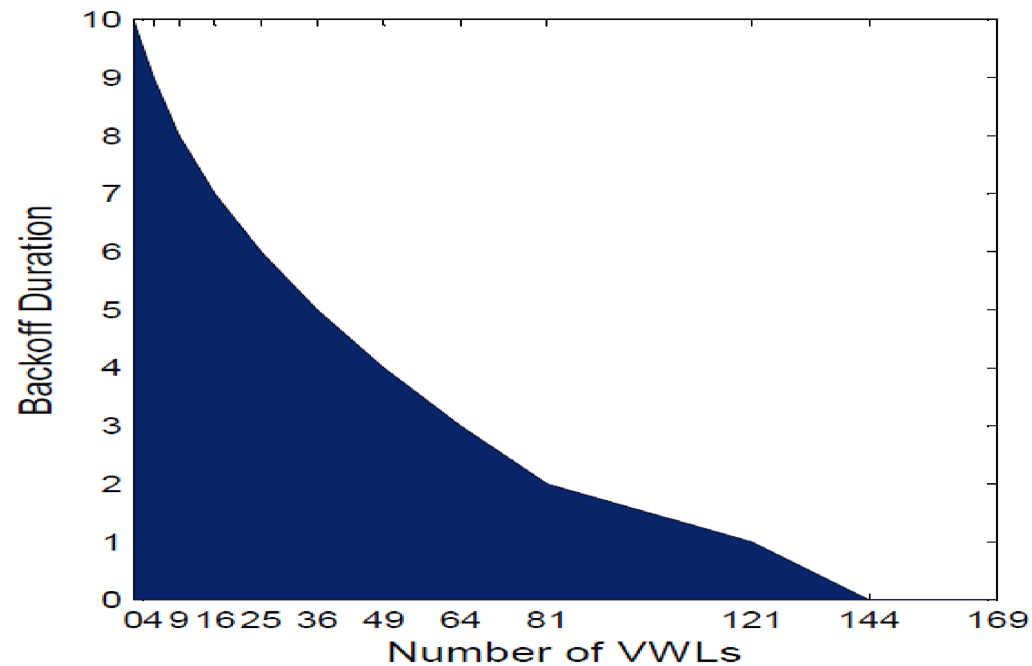

Figure 4.3: Backoff duration versus number of virtual wireless links

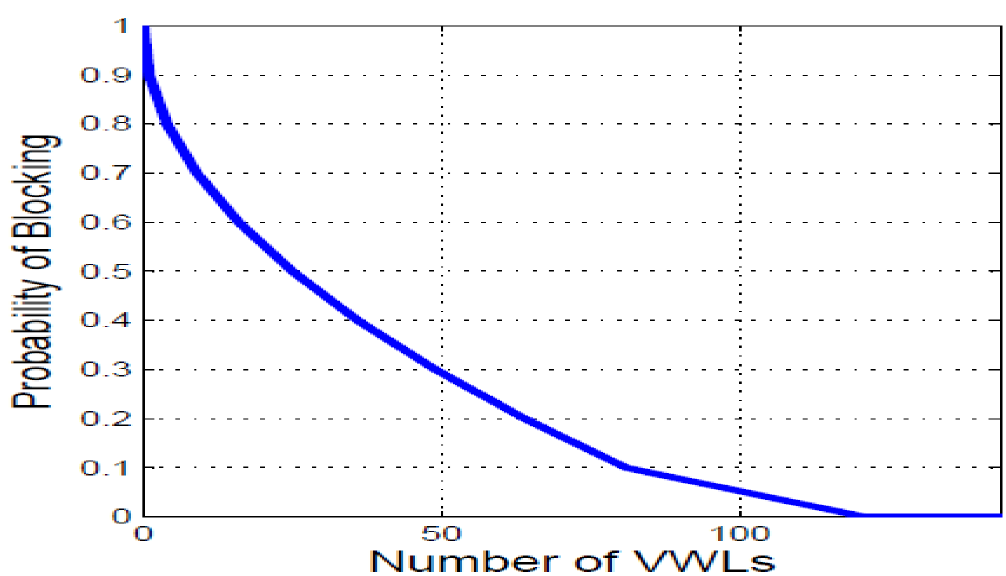

Figure 4.4: Probability of blocking versus number of virtual wireless links

As the number of free channels increases, the probability of failure in cognitive radio networks decreases as depicted in Figure 4.5.

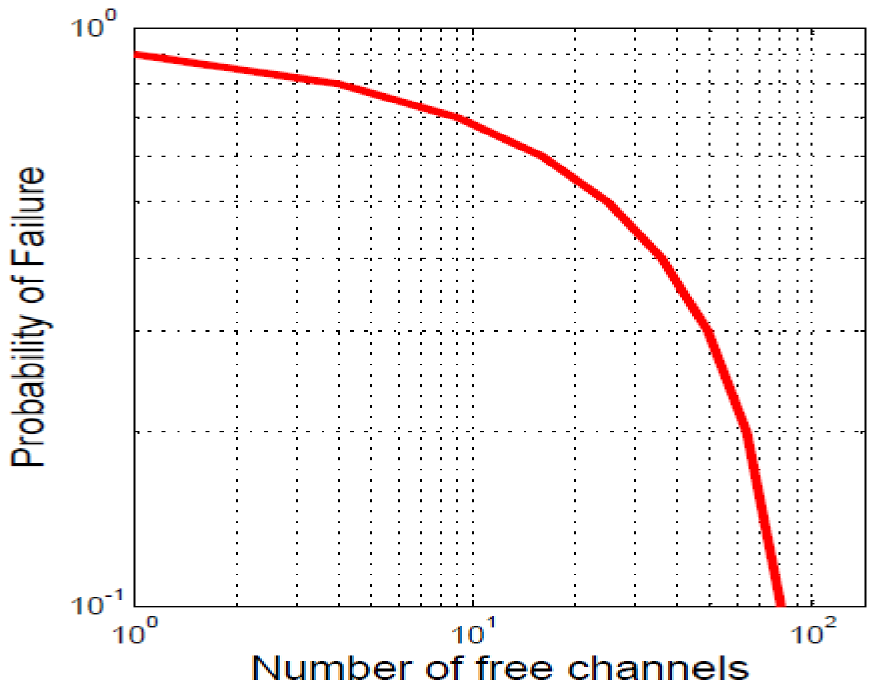

Figure 4.5: Probability of failure versus number of free channels

4.2 System Performance Evaluation

We investigate the performance of the VWL through the evaluation of the Secondary User Failure Probability (SU_{FP}). SU_{FP} is the probability that an arriving SU traffic (data or voice) will not receive the service it requires and it is calculated by using the blocking probability (P_B) & dropping probability (P_D). Blocking Probability is the probability that all radio channels are busy, in which case an arriving call is refused service & Dropping Probability is the probability that the SU traffic is dropped due to the reason that the channel is wanted by the licensed user or that there are not enough channels for transferring the call [25]. SU_{FP} is used to compare the overall performance of SU and PU traffic and can be expressed as:

$$SU_{FP} = P_B + (1 - P_B) * P_D \qquad 4.1$$

Let N be the total number of free channels stored in the CFCDB and let M be the maximum number of virtual wireless links that could be established between the given CR nodes. We can approximate the SU_{FP} in terms of N and M as shown by the formula below:

$$SU_{FP} = \frac{1}{4N}\log_{10} 2M \qquad 4.2$$

From Eq. (4.1) and (4.2), we can conclude that as the number of free channels stored in the CFCDB increases, both the blocking and dropping probabilities decrease, thereby decreasing the SU_{FP}. The relationship between SU_{FP}, Number of free channels & the number of virtual wireless links (M) is depicted from Figure 4.6 to Figure 4.10. As can be seen in the figures, the resulting performance depends on both the number of primary users and the number of free channels stored in the CFCDB. As the number of free channels increases, SU failure probability decreases, as there is an increased probability that one of the networks has available resources. Second, increases in total number of virtual links result in an increase in the SU_{FP}. This is because larger PU networks have a higher baseline utilization level than smaller networks, leaving a lower probability of having resources available for cognitive users.

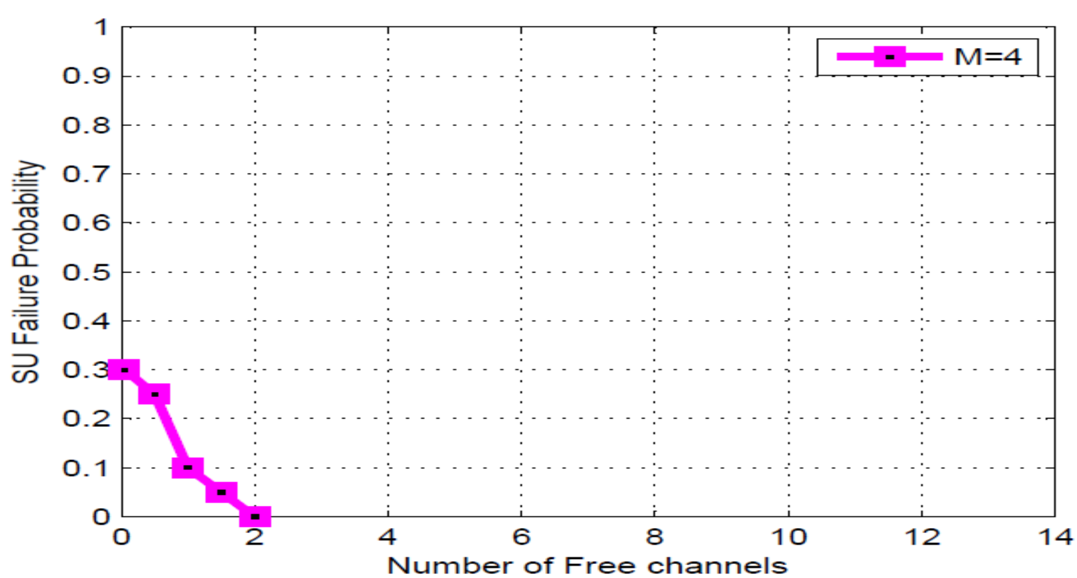

Figure 4.6: SU Failure Probability as a function of the number of free channels and VWLs (M=4)

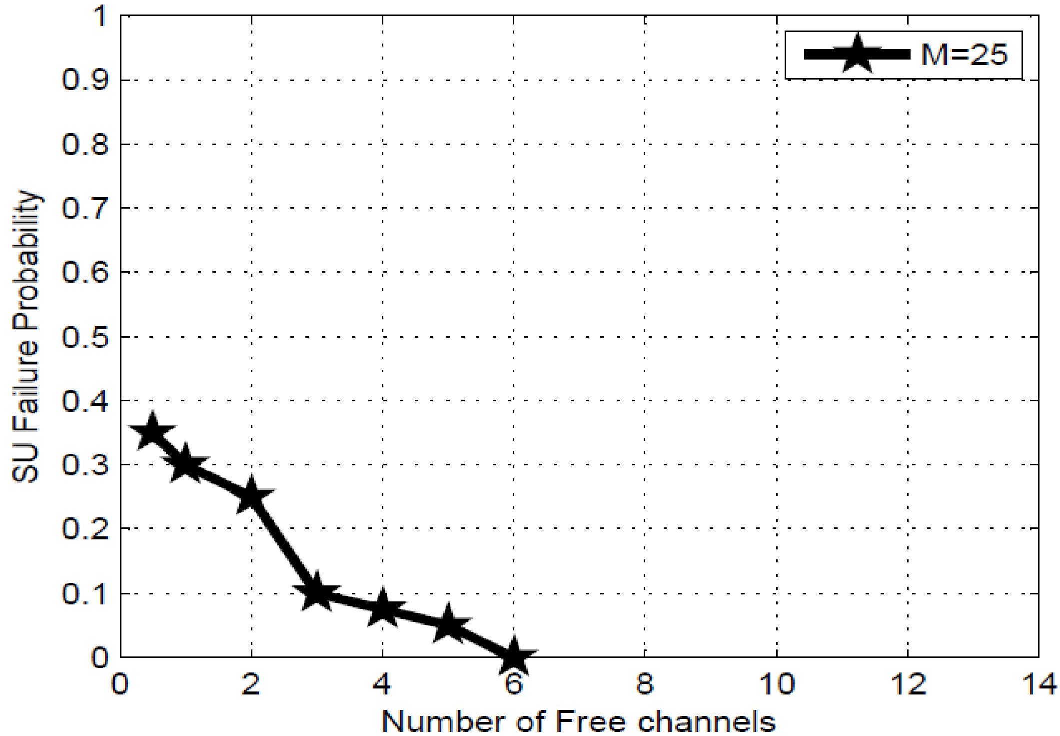

Figure 4.7: SU Failure Probability as a function of the number of free channels and VWLs (M=25)

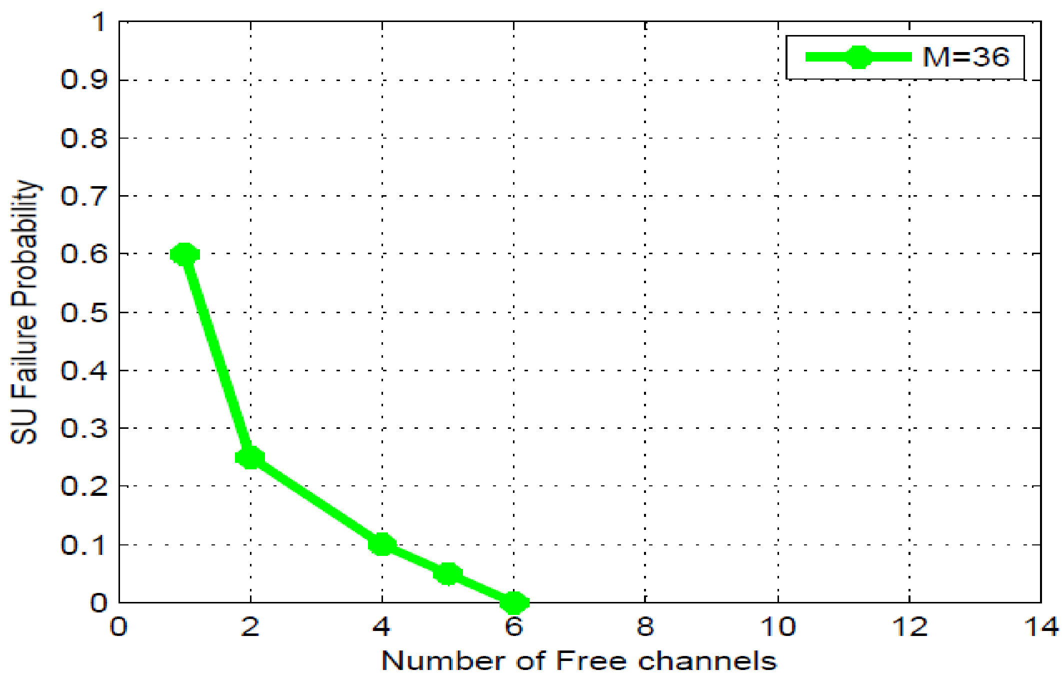

Figure 4.8: SU Failure Probability as a function of the number of free channels and VWLs (M=36)

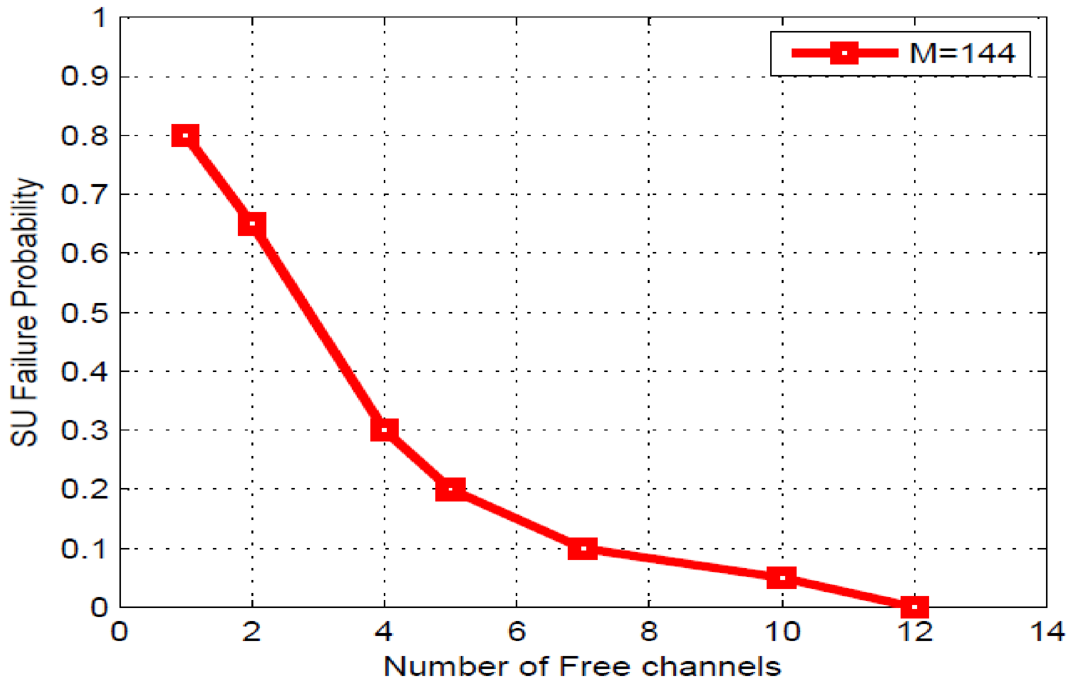

Figure 4.9: SU Failure Probability as a function of the number of free channels and VWLs (M=144)

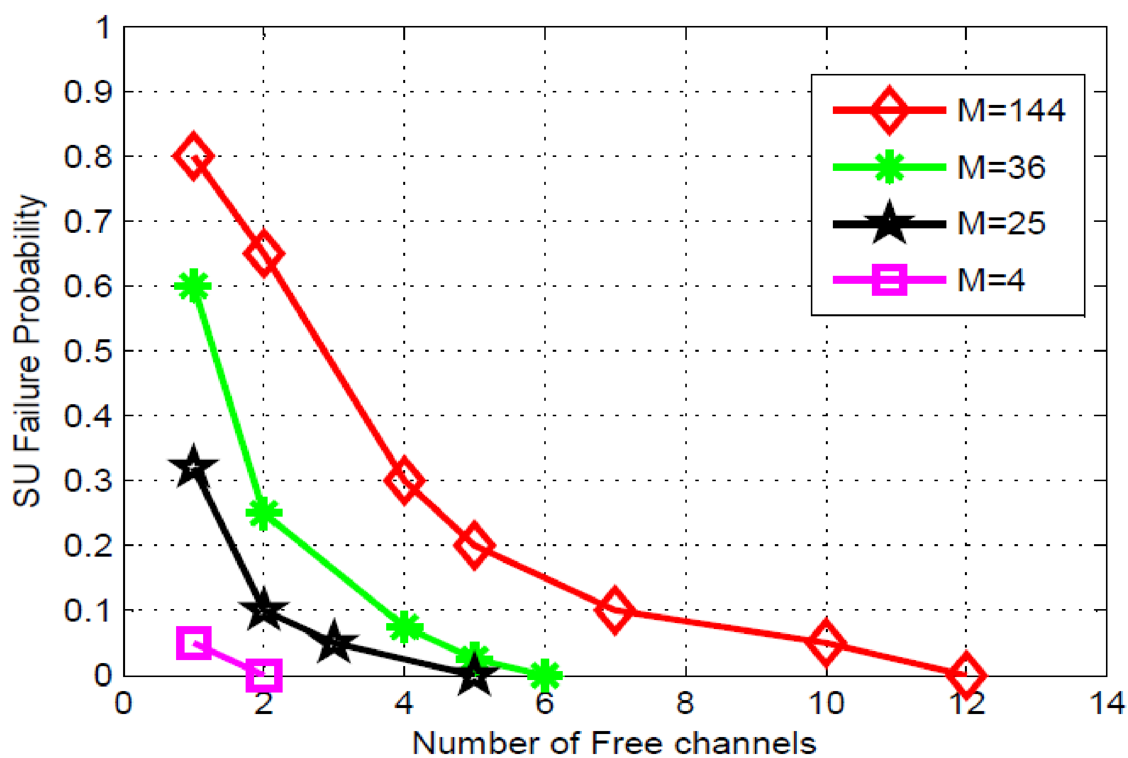

Figure 4.10: SU Failure Probability as a function of the number of free channels and VWLs (M=4, 25, 36, and 144)

4.3 Discussions

Cooperative users offering alternative paths for their partners can significantly improve link reliability and increase throughput without consuming extra resources. In the context of cognitive radio, secondary users opportunistically exploit the existence of spectrum holes to improve spectrum utilization. In Figure 4.11, the CRN system throughput increases when the number of available free channels stored in the CFCDB increases. Increased throughput means more efficient usage of power and spectrum. Overall, the throughput with the virtual wireless link structure is much larger than the one without a virtual wireless link structure.

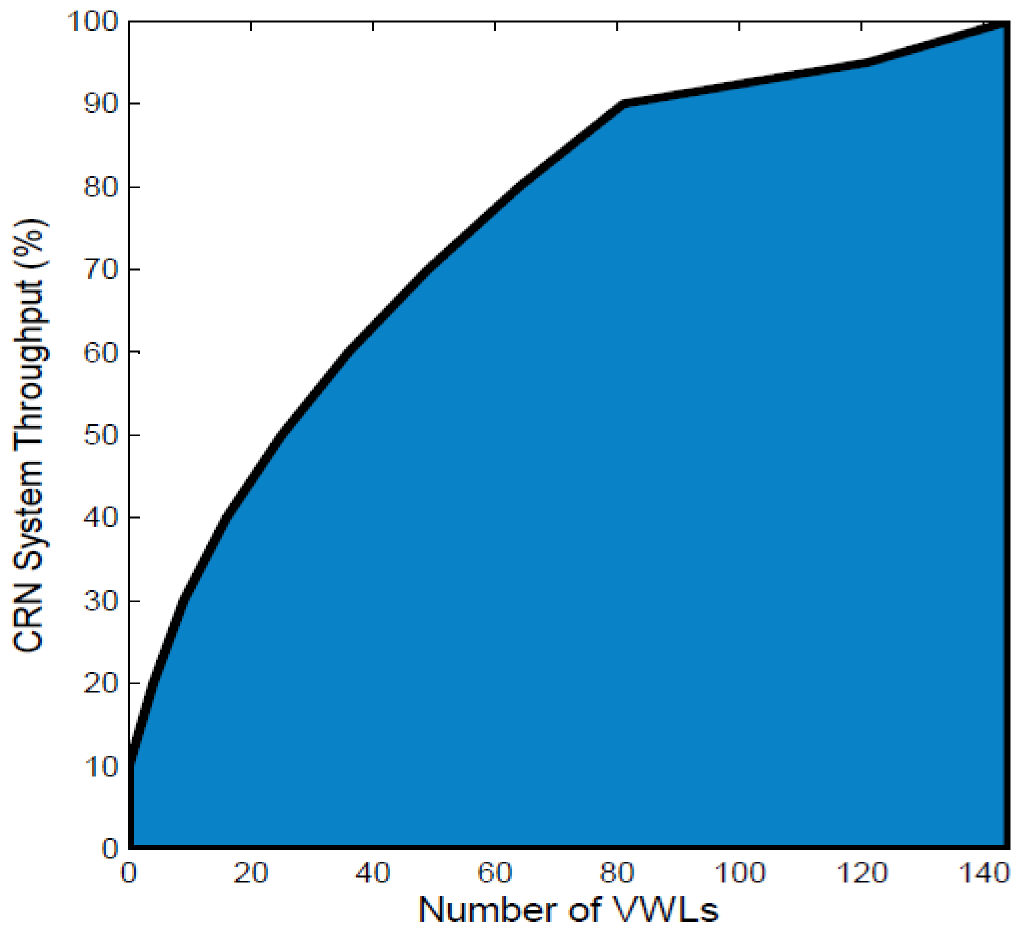

Figure 4.11: Cognitive radio network system throughput as a function of the number of virtual wireless links

As shown in Figure 4.12, system utility and throughput are improved in our approach in comparison with CRNs without a virtual wireless link. The one with the virtual wireless link structure increases faster than the one without the virtual wireless link over time. The simulation results verify our theoretical analysis and show that the efficiency of our approach is significantly improved compared with the one without a virtual wireless link.

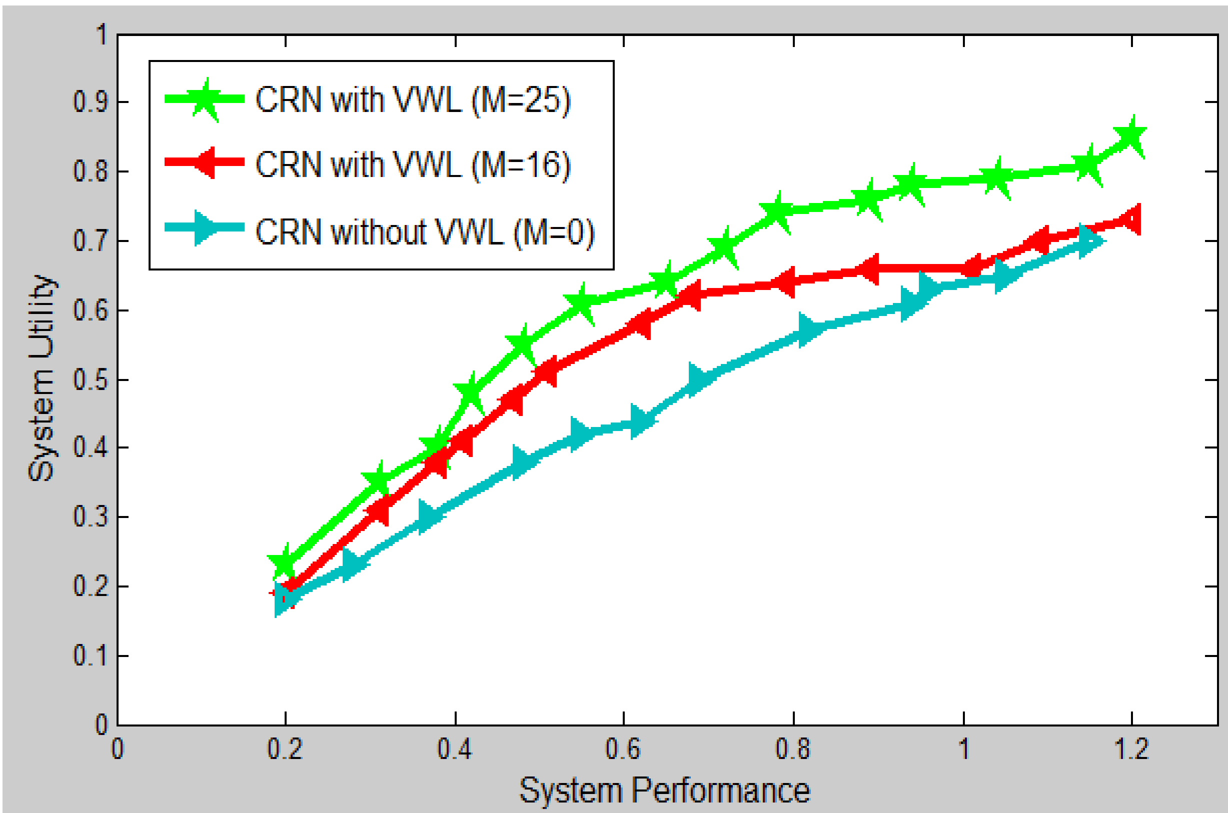

Figure 4.12: System utility as a function of system performance and number of virtual wireless links

CHAPTER 5: CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

Spectrum mobility in cognitive networks is unavoidable to reduce the impact of SUs on PUs. In this thesis, virtual wireless link is introduced as a new link maintenance strategy to reduce the blocking and dropping probability of SU sessions. We observed that the establishment of the VWL schemes improved the system performance and when the number of VWLs increases the system utility obtained improves as well. We showed that channel linking is generally beneficial, though the extent of the benefits depend on the features of the CRN, including CRN size and the total number of channels available for linking. In addition, we showed that performance benefits can be realized by adaptively changing the number of virtually linked channels depending on network conditions.

5.2 Recommendations and Future Works

Lastly, this work forms the basis for further study in interactions between RATs in heterogeneous wireless environments. This area will become increasingly important as devices contain more radios and users try to take advantage of these extra resources by using multiple radios simultaneously without negative effects. Additionally, the link maintenance model should be applied to secondary usage systems using negotiated spectrum sharing and the influence of a proper sub-channel selection algorithm should be investigated. Another area is the investigation of a multi-user scenario. Multiple SU communications could select the same sub channels and thus would interfere with each other. Means to prevent harmful interference of different SU communications should be developed.

Publications and Conferences from this work

[1] Daniel Hailu, P.K.Langat, and H.Tarus, "Design of a Virtual Wireless Link Selection Algorithm for Reliability of Cooperative Cognitive Radio Networks," in *International Annual Conference on Sustainable Research and Innovation (SRI)*, Nairobi, 2014, pp. 281-284 [Accepted and Presented].

[2] Daniel Hailu, P.K.Langat, and H.Tarus, "Enhancing Reliability in Heterogeneous Wireless Communication Networks: A Cognitive Radio Perspective," in *the 8th annual conference of Ethiopian Society of Electrical Engineers (ESEE)*, Adama, Ethiopia, 2014 [Accepted and Presented].

[3] Daniel Hailu, P.K.Langat, and H.Tarus, "Reliability in Heterogeneous Wireless Networks:A Cognitive Radio Perspective," *Journal of Sustainable Research in Engineering (JSRE)*, vol. 1, no. 2, 2014 [Under Review].

[4] Daniel Hailu, P.K.Langat, and H.Tarus, "Enhancing Reliability in Heterogeneous Wireless Communication Networks: A Cognitive Radio Perspective," *Journal of the Ethiopian Society of Electrical Engineers*, vol. 8, pp. 38-42, August 2014 [Published].

REFERENCES

[1] A. F. Molisch, *Wireless Communications*, 2nd ed. West Sussex , UK: John Wiley & Sons, 2011.

[2] T. S. Rappaport, *Wireless Communications: Principles and Practice,* 2nd ed.: Prentice Hall, 2002.

[3] A.J. Goldsmith, *Wireless Communications*. New York, USA: Cambridge University Press, 2005.

[4] M.Stella Iacobucci, *RECONFIGURABLE RADIO SYSTEMS, NETWORK ARCHITECTURES AND STANDARDS*, 1st ed., Giancristofaro Domenico and Lofrumento Giovanni, Eds. West Sussex, United Kingdom: John Wiley & Sons, Ltd, 2013.

[5] J. Gross, A.Wolisz, and D.Willkomm, "Reliable Link Maintenance in Cognitive Radio Systems," in *Proceedings of the IEEE Symposium on New Frontiers in Dynamic Spectrum Access Networks (DySPAN 2005)*, Baltimore (MD), 2005, pp. 1-8.

[6] OMNeT++ User Manual version 4.3.1. [Online]. http://inet.omnetpp.org/doc/inet-manual-DRAFT.pdf

[7] MiXiM official website. [Online]. http://mixim.sourceforge.net/

[8] T.Yucek and H. Arslan, "A Survey of Spectrum Sensing Algorithms for Cognitive Radio Applications," *IEEE COMMUNICATIONS SURVEYS & TUTORIALS*, vol. 11, no. 1, pp. 116-130, 2009.

[9] R. Engelman, K.Abrokwah, G.Dillon, and G.Foster , "Report of the Spectrum Efficiency Working Group," Federal Communications Commission Spectrum Policy Task Force, 2002.

[10] S. Senthuran, A. Anpalagan, and O. Das , "Throughput Analysis of Opportunistic Access Strategies in Hybrid Underlay–Overlay Cognitive Radio Networks," *IEEE TRANSACTIONS ON WIRELESS COMMUNICATIONS*, vol. 11, no. 6, pp. 2024-2035, June 2012.

[11] J. Mitola III, *Software Radio Architecture*. New York, USA: Wiley Interscience, 2000.

[12] S. Haykin, "Cognitive radio: brain-empowered wireless communications," *IEEE Journal on Selected Areas in Communications*, vol. 23, no. 2, pp. 201-220, February 2005.

[13] M.Subhedar and G.Birajdar, "SPECTRUM SENSING TECHNIQUES IN COGNITIVE RADIO NETWORKS: A SURVEY," *International Journal of Next-Generation Networks (IJNGN)*, vol. 3, no. 2, pp. 37-51, June 2011.

[14] F.Khozeimeh and S.Haykin, "Brain-Inspired Dynamic Spectrum Management for Cognitive Radio Ad Hoc Networks," *IEEE TRANSACTIONS ON WIRELESS COMMUNICATIONS*, vol. 11, no. 10, pp. 3509-3517, October 2012.

[15] FCC, ET Docket No 03-222, Notice of Proposed Rulemaking and Order, 2003.

[16] F.K. Jondral, "Software-defined radio-basic and evolution to cognitive radio," *EURASIP Journal on Wireless Communication and Networking*, vol. 1, no. 3, pp. 275-283, August 2005.

[17] B.A.Fette, *Cognitive Radio Technology*, Second ed. USA: Elsevier Inc., 2006.

[18] H.I.Volos and R. M.Buehrer, "Cognitive Radio Engine Training," *IEEE TRANSACTIONS ON WIRELESS COMMUNICATIONS*, vol. 11, no. 11, pp. 3878-3889, November 2012.

[19] Y. Zeng and Y.C. Liang, "Spectrum-Sensing Algorithms for Cognitive Radio Based on Statistical Covariances," *IEEE Transactions on Vehicular Technology*, vol. 58, no. 4, pp. 1804–1815, May 2009.

[20] B.Rawat and G.Yan, "Spectrum Sensing Methods and Dynamic Spectrum Sharing in Cognitive Radio Networks: A Survey," *International Journal of Research and Reviews in Wireless Sensor Networks*, vol. I, no. 1, pp. 1-13, March 2011.

[21] M.Nekovee, Y. T. Hou, and A. M. Wyglinski, *Cognitive Radio Communications and Networks: Principles and Practice*, 1st ed. Burlington, MA , USA: Elsevier, 2010.

[22] ETSI TR 102 684, "Reconfigurable Radio Systems (RRS); Feasibility Study on Control Channels for Cognitive Radio Systems," European Telecommunications Standards Institute, Sophia Antipolis Cedex, Technical DTR/RRS-03008, 2012.

[23] J. G. Proakis, *Digital Communications*, Fourth ed. Boston, MA: McGraw Hill, 2000.

[24] D. Cabric, A. Tkachenko, and R. Brodersen, "Spectrum sensing measurements of pilot, energy, and collaborative detection," in *in Proc. IEEE Military Commun. Conf.*, Washington D.C., 2006, pp. 1-7.

[25] S.Stotas and A.Nallanathan, "On the Throughput and Spectrum Sensing Enhancement of Opportunistic Spectrum Access Cognitive Radio Networks," *IEEE TRANSACTIONS ON WIRELESS COMMUNICATIONS*, vol. 11, no. 1, pp. 97-107, January 2012.

[26] A. Papoulis and S. U. Pillai, *Probability, random variables, and stochastic processes*, 4th ed. Boston, USA: McGraw-Hill, 2002.

[27] B. Choi, K. Kim, and M. da Silva, Distributed Spectrum Sensing for Cognitive Radio Systems, 2007, Information Theory and Applications Workshop.

[28] M. Bkassiny, S.K. Jayaweera, Y.Li and K.A. Avery , "Wideband Spectrum Sensing and Non-Parametric Signal Classification for Autonomous Self-Learning Cognitive Radios," *IEEE TRANSACTIONS ON WIRELESS COMMUNICATIONS*, vol. 11, no. 7, pp. 2596-2605, July 2012.

[29] A. Ghasemi and E. S. Sousa, "Asymptotic performance of collaborative spectrum sensing under correlated log-normal shadowing," *in proc IEEE Commun. Lett.*, vol. 11, no. 1, pp. 34-36, 2007.

[30] ETSI TR 102 681, "Reconfigurable Radio Systems (RRS); Radio Base Station (RBS) Software Defined Radio (SDR) Status, Implementations, and Costs Aspects, Including Future Possibilities," ETSI, Technical v1.1.1, 2009.

[31] A. Calce, N. Farsad, and A. W. Eckford, "An experimental study of fractional cooperation in wireless mesh networks," in *Proceedings of the 22nd Annual IEEE Symposium on Personal Indoor Mobile Radio Communications (PIMRC 2011)*, Toronto, 2011, pp. 990-994.

[32] M.J.Neely and R.Urgaonkar, "Opportunistic Scheduling with Reliability," in *PROC. IEEE INFOCOM*, PHOENIX, AZ, 2008, pp. 1-9.

[33] N.Kaabouch and H.Reyes, "Improving the Reliability of Unmanned Aircraft System Wireless Communications through Cognitive Radio Technology,"

Scientific Research, vol. 5, pp. 225-230, August 2013.

[34] OMNeT++ official website. [Online]. http://www.omnetpp.org

[35] D. Cabric, S. Mishra, and R. Brodersen, "Implementation Issues in Spectrum Sensing for Cognitive Radios," in *Asilomar Conf. on Signals, Systems and Computers*, Pacific Grove, CA, 2004, pp. 772-776.

[36] Q. Zhao, L. Tong, A. Swami, and Y. X. Chen , "Decentralized Cognitive MAC for Opportunistic Spectrum Access in Ad Hoc Networks: A POMDP Framework," *IEEE JSAC*, vol. 25, no. 3, pp. 589-600, April 2007.

[37] A. Ghasemi and E.S. Sousa, "Collaborative spectrum sensing for opportunistic access in fading environments," in *in proc First IEEE International Symposium on DySPAN*, 2005, pp. 131-136.

[38] W. Zou, W. Wang, L. Zhang and Z. Zhou , "On the distributed cooperative spectrum sensing for cognitive radio," in *International Symposium on Communications and Information Technologies*, 2007, pp. 1496–1501.

[39] Y.Li and A.Nosratinia, "Hybrid Opportunistic Scheduling in Cognitive Radio Networks," *IEEE TRANSACTIONS ON WIRELESS COMMUNICATIONS*, vol. 11, no. 1, pp. 328-337, January 2012.

[40] H. Xiaole, H.C.Man, W.S.Vincent, and C.M.Victori , "Hedonic Coalition Formation Game for Cooperative Spectrum Sensing and Channel Access in Cognitive Radio Networks," *IEEE TRANSACTIONS ON WIRELESS COMMUNICATIONS*, vol. 11, no. 11, pp. 3968-3979, November 2012.

[41] ETSI TR, "Reconfigurable Radio Systems (RRS); SDR Reference Architecture for Mobile Device," ETSI, Technical 102 680, 2009.

[42] Zhao Nan, Pu Fangling, and Xu Xin, "Optimisation of multi-channel cooperative sensing in cognitive radio networks," *IET Communications*, vol. 7, no. 12, pp. 1177-1190, May 2013.

APPENDIX A

Source Code

```
* file:     CognitiveBaseNetwLayer.cc

#include "CognitiveBaseNetwLayer.h"

#include <cassert>

#include "NetwControlInfo.h"
#include "EngineBaseLayer.h"
#include "AddressingInterface.h"
#include "SimpleAddress.h"
#include "FindModule.h"
#include "NetwPkt_m.h"
#include "ArpInterface.h"
#include "NetwToMacControlInfo.h"

Define_Module(CognitiveBaseNetwLayer);

void CognitiveBaseNetwLayer::initialize(int stage)
{
    EngineScannerLayer::initialize(stage);

    if(stage==0){
            coreDebug = par("coreDebug").boolValue();
        headerLength= par("headerLength");
        arp = FindModule<ArpInterface*>::findSubModule(findHost());
    }
    else if(stage == 1) {
            // see if there is an addressing module available
            // otherwise use module id as network address
        AddressingInterface* addrScheme =
FindModule<AddressingInterface*>::findSubModule(findHost());
        if(addrScheme) {
            myNetwAddr = addrScheme->myNetwAddr(this);
        } else {
            myNetwAddr = LAddress::L3Type( getId() );
        }
        coreEV << " myNetwAddr " << myNetwAddr << std::endl;
    }
}

/**
 * Decapsulates the packet from the received Network packet
```

```
 **/
cMessage* CognitiveBaseNetwLayer::decapsMsg(netwpkt_ptr_t msg)
{
   cMessage *m = msg->decapsulate();
   setUpControlInfo(m, msg->getSrcAddr());
   // delete the netw packet
   delete msg;
   return m;
}

/**
 * Encapsulates the received ApplPkt into a NetwPkt and set all needed
 * header fields.
 **/
CognitiveBaseNetwLayer::netwpkt_ptr_t
CognitiveBaseNetwLayer::encapsMsg(cPacket *appPkt) {
   LAddress::L2Type macAddr;
   LAddress::L3Type netwAddr;

   coreEV <<"in encaps...\n";

   netwpkt_ptr_t pkt = new NetwPkt(appPkt->getName(), appPkt->getKind());
   pkt->setBitLength(headerLength);

   cObject* cInfo = appPkt->removeControlInfo();

   if(cInfo == NULL){
         EV << "warning: Application layer did not specifiy a destination L3
address\n"
            << "\tusing broadcast address instead\n";
         netwAddr = LAddress::L3BROADCAST;
   } else {
         coreEV <<"CInfo removed, netw addr="<<
NetwControlInfo::getAddressFromControlInfo( cInfo ) << std::endl;
      netwAddr = NetwControlInfo::getAddressFromControlInfo( cInfo );
         delete cInfo;
   }

   pkt->setSrcAddr(myNetwAddr);
   pkt->setDestAddr(netwAddr);
   coreEV << " netw "<< myNetwAddr << " sending packet" <<std::endl;
   if(LAddress::isL3Broadcast( netwAddr )) {
      coreEV << "sendDown: nHop=L3BROADCAST -> message has to be
broadcasted"
        << " -> set destMac=L2BROADCAST\n";
      macAddr = LAddress::L2BROADCAST;
```

```
    }
    else{
        coreEV <<"sendDown: get the MAC address\n";
        macAddr = arp->getMacAddr(netwAddr);
    }

    setDownControlInfo(pkt, macAddr);

    //encapsulate the application packet
    pkt->encapsulate(appPkt);
    coreEV <<" pkt encapsulated\n";
    return pkt;
}

/**
 * Redefine this function if you want to process messages from lower
 * layers before they are forwarded to upper layers
 *
 *
 * If you want to forward the message to upper layers please use
 * @ref sendUp which will take care of decapsulation and thelike
 **/
void CognitiveBaseNetwLayer::handleLowerMsg(cMessage* msg)
{
    netwpkt_ptr_t m = static_cast<netwpkt_ptr_t>(msg);
    coreEV << " handling packet from " << m->getSrcAddr() << std::endl;
    sendUp(decapsMsg(m));
}

/**
 * Redefine this function if you want to process messages from upper
 * layers before they are send to lower layers.
 *
 * For the CognitiveBaseNetwLayer we just use the destAddr of the network
 * message as a nextHop
 *
 * To forward the message to lower layers after processing it please
 * use @ref sendDown. It will take care of anything needed
 **/
void CognitiveBaseNetwLayer::handleUpperMsg(cMessage* msg)
{
            assert(dynamic_cast<cPacket*>(msg));
    sendDown(encapsMsg(static_cast<cPacket*>(msg)));
}

/**
```

```
 * Redefine this function if you want to process control messages
 * from lower layers.
 *
 * This function currently handles one messagetype: TRANSMISSION_OVER.
 * If such a message is received in the network layer it is deleted.
 * This is done as this type of messages is passed on by the EngineBaseLayer.
 *
 * It may be used by network protocols to determine when the lower layers
 * are finished sending a message.
 **/
void CognitiveBaseNetwLayer::handleLowerControl(cMessage* msg)
{
	switch (msg->getKind())
	{
	case EngineBaseLayer::TX_OVER:
		delete msg;
		break;
	default:
		EV << "CognitiveBaseNetwLayer does not handle control messages
called "
		   << msg->getName() << std::endl;
		delete msg;
		break;
	}
}

/**
 * Attaches a "control info" structure (object) to the down message pMsg.
 */
cObject* CognitiveBaseNetwLayer::setDownControlInfo(cMessage *const pMsg,
const LAddress::L2Type& pDestAddr)
{
	return NetwToMacControlInfo::setControlInfo(pMsg, pDestAddr);
}

/**
 * Attaches a "control info" structure (object) to the up message pMsg.
 */
cObject* CognitiveBaseNetwLayer::setUpControlInfo(cMessage *const pMsg, const
LAddress::L3Type& pSrcAddr)
{
	return NetwControlInfo::setControlInfo(pMsg, pSrcAddr);
}
```