POWER CONTROL AND COOPERATIVE SENSING IN COGNITIVE RADIO

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Abstract

The traditional ways of spectrum management is inefficient as large portions of useable spectrum is left idle most periods of the day hence the call for more dynamic spectrum management techniques. Cognitive Radio (CR) is considered a viable means to vastly improve the efficiency of spectrum since it allows unlicensed users access to licenced spectrum as long as the quality of service is not downgraded.

This research investigates the major problems associated with designing CRs. An in-depth analysis shows that the two major problems that hinders the successful design of CR systems are that of spectrum sensing (How the device detects the Primary User (PU)) and Power Control (which focuses on the level of transmit power of CR devices so as not to induce interference to PUs).

To solve the problem of power control in this research, we consider a single cell scenario where N CR terminals are operating in a network with a Cognitive base station (CBS) together with one PU along with its Primary Base station (PBS). In the scenario, CR devices will generally seek to improve quality of service by increasing it's transmit power. This increase introduces interference to the PU. To mitigate this, the CR devices are modelled as players of a non-cooperative game where offending devices are penalised till a Nash equilibrium level is achieved. At this point, the players can no longer influence the state of the game no matter the strategy they chose to play. The work is extended to cover CR internet of things devices by exploiting the adequate path loss exponent for the operational environment. The power control algorithm is compared with two other known power control algorithms and it outperforms them in average power, average SNR and rate of convergence.

Spectrum sensing in CRs has been shown in literature to improve when done cooperatively rather than individually. To this end, this research focuses on cooperative sensing which allows the radios to make decision on their channel state based on the combine results of individual radios. The channel is modelled as a frame-by frame structure of equal length using the slotted aloha access contention technique. Each frame has a fixed length and is made up of sensing, prediction and transmission periods. It is seen observed that longer sensing periods results in better sensing results but considerable lower throughput. The scenario researched involves a CR

network with K CRs and M sub-channels. It is assumed that the conditions of all sub-channels are equal, and each CR randomly chooses any one to sense and the throughput is measured. The interference caused to the PU are measured by collisions in the system. This are of two types.: (1) Collisions with PUs due to missed detections and (2) collisions with other CRs due to access contention. Whenever there is a collision, the packet is withheld by the system and transmission is stopped. The throughput is a measure of successful packet transmissions. The derived algorithm improved the throughput by detecting the optimal sensing period. Using the K-of-M fusion decision rule, the sensing algorithm guarantees that optimal throughput can be achieved when 50% of the cognitive radio correctly detects the state of the spectrum.

Cognitive radio throughput will be of very grave importance. Especially in spectrums like TVWSs and radar systems. A throughput model with power control is presented. The aim is to improve the throughput in interweave scenarios.

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Acronyms

FCC	Federal Communications Commission
OFCOM	Office of Communications
SU	Secondary User
RF	Radio Frequency
SPTF	Spectrum Policy Task Force
OSA	Opportunistic Spectrum Access
CR	Cognitive Radio
PU	Primary User
SINR	Signal-to-Interference-plus-Noise Ratio
SNR	Signal to Noise Ratio
TVWS	Television White Spaces
TV	Television
IEEE	Institute of Electrical and Electronics Engineers
ED	Energy Detector
CRN	Cognitive Radio Network
BEB	Binary Exponential Backoff
CBS	Cognitive Base Station
PBS	Primary Base Station
NE	Nash Equilibrium
IOT	Internet-of-Things

H2H	Human-to-Human
M2M	Machine-to-Machine
QoS	Quality of Service
CR-IoT	Cognitive Radio – Internet of Things
LOS	Line of Sight

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Last but not the least I will like to express my gratefulness to the School of Architecture, Computing and Engineering (ACE), The Graduate School at University of East London (UEL) and anyone who has supported me in any aspect, during this research.

Dedication

I love to dedicate this thesis to my siblings, Ndifreke Emmanuel Etim and Edidiong Emmanuel Etim, for their words of encouragement when I lost every hope. Without them, I will not have completed this research

Chapter One:

Introduction

1.0 Introduction

This chapter presents an introduction to the works presented in this thesis. It begins with a simple overview of radio spectrum taxonomy, the present spectrum regulatory policies and the reason to necessitate a change of approach. It further presents the aims, motivation, problem statement, a summary of the contributions to knowledge and the organisation of the thesis.

1.1 Background

Communication has always played a major role in the lives of humans since the beginning of time hence the formation of forms of communications such as speech, signs and other symbolic gestures. As human existence progressed, then came the need for communications over a longer distance. The use of letters served appropriately. With the discovery of electricity, there came the need for faster and accurate forms of communication to aid the industrial boom. Communication systems which used electricity such as telegraphs ruled the day as it provided a faster means of communication and could be transmitted over a long distance.

In 1895, an inventor by the name of Guglielmo Marconi in the Isle of Man demonstrated the capability of transmitting signals over a wireless medium. The potential benefits of such transmission were overwhelming as it could significantly increase the size of information passed and reduced the need for point-to-point hard wiring.

Since the discovery of wireless communications, the impact it has played has been momentous. This discovery led to the inventions of Radio systems and Televisions with which information and entertainment are delivered to a vast number of people over large geographical locations. Wireless communications involve the transfer of information within the earth’s atmosphere.

The atmosphere is made up of waves of different wavelengths. This sequence of wavelengths from the smallest to the largest is known as the Electromagnetic spectrum (ES). The electromagnetic spectrum is a crucial resource for human existence. Table 1.1 shows the classification of the Electromagnetic spectrum and each wavelength covered by each class. Such is the importance of the electromagnetic spectrum that human actions such as sight, sound, heating are controlled by waves which fall within the spectrum.

Table 1.1 Classification of the Electromagnetic spectrum

Electromagnetic waves	Range
Radio waves	3 kHz - 300 GHz (Frequency)
Sub-millimetre waves	100 μm – 1 mm (Wavelength)
Infrared	780 nm – 100 μm (Wavelength)
Visible light	380 nm – 780 nm (Wavelength)
Ultraviolet	10 nm – 380 nm (Wavelength)
X-ray	120 eV – 120 keV (Energy)
Gamma rays	120 keV and above (Energy)

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Radio waves form part of the electromagnetic spectrum with wavelengths between 3kHz – 300kHz. This part are used for all forms of wireless communication. This resource is non-expanding but is renewable. Unlike most resources, the radio spectrum cannot be stored for future use and as such, should be managed accordingly. A further investigation into the radio spectrum reveals it is subdivided into classes with different wavelengths which depicts the propagation properties of each class. Frequency bands with lower wavelengths show the ability to travel further distances but carry smaller information, but bands with higher wavelength travel shorter distance but can carry larger information bits. Table 1.2 shows the classification of radio waves.

Table 1.2 Classification of radio waves

Frequency Band	Frequency Range	Applications
Very Low Frequency (VLF)	3 kHz – 30 kHz	Radio navigation, maritime mobile (communication on ships)
Low Frequency (LF)	30 kHz – 300 kHz	Radio navigation, maritime mobile
Medium Frequency (MF)	300 kHz – 3 MHz	AM radio broadcast, aeronautical mobile
High Frequency (HF)	3 MHz – 30 MHz	Maritime mobile, aeronautical mobile
Very High Frequency (VHF)	30 MHz – 300 MHz	Land mobile, FM broadcast, TV broadcast, aeronautical mobile, radio paging, trunked radio
Ultra High Frequency (UHF)	300 MHz – 1 GHz	TV broadcast, mobile satellite, land mobile, radio astronomy
L band	1 GHz – 2 GHz	Aeronautical radio navigation, radio astronomy, earth exploration satellites
S band	2 GHz – 4 GHz	Space research, fixed satellite communication
C band	4 GHz – 8 GHz	Fixed satellite communication, meteorological satellite communication
X band	8 GHz – 12 GHz	Fixed satellite broadcast, space research
Ku band	12 GHz – 18 GHz	Mobile and fixed satellite communication, llite broadcast sate
K band	18 GHz – 27 GHz	Mobile and fixed satellite communication
Ka band	27 GHz – 40 GHz	Inter- satellite communication, mobile satellite communication
Millimeter	40 GHz – 300 GHz	Space research, Inter-satellite communications

The radio frequency (RF) spectrum is a resource managed by government regulators, such as the Office of Communications in the United Kingdom (OFCOM) and the Federal Communications Commission (FCC) in the United States, Nigerian Communications Commission (NCC) in Nigeria. These bodies are tasked with the sharing of the spectrum to different wireless services while ensuring that the quality of services of these wireless services is not inhibited by interference. Within current spectrum management paradigm operated by these regulators, all frequency bands are licensed to wireless networks on a long-term basis for large geographical regions, and such bands are the exclusive rights of such licensed users. The advantage of this scheme is that as these bands are under the exclusive control of individual licenses, the interference levels in such bands are directly controlled by the owners.

In recent times, the increasing numbers of new wireless products and developments of mobile internet applications has stretched demands on RF spectrum. This boom in need for electromagnetic spectrum for wireless services has created a semblance of spectrum scarcity. Seeking ways to address this scarcity, regulatory bodies created research groups to investigate the problems. Investigations such as one performed by the Spectrum Policy Task Force (SPTF), a body within the FCC, reported that in licensed bands, spectrum utilisation ranges from 15% to 85% depending on periods under investigation (Haykin, 2005b). Various other research presented similar results. The research concludes that the problem of spectrum scarcity does not exist as most bands are underutilised. With adequate utilisation, the available spectrum can efficiently take care of the demand.

An experiment to access the rate of spectral occupancy in the 30MHz to the 3GHz range in the USA, New York recorded the highest spectral utilization rate.

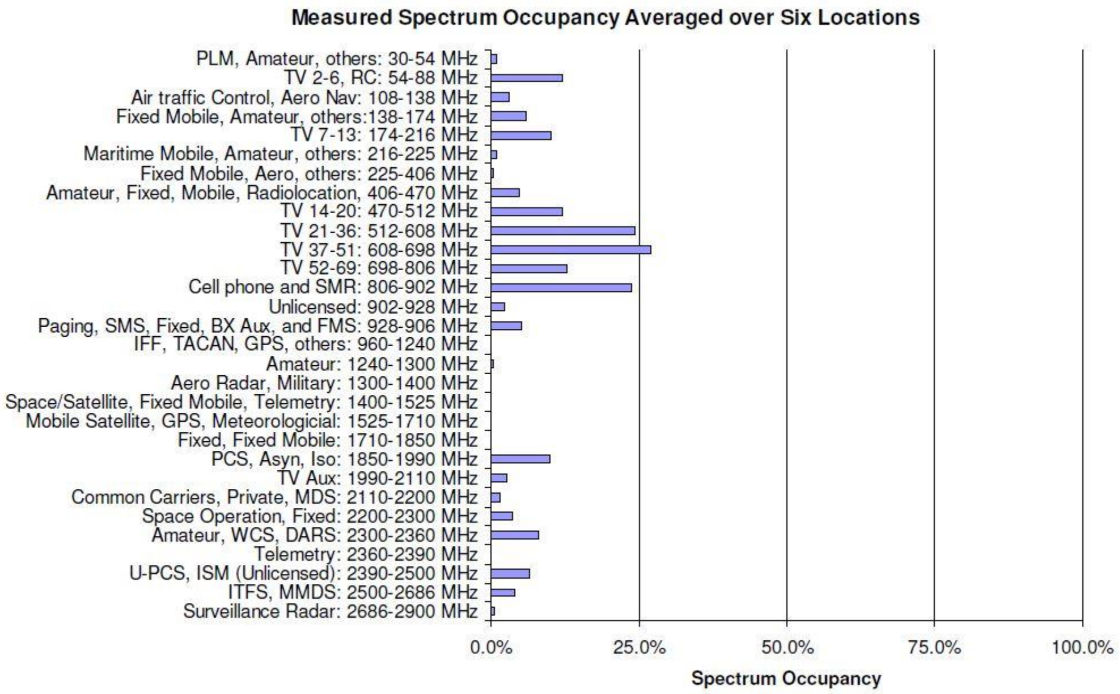

Figure 1.1: *Spectrum occupancy measurement results averaged over six locations (McHenry, 2005)*

Figure 1.1 shows the actual measurement averaged over six locations within New York. In the period under investigation, TV channels 37 to 51, with an average percentage of just over 26%, was the most occupied spectrum. Observation shows that some spectrum bands recorded values below 2%. While such underutilization can be attributed to factors such as conservative allocation of guard bands, and variations in demand during the various period of the day, conclusions can be drawn that the current spectrum sharing paradigm requires change.

The disadvantage of the present spectrum sharing paradigm, which gives the exclusive use of licenced spectrum to the owners, is that it is often challenging to reassign such spectrum to other services even when such bands are not in use and or such services become obsolete.

Due to startling results inferred from the researchers regarding the spectrum usage, the governing bodies concluded that the spectrum management policies need to be revised. There needs to be a more flexible rule regarding the access and use of licensed bands. With such change, devices with the capability should be allowed access to licensed spectrum with the condition that the quality of service of licensed holders remains intact. The essense of this is to provide spectrum for future technologies while improving the current problem of underutilisation of the spectrum.

Opportunistic spectrum access (OSA) techniques have been recommended to improve the spectrum efficiency. Such techniques allow the use of licensed spectrum by unlicensed users. However, for the success of OSA, the licensed users, also known in this thesis as Primary Users (PU), must be protected from the harmful effect of the secondary users (SU). PUs are the licensed owners of the spectrum and have legal rights on such spectrum while SUs are opportunistic radios that seek to use the licenced spectrum as an unlicensed user. SUs are required to identify spectrum holes (SH), a term used to define points in time and frequency when the spectrum is vacant, for use and to vacate such spectrum when it becomes occupied. Although in the previous paradigm, controlling the interference introduced into the spectrum was carried out by the license holder, it is not its duty to ensure that the OSA devices ensure that the interference is kept at an acceptable level.

Cognitive Radio (CR) is presented as a device with the capability of improving the use of spectrum opportunistically. It has the capability of adapting and reconfiguring its parameters to ensure that the quality of service of PUs is guaranteed. CR should be able to observe its operational environment, learn the characteristics of such environment and make decisions based on whatever stimuli received from the environment. This research investigates the problem of spectrum sensing and power control in cognitive radio networks. Some of the

1.2 Problem Statement

With the rapid increase in wireless products requiring the use of radio spectrum, current spectral management paradigm is inefficient to handle such boom thereby leading to scarcity. Many spectrum reuse technologies are proposed to help alleviate such scarcity. Cognitive radio (CR) offers a means to solve spectrum usage problem by allowing opportunistic access to the spectrum by unlicensed users.

After a review of available literature, Cognitive radio offers advantages way beyond that improved spectrum management only. Advantages such as improved throughput and creative services in radio devices as well as increased spectral efficiency prove that cognitive radio is the leading technology to solve the spectrum scarcity conundrum. It is therefore surprising that commercial implementation of Cognitive radio is still way behind the literature. This implementation of cognitive radios is hindered by many factors which include but are not limited to; Spectrum sensing, Power control, Availability of adequate Software, Adequate Antenna. These research focuses on the problem of spectrum sensing and Transmit power control. Spectrum sensing allows the secondary user(s) to detect the presence of the primary user(s) before accessing the spectrum, and power control investigates the required transmission power of CR systems to mitigate the effect of transmission power on the quality of service of the primary radio.

Literature has shown that while Matched filter is the optimal technique for spectrum sensing, it is inefficient in cognitive radio systems where the primary user characteristics are unknown. Cooperative detection based on Energy detection is used in spectrum this research as it allows the detection of primary users without prior knowledge of its characteristics. It also helps in reducing the damage to the PU quality of service due to the hidden node problem, a problem that arises when an active primary user is in a spectrum where the cognitive radio wrongly detects as idle. Further improvement is achieved by using a cross-layered approach to improve the sensing performance of CR in the spectrum with low Signal-to-Information-plus-noise-ratio (SINR) and to increase the throughput of the CR system. Power control in cognitive radios systems could be treated a non-cooperative game since cognitive radio systems will continue to increase their powers to achieve optimal performance without considering other users. This will ensure the players stick by the prearranged rules before access.

1.3 Research Questions

Based on the promising potential of cognitive radio to spectrum management discovered in literature, it only raises questions as to the slow rate of implementation for commercial. Some of these questions will form the cornerstone of this research such as:

1. Can Cognitive radios ensure optimal and efficient spectrum usage?
2. What are the significant problems associated with cognitive radio design?
3. How can the performance of cognitive radios be improved in areas of low SINR?
4. CR transmissions are mostly lost to collisions, how can this loss be addressed to improve throughput?
5. What models can be designed to help with solving these issues raised?

1.4 Summary of Contributions

The significant contributions of this thesis are outlined below:

C1 A power control algorithm for the cognitive radio-based internet-of-things devices given in chapter 5. This contribution improves the performance of CR in the spectrum by reducing the transmit power required to successfully send packets. As most environmental loses are already included in the signal path loss, the algorithm leverages on this to reduce power using game theory. With the idea presented, researchers will be able to develop power control mechanism for environment dependent devices. If the right environmental characteristics are used, the algorithm shows that battery enabled CR-IoT devices will be able to run longer on battery due to lower transmit power levels and the capacity of the network can be increased.

C2 A contention-based cooperative spectrum sensing-throughput model using slotted aloha is presented in chapter 4. An algorithm is presented to solve the maximisation problem finding the optimal fusion technique to enhance throughput. It uses the interference to the PU to maximise the optimisation problem. A search algorithm is used to seek optimum fusion technique to ensure that the optimal can be attained thereby reducing loses due to collision. Results show that optimum performance of the radios can be achieved when the fusion centre receives about 50% of the decision statistics from the CRs correctly.

1.5 Publication

Etim, I.E. and Lota, J., 2016, October. Power control in cognitive radios, Internet-of-Things (IoT) for factories and industrial automation. In *Industrial Electronics Society, IECON 2016-42nd Annual Conference of the IEEE* (pp. 4701-4705). IEEE.

1.6 Thesis Outline

Chapter two:	This chapter is a review of available literature on Cognitive Radio and some problems already identified in the problem statement. It begins with an overview of Cognitive radios and then progresses to spectrum sensing and power control.
Chapter three:	this chapter outline the methodology used in performing this research and states reasons for such methods.
Chapter Four:	In this chapter, an algorithm to solve the sensing- transmission trade-off is presented. The throughput is maximised using the interference to the primary users as constraints. A search algorithm is used to solve the maximisation problem by seeking

the optimal sensing period based on the received samples and the optimum number of SUs required to make a decision.

Chapter Five: This chapter presents a non-cooperative game for cognitive radio Internet of things devices. It explores the concept of saving power by proposing the use of adequate attenuation for IoT devices based on their physical location and distances from the Base station. With such reduction in power, the number of IoT devices may be increased.

Chapter Six: This chapter presents a means to calculate the throughput of cognitive radio systems in an interweave system. The cognitive radio transmits at maximum power when the channel is detected as idle, and power control is employed in busy channels. This allows the throughput of cognitive radios to be maximized.

Chapter Seven: This chapter presents a validation of power control algorithm in chapter 5. It uses the key performance indicators of SNR, transmit power and rate of convergence to compare against other power control algorithms.

Chapter Eight: This chapter presents a conclusion, recommendations and future works. A summary of the key contributions and other chapters are also given.

Chapter Two:

Literature Review

2.1 Introduction

The need for a dynamic spectrum access technique that can provided adequate protection for PUs cannot be overstated. CR is proposed as a technique that allow the coexistence of PUs and SUs in one spectrum while ensuring the quality of service of the PU is not voided.

This chapter investigates the CR, beginning with a brief overview then it looks at its definitions, applications. Then it further investigates the problems of spectrum sensing and power control. A short review detailing the state in are is attached to each problem.

2.2 Cognitive Radio

Cognitive radio is being suggested as a new paradigm to implement efficient reuse of pooled radio spectrum assigned to multiple wireless communication systems, by exploiting a wide variety of intelligent behaviours. This is believed to hold a key towards achieving higher spectrum efficiency by employing opportunistic access to licensed spectrum. A typical CR network is shown in figure 2.1. The performance of the CRs are controlled by a BS. The CRs are given strict rules to ensure that the SINR of the PUs remains within an acceptable limit. To ensure that such limits are adhered to, the CRs should be able to monitor the spectrum for PU activities at all time. This will ensure that it uses the spectrum at periods when the spectrum is vacant.

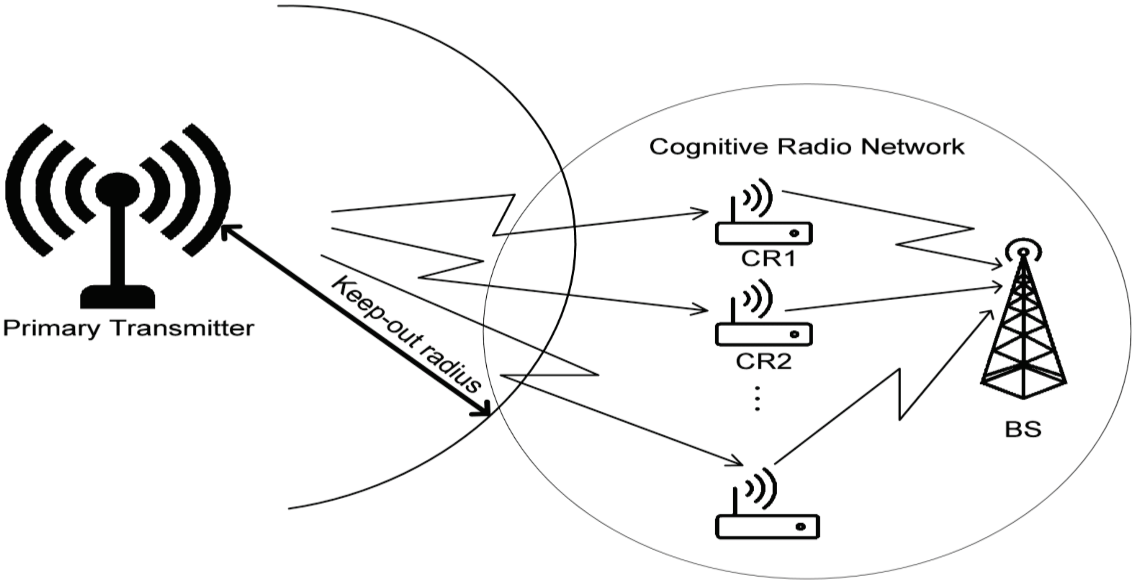

Figure 2.1 Typical coexistence between CR and PR.

If the CR uses the channel only when the channel is vacant or when a SH is identified, such form of access is known as Overlay spectral access. CR may also be able to access spectrum concurrently with the PUs, but the CR must ensure that the interference introduced is below the acceptable limit. This is achieved by reducing their transmit powers.

The maximum acceptable limit of interference that can be tolerated in a spectrum is known as the interference temperature of the spectrum and its measured in Kelvin. The total interference introduced by all the SUs in the spectrum must never exceed this value.

$$I_t \geq I_i + \sum_{j=1, j\neq i}^{N} I_j \qquad 1$$

Where I_t represents the interference temperature and I_i is the refrence SU and I_j represents the other SUs in the spectrum. If the SUs keeps to this, the QoS of the PU is guaranteed.

The term "Cognitive radio" was first coined by Joseph Mitola in a seminar paper presented in 1999 as an extension of the Software Defined Radio (SDR). In the paper, Mitola defines CR as:

"*A radio that employs model-based reasoning to achieve a specified level of competence in radio-related domains*".

Since that paper, with interest from regulatory bodies and shareholders, other definitions have been given with each choosing to concentrate on some key attributes. Some of those definitions include;

Simon Haykin in the paper reviewing the state of Cognitive radio defines it as (Haykin, 2005a):

"Cognitive radio is an intelligent wireless communication system that is aware of its surrounding environment (i.e. outside world), and uses the methodology of understanding-by-building to learn from the environment and adapt its internal states to statistical variations in the incoming RF stimuli by making corresponding changes in certain operating parameters (e.g., transmit-power, carrier-frequency, and modulation strategy) in real-time, with two primary objectives in mind:

- ***highly reliable communications whenever and wherever needed;***

- ***efficient utilisation of the radio spectrum."***

The FCC gives its definition as (FCC, 2005):

"A radio that can change its transmitter parameters based on interaction with the environment in which it operates."

The international spectrum regulatory community defines it as:

"A radio or system that senses and is aware of its operational environment and can dynamically and autonomously adjust its radio operating parameters accordingly."

IEEE USA offers the following definition (Singh et al., 2013):

"A radio frequency transmitter/receiver that is designed to intelligently detect whether a particular segment of the radio spectrum is currently in use, and to jump into (and out of, as necessary) the temporarily-unused spectrum very rapidly, without interfering with the transmissions of other authorised users."

The IEEE 1900.1 group defines it as (Bayhan et al., 2007):

"A type of radio that can sense and autonomously reason about its environment and adapt accordingly. This radio could employ knowledge representation, automated reasoning and machine learning mechanisms in establishing, conducting, or terminating communication or networking functions with other radios. Cognitive radios can be trained to dynamically and autonomously adjust its operating parameters."

Another definition is by the SDR Forum (Dalvi et al., 2011):

"A radio that has, in some sense, (1) awareness of changes in its environment and (2) in response to these changes adapts its operating characteristics in some way to improve its performance or to minimise a loss in performance."

There are a lot of different definitions of Cognitive Radio out there, while everyone seems to agree on the benefits of Cognitive radios, is safe to say that the harmonisation of these definitions will still be a significant problem shortly. However, from the definitions above, it is deduced that Cognitive radios are radios which have some form of cognition and will also be able to operate autonomously. They should be able to observe the environment, adapt its characteristics with response to stimuli received and finally have the intelligence to use the received information towards achieving a set goal.

For this research, the difinition of CR that best fits our purpose is the one proposed in Haykin, 2005 as :

"Cognitive radio is an intelligent wireless communication system that is aware of its surrounding environment (i.e. outside world), and uses the methodology of understanding-by-building to learn from the environment and adapt its internal states to statistical variations in the incoming RF stimuli by making corresponding changes in certain operating parameters (e.g., transmit-power, carrier-frequency, and modulation strategy) in real-time, with two primary objectives in mind:

- ***highly reliable communications whenever and wherever needed;***
- ***efficient utilisation of the radio spectrum."***

This definition shall be adopted as the working definition of cognitive radio throughout this thesis.

The operation of Cognitive radio can further be grouped into two aspects, Cognitive Capability and Reconfigurability (Jahed et al., 2011, Akyildiz et al., 2011, Akyildiz et al., 2006).

- The cognitive capability enables the cognitive radio to interact with its environment in a real-time manner, and intelligently determine appropriate communication parameters based on the quality of service (QoS) requirements. The cognitive capability involves actions such as spectrum sensing, spectrum analysis, and spectrum decision.
- Reconfigurability allows the cognitive radio to adapt its characteristics to match those required by the spectrum. These characteristics include *Operating frequency, Modulation scheme, Transmission power, Communication technology* and so forth (Alsarhan and Agarwal, 2009). This aspect of cognitive radios will be achieved by leveraging on the intelligence of software-defined radios.

The operation of a cognitive radio can be represented by a cognitive cycle as shown in Figure 2.2. In this cycle, the Cognitive radio will be able to gather information about its operational environment (Outside World) by direct observation (Observe). This information is evaluated (Orient) to determine if it is essential or not. The cognitive radio then generates a course of action (Plan) and chooses a plan which will improve its state (Decide). The Cognitive radio then implements the selected action (Act). Over time, the cognitive radio should be able to improve its operation as a result of the knowledge it has acquired (Learn).

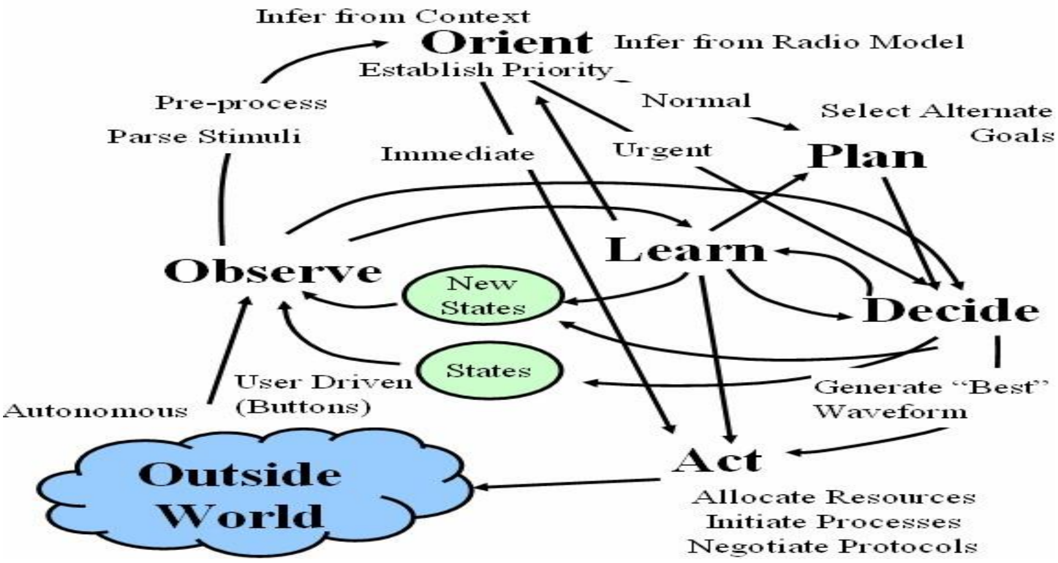

Figure 2.2: *The cognitive radio cycle* (Akyildiz et al., 2006).

CR is designed to allow unlicensed users (also called secondary users) access licensed spectrum opportunistically without causing harmful effects to the quality of service of the primary user (Razavi, 2010, Jondral, 2007, Naguib et al., 2012).

Based on the cognitive ability and reconfigurability of Cognitive radios, they will be able to study, analyse, learn and make informed decisions about spectrum in which they are deployed (Costantine et al., 2013). These are the main operational functions of CRs cognitive cycle.

Analysis: SHs identified by the CR have different time-varying characteristics of which the CR is expected to choose the hole which adequately fits its requirements. This is done by the information which the CR has acquired over periods of sensing and learning. Such characteristics include interference, the path loss within the spectrum, the link errors, the bandwidth and operational frequency.

Decision: after the characteristics of the channels available have been collated, the CR will then make an informed decision on the channel to select. This decision will be based on its achievable QoS and also the pre-set decision rule of the CR.

Learn: It is expected that CR will be able to learn distinct features of their operational environment over time. This information will be saved and will be continually updated. This will help the radio make faster decisions in the future.

Sensing: this is the most important function of the Cognition cycle. This function is responsible for observation of the operational environment and with the sole aim of identifying vacant spectrum. The performance of this function is dependent on the properties of the spectrum such as the shadowing, the fading and the SINR in the channel.

To achieve the level of interaction required with the environment, cognitive radios should have the capability to differentiate between PU and SU signals. This will help simplify the task of protecting PUs from interference. Further to these, there may be different forms of PU signals which complicate the matter further as in the case of Ultra High Frequency (UHF) bands which have been made available for OSA and may contain primary signals such as digital and Analog Television, microphones or even health applications.

2.1.1 Cognitive Radio standards

With the increase in interest in cognitive radios, regulatory bodies have rushed to produce standards to stay as guidelines for the use of CRs. Some of them include;

The IEEE 802 group were the first to produce standards for the use of CR.

IEEE 802.22 This is the first standard completed by the 802 group. The standard typically involves the use of the Very High Frequency (VHF) and UHF signal typically used for Television, microwave, point-to-point links and land mobile radios. It has been proven that on average, spectrum has efficiently been underutilised in each application. TV signals have the benefit of primary signals that are easy to detect when compared to microwave point-to-point links.

Historically, UHF bands have been under-designated because regulators undervalued the practicability of creating new TV towers in these bands. Smaller TV stations operated economically until the introduction of cable TV. With the introduction of HDTV technology, regulators envisage a switch to a more efficient modulation together with integration and de-allocation from analog TV (Rast, 2005).

In considering these UHF bands, the 802.22 working group targets the creation of a waveform geared towards providing high bandwidth access in suburbs and rural areas using cognitive radio technology. The 802.22 standard is aimed at achieving spectral efficiencies with a span of 3bits/sec/Hz by peak download rates at a coverage edge of 1.5Mbps, at the same time gaining coverage of about 100km (Cordeiro et al., 2005).

Cognitive Radios are required to identify and allocate signals in its environment. The 802.22 protocol presently considers the utilisation of spectrum usage tables that will be updated automatically and manually. This reduces the induced interference to these signals as live updates are made and can be accessed. The 802.22 standard also assigns traditional maximum transmission power limits and out-of-band emission limits to curb the effect when the system is unable to identify the primary systems.

802.11k This standard is the standard used for the addition of cognition to Wireless Local Area Networks (WLAN). This ability will allow the WLAN to interact with the environment and be able to decipher other radio signals within its operational environment.

802.11h This protocol was not designed as a CR standard, but a vital part of the protocol is the dynamic frequency selection which can estimate channel characteristics and can also determine the state of the channel such as the presence of other users. The protocol also has the capability of changing its frequency or adjusting the transmit power. It is observed that only mission part of CR is the ability to learn and the recollection of past actions.

2.2.1 Potential Application of Cognitive Radios

Since CRs are fully aware of the RF environment and can adapt its transmission parameters to the RF spectrum environment, cognitive radios and the concepts of cognitive radio can be deployed to a variety of wireless communication environments, especially in commercial and military applications. A few of applications are listed below:

- *Coexistence of wireless technologies (Aijaz and Aghvami, 2015a, Ali et al., 2015, Etim and Lota, 2016)*: CR were primarily considered for reusing the spectrum, but due to its ability to reconfigure and adapt its parameters, CR is expected to play a significant part in realization of new technologies such as machine-to-machine communications (M2M) and Internet-of-things (IoT).

- *Military networks (Tuukkanen and Anteroinen, 2015, Slimeni et al., 2015)*: In military communications, bandwidth is often at a premium. By using cognitive radio concepts, military radios can not only achieve substantial spectral efficiency on a noninterfering basis but also reduce implementation complexity for defining the spectrum allocation for each user. Furthermore, military radios can obtain benefits from the opportunistic spectrum access function supported by the cognitive radio. For example, the military radios can adapt their transmission parameters to use Global System for Mobile (GSM) bands, or other commercial bands when there is jamming in their original frequencies.

- *Heterogeneous wireless networks (Akyildiz et al., 2008)*: Cognitive radio device can dynamically discover information about access networks, e.g. WiFi and GSM, and makes decisions on which access network is most suitable for its requirements and preferences. Then the cognitive radio device will reconfigure itself to connect to the best access network.

2.3 Spectrum Sensing

CR has the technology that provides it with the capability to use the RF spectrum in a dynamic manner (Haykin et al., 2009). With this capability, the CR is required to seek spectral holes which are used by the radio without causing harmful interference to the Primary Users (PU) (Letaief and Zhang, 2009). This task is fulfilled by the function of spectrum sensing. Spectrum sensing involves the detection of useable spaces in the spectrum called spectrum holes or white spaces. Figure 2.3 shows a typical spectrum in which cognitive radio can help achieve dynamic spectrum management. Spectrum sensing in CR is in two stages. The first stage is the out-of-band sensing where the secondary user scans the spectrum for a PU and the second stage is in-band sensing which the secondary user keeps scanning the spectrum after accessing it for the return of the PU.

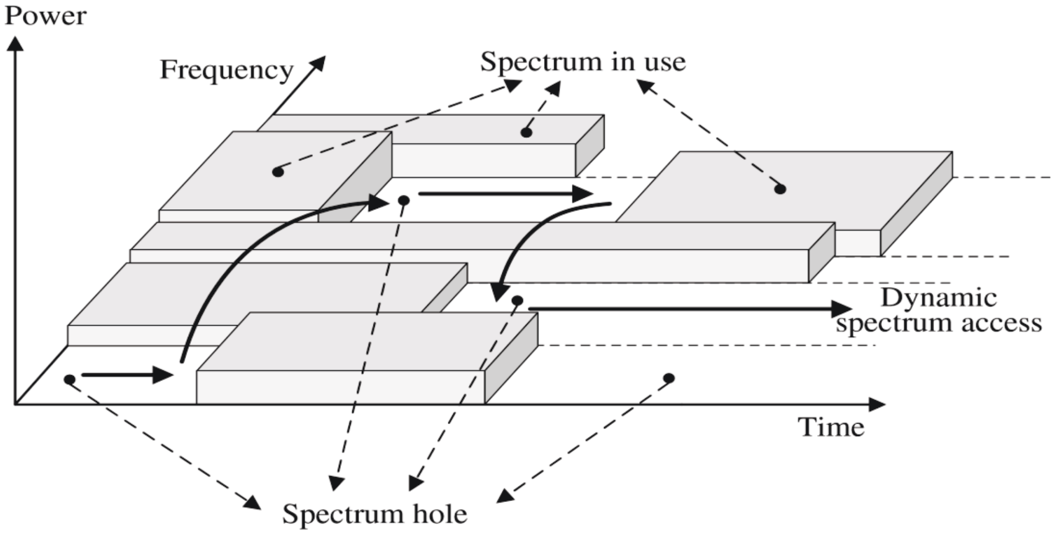

Figure 2.3: *Illustration of spectrum holes and the concept of dynamic spectrum access (Akyildiz et al., 2008).*

However, there are two challenges in spectrum sensing, One of them is because of multipath and shadowing, cooperative spectrum sensing techniques are often used to combat the effect of fading. Another significant challenge is sensing the whole of the spectrum at a particular physical location in short observation time. Hence, wideband spectrum sensing is therefore of prime importance to ensure efficient operation of both the primary and the secondary (cognitive radio) networks. Spectrum sensing is the foundation of all other cognitive radio functions.

2.3.1. Spectrum Sensing Techniques

In any spectrum, PU systems have higher priority than secondary users for using the allocated frequencies. Therefore, CRs should either avoid interference to PUs, or keep the interference level lower than a pre-defined threshold.

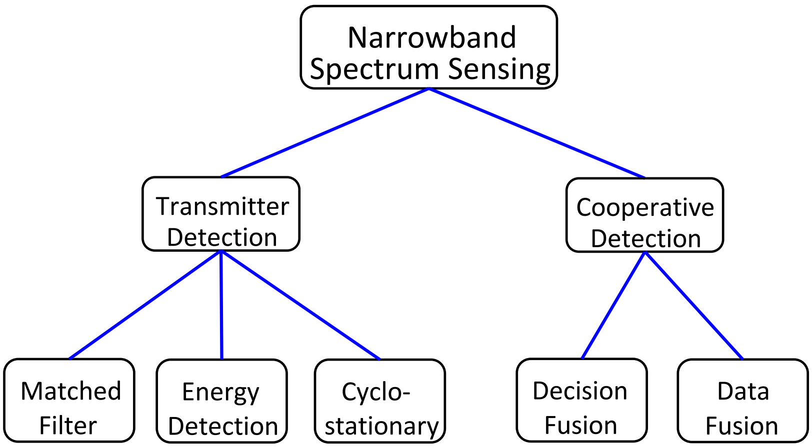

Figure 2.4: *Narrowband spectrum sensing algorithms (Letaief and Zhang, 2009).*

Three techniques mostly used for detecting the primary transmitters are matched filtering (Yucek and Arslan, 2009), energy detection (Cabric et al., 2004) and cyclostationary detection (Zeng et al., 2010). Table 2.1 shows the advantages and disadvantages of these techniques while figure 2.4 shows an organogram of sensing techniques used in narrowband communications.

Table 2.1: *Summary of advantages and disadvantages of narrowband spectrum sensing algorithms (Yucek and Arslan, 2009)*

Sensing algorithm	Advantages	Disadvantages
Matched filter	Optimal performance Low computational cost	Require prior information of the primary user
Energy detection	Do not require prior information Low computational cost	Poor performance for low SNR Cannot differentiate users
Cyclostationary	Valid in slow SNR region Robust against interference	Require partial prior information High computational cost

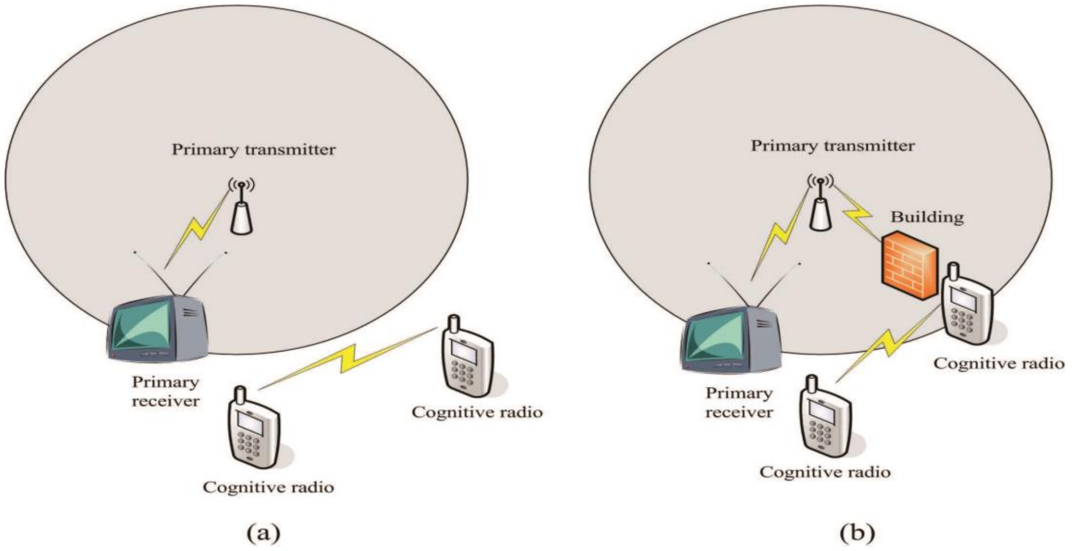

Figure 2.5: *Transmitter detection problems: (a) hidden terminal problem, (b) shadowing uncertainty (Haykin, 2005b).*

CR may not be able to avoid causing harmful interference to the PUs when the primary transmitter is out of the cognitive radio's detectable range. This is known as the hidden terminal problem as shown in Figure 2.5(a). Additionally, in scenarios where spectrum has high shadowing as illustrated in Figure 2.5(b), a cognitive radio user may not be able to distinguish between a deeply faded band and an idle one.

2.3.2 Energy Detection

Energy detector (ED) is the most commonly studied detector in spectrum sensing for cognitive radios. It is also known as a radiometer. The interest in ED is due to its low computational complexity and the ease of implementation both on hardware and on software.

A major advantage of ED is that detection does not require the knowledge of the PU signals as it is a generic detector. The operation of ED, however, requires the knowledge of two characteristics of the channel. The first is the noise power which must be known to the detector, and secondly, the noise must be statistically stationary.

These assumptions do not hold for all scenarios, but research has accepted them to be valid.

As a trade-off for simplicity, the ED has worse performance than other sensing techniques. The performance of the ED is even worse when it is deployed in areas of high noise powers or areas where the noise power fluctuates.

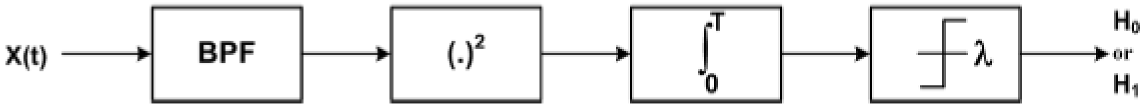

Figure 2.6: *Block diagrams for energy detection*

ED has an output that is a measure of the averaged power of the received signal and can be performed either in the time domain or the frequency domain with equal success.

Under AWGN channel conditions, the SNR value is fixed, and it affects the separation between conditional probability distribution functions. A high SNR separates the distributions enough to decide safely and with a reasonable probability of error. However, under low SNR conditions, it is difficult to distinguish between H_o and H_1 probability distributions.

In the single threshold ED, the decision for H_o and H_1 depends solely on the predetermined threshold of the channel. The probability of detection, P_d, and the probability of false alarm, P_f , for a single SU under AWGN channel can be calculated using the values of the threshold (Digham et al., 2007).

2.3.3 Matched Filter

The optimal spectrum detector is the matched filter. This is applicable when there is prior knowledge of the PU signal characteristics. It works by the correlation of unknown signals against a known signal. The advantage of the matched filter is that optimal detection is performed in a concise period.

Matched filter fails in spectrum without a complete knowledge of the PU signal and it will also be economically impossible to design the detector for all PU signals as CR is expected to operate with different PUs.

2.3.4 Cyclostationary Detection

Radio signals generally exhibit some periodic characteristics which repeat its self in time. This type of signals are commonly known as cyclostationary signals. These periodic characteristics could be caused by modulation, multiplexing, coding and so on or could be added to the signal intentionally. Cyclostationary detection involves the exploitation of such periodic properties for the detection of primary PU signals.

With such technique, the performance of the detector is optimised as it does not suffer from the effect of noise as the signals given off by noise are uncorrelated and hence no repeated properties.

The major problem with this method is the fact that the CR must have a prior knowledge of the signal characteristics and its performance in a spectrum with high shadowing or fading effects. Another drawback is the complexity that arises with its implementation.

2.3.5 Compressive sensing

Compressive sensing is a form of wideband sensing that exploits the sparsity to detect signals. This technique improves on the earlier detection techniques it removes the delay or computational complexity involved in attempting to sense wideband signal. CS samples wideband signals at a sub-Nyquist rate. This detection technique postulates that it is possible to recover and reconstruct signals from a fewer number of observations. To achieve detection in CS, the primary user signal must be sparse in time. CS works on the assumption that the spectrum is currently underutilised and will not work in the spectrum with high usage.

2.3.6 Cooperative Sensing

To improve the performance of detection techniques in CR networks, Cooperative spectrum sensing has been proposed. This exploits the detection capability of multiple CR to arrive at a fixed decision on the state of the primary user within a spectrum. In channels with high levels of fading or shadowing, the destructive effects on the PU signal is compensated by the spatial effect of multiple CR sensing. As multiple SUs co-exists within the spectrum with the PU, it is easier for most of them to avoid the effects of hidden node problem and midsection as a result of the position of the radios.

In cooperative sensing, the individual radios collect data from the spectrum, and this data is transmitted to the fusion centre. The fusion centre collates and combines this result, and a sensing decision is reached by the application of a predetermined combination rule. It is believed with the fusion of results from multiple SUs, the chances of a better sensing result is improved.

As stated in chapter one, there are two fusion decision schemes used for the arrival of detection results in cooperative sensing. The first is the soft fusion. In the soft fusion, the SU is expected to sense the spectrum and send all observation back to the fusion centre. The second is the hard fusion, In this scheme, the individual SUs make a decision based on the sensed results and communicates the decision back to the fusion centre. The fusion centre collates the decisions and sends the report back to the radios.

Three phases, sensing, reporting and relaying can be considered for the sensing. During the sensing phase, Each SU listens in the spectrum for the PU signal and processes its received data. The processed data or measurement is forwarded to the fusion centre in the reporting phase. This can either be done in an orthogonal or non-orthogonal manner. The orthogonal manner involves the reporting channel divided into micro time slots and each CR is given a dedicated channel to transmit to the FC. In the non-orthogonal manner, the radios all report back to the fusion centre at the same time. The non-orthogonal manner is therefore more bandwidth friendly and since it uses fewer reporting channel. Logically, the non-orthogonal scheme introduces more interference to the spectrum.

In soft fusion technique, the SUs can share richer information, such as their likelihood ratios, to improve the sensing result. These schemes require therefore a larger secondary network capacity. Note that the amount of data to be shared depends on the metric chosen and its representation.

While research has shown that the soft fusion achieves better performance when compared to hard fusion, the difference is not vast when there are many cooperative users in the spectrum (Mishra et al., 2006). Current research focuses on hard fusion for cooperative sensing.

When hard decisions are used, sensing decisions can be reached using any of these ways. The AND, OR, MAJORITY or the M-out-of-N methods can be used for combining the information from different cognitive radios (Peh and Liang, 2007).

The AND rule decides that a signal is detected if all sensors have detected a signal. That is, the cooperative test using the AND rule decides on H_1 if;

$$\sum_{m=0}^{M-1} D^{(m)} = M \tag{2}$$

The OR rule decides on signal presence if any of the sensors report signal detection. Hence, for the OR rule, the cooperative test decides on H_1 if.

$$\sum_{m=0}^{M-1} D^{(m)} \geq 1 \tag{3}$$

The M-out-of-N rule decides that a signal is present if at least K of the M sensors have detected a signal, for $1 \leq K \leq M$. The test decides on H_1 if;

$$\sum_{m=0}^{M-1} D^{(m)} \geq K \tag{4}$$

Therefore, the AND rule and the OR rule may be considered as special cases of K-out-of-M rule where K= M and K= 1 respectively.

M is the number of CRs sending the decision to the fusion centre, D is the fusion centre while K is the minimum required H_1 results for the fusion centre to decide that there is a primary user in the spectrum.

A comprehensive classification of cooperative sensing is examined in (Akyildiz et al., 2011) and research challenges are listed. It is shown that the increase in the number of cooperative users results in significant increase in the sensing performance and the spectrum utilisation (Zou et al., 2009).

2.4 Spectrum sensing in Cognitive radio

Spectrum sensing in cognitive radio systems needs to have a very efficiency factor such that the detection of PU is immediate. The primary challenge is to control or remove the amount of interference to the PU. As stated earlier, two transmission schemes are used in CR systems. The underlay and the overlay transmission scheme.

A “perfect” overlay scheme which allows transmission during idle time will offer zero interference, while an underlay system which increases transmission capacity when combined with the right power control scheme has considerable risks of increasing interference to the PU.

Designing perfect overlay systems is incredibly complicated as it needs to be able to vacate the spectrum as soon as it becomes active. To solve this problem, it has been proposed that SUs should only transmit for a limited time frame after detection of an idle channel (Huang et al., 2008). This, therefore, means in practical scenarios, even the overlay schemes will cause some form of interference to the PU.

In CR networks, interference to PU is usually because of any sensing errors in the channel and the sensing transmission strategy employed by the radios. In sensing, it is assumed that a CR sees all possible channels available and decides which to use. Then it is also assumed the PU could return to the channel at any point in time.

One common strategy in spectrum sensing research is that the SU keeps sensing an active channel till such channel becomes idle and it utilises such channel (Zhao et al., 2007a, Kim and Shin, 2008) while another school of thought is that once a channel is sensed as busy, the SU goes resting for a while before sensing is performed again. This advantage of this strategy is that its saves battery life. This strategy is used in our research in chapter five.

Various studies in SU sensing are carried out with the aim of maximising access opportunity for CR systems while guaranteeing the PU quality of service is not damaged. In Zhao et al., 2007, it is assumed that sensing occurs periodically and by setting some PU performance constraints, the channel is correctly sensed although the channel was modelled as a perfect system. The same objective was investigated in Kim and Shin (2008) and in Huang et al., (2008). The perfect system was assumed in both cases. The problem of sensing was again investigated in (Qinghai et al., 2008), the possibility of sensing errors was not considered. A policy for transmission over channels at different times was proposed in (Zhao et al., 2007b) with the aim of maximising SU throughput but the interference caused to the PU was not considered. Transmission strategies in an idle channel were investigated in (Mehanna et al., 2009) with the aim of finding an optimal access strategy.

Cooperative sensing offers some improvement in sensing channel state. As stated earlier, in centralised cooperative sensing, the sensing decision is based on the final sensing information received from the fusion centre. Cooperative sensing is most beneficial with energy detection as it can be achieved easily. Most used technique in energy detector based spectrum sensing is the likelihood ratio test (LRT) detector which is a monotonic function of the energy levels in the bandwidth and compares it to a given threshold (Kaligineedi and Bhargava, 2008, Gandetto and Regazzoni, 2007). The soft combination has been shown to be the optimal detector for cooperative sensing, but as raw data over bandwidth is involved, it is deemed challenging and expensive.

A comprehensive study and classification of comprehensive sensing are done in (Akyildiz et al., 2011) which also lists the challenges.

Research in cooperative sensing has focused on the derivation of an optimal decision rule for different scenarios such as when the SINR values are known within the channel or when the SINR levels are unknown. The optimal rules are often very complicated therefore the need for sub-optimal rules. The “K of N” rule has been proposed as the suboptimal rule in (Quan et al., 2007).

In Kaligineedi and Bhargava, (2008), the authors proposed a sensing K out of N scheme where the SU observations are identical and independently distributed. The work shows an analytical solution for fusion based on the K out of N model. The authors in (Ghasemi and Sousa, 2007) investigate the performance of cooperative sensing while considering the effects of fading in the system which also shows that the performance of cooperative systems also surpasses individual systems. A cooperative sensing scenario where the sensed information involved imperfect channel states is investigated in (Oh and Lee, 2010). Hard fusion was used in the work as the fusion rules. The research in (Atapattu et al., 2011) investigates energy detection in a cooperative scenario. The work focuses on a variation of the K out of N rule to perform sensing. In (Hoseini and Beaulieu, 2010), cooperative sensing is investigated as a means of improving SU throughput given a bound of imposed interference throughput. It further shows how the problem could be modelled as convex optimisation problem if certain practical constraints are applied. This work closely resembles our work in that it seeks to improve throughput. It is different from our work because a slotted aloha setup is used as channel while the channel in the work is assumed to be a single continuous channel. In (Yang, 2014), the author proposes new algorithms for ensuring that cooperative systems are more energy efficient by ensuring that less energy is used. An iterative algorithm is used which reduces the optimality of the system.

2.5 Transmit Power Management

The management of the transmit power in wireless systems has always been a known problem. This is because the radios require a certain amount of transmit power to successfully transmit their signal or data. In wireless communication, power control is one of the resource management tools put in place to regulate the QoS of the network by controlling the transmit power of users as they coexist within the spectrum. Power control helps the users in a two-part manner. It helps with interference control by reducing the interference introduced to the spectrum. It also helps with the battery power, as a lower power could help prolong battery life.

This is further complicated in CR networks as they will be required to operate in networks which they will have to restrict those power levels for the protection of the primary owners of the spectrum.

Power control in Cognitive radios can be performed either as a distributed or a centralised manner. In the distributed manner, the individual CRs uses the local information available to them and attempts to control its transmit power based on the information it has. It does not require the knowledge of the channel conditions of other SUs. While in a centralised manner, the network of SUs has a centralised control station (a base station) which gives the individual CRs the information to perform the power control with. Such information may include path loss, and channel gains.

The power-control problem in wireless networks with competitive users was also investigated in the literature. The power-control problem for traditional cellular wireless networks was addressed in several classic papers (Shah et al., 1998, Goodman and Mandayam, 2000). A non-cooperative uplink power-control game was formulated in (Saraydar et al., 2002), the outcome of which resulted in a Nash equilibrium that was inefficient. The research showed that in competitive wireless systems, every device seeks to increase its power to achieve its quality of service. To counteract this and obtain an efficient system, a pricing scheme was introduced to obtain Pareto improvement.

Power control in cognitive radio is based on traditional wireless power control. The difference is while power control is done centrally in traditional wireless systems, each CR device must perform its power control. While there are other ways postulated in literature for handling power control in cognitive radios, like the water-filling algorithm and the beamforming algorithm, the independence of CRs to act selfishly to achieve its quality of service requirements poses a complex problem. Game theory proposes a means to solve the power control problem due to its efficiency in solving complex problems.

In CRNs, two game-theoretic power-allocation algorithms were proposed in (Huang et al., 2006) to achieve efficiency and fairness for SUs. The pricing scheme in the research was based on the efficiency of an OFDM system. However, the utility maximisation for each SU was not considered. In (Jia and Zhang, 2007), the authors propose a general power control model for CR based on non-cooperative game theory. The primary network was considered to regularly monitor the interference from all SUs. The utility function of each SU in the network was modelled as the logarithm of the user's *Signal to Interference and Noise Ratio* (SINR) which represents the throughput of communication systems. The existence, uniqueness and Pareto efficiency of the Nash equilibrium were also investigated. In (Daoud et al., 2008), the authors addressed the problem of utility-maximization for PUs and presented a Stackelberg game model for PUs and SUs. However, the constraints to ensure that the quality of service of the PU was completely ignored. Stackelberg game is a dynamic model of duopoly proposed by Stackelberg in 1934 where there are leaders and followers in the game. The leader moves first, and followers move after.

Pricing schemes in CR are extensively studied in the literature. There is always the need to improve such prices to ensure that the interference to CR is reduced or eliminated. The concept of Interference temperature was proposed in (Haykin, 2005a) as a means to ensure interference to the PU is always below the required limit. A non-cooperative game with exponential utility was proposed in (Wang et al., 2007) which interference temperature was applied. The authors do not investigate if the game achieves Nash equilibrium. The significant problems of pricing-based utility-maximisation for the spectrum owners was addressed in (Niyato and Hossain, 2008); while it discusses Nash equilibrium and building more efficient games, the resource constraints and performance guarantees for SUs were not considered. In (Yu et al., 2010), the pricing issue was studied in a non-cooperative CR network in which the SUs strategically adjusted their uplink transmit-power levels to maximise their utilities, and the primary service provider charged the SUs on their transmit-power levels to enhance its utility. The significant contributions of the related research on power control can be summarised as follows: to find the optimal transmit power that maximises each SU's utility and guarantees the fairness among SUs.

The problem of power-control and rate-adaptation for SUs in a CDMA environment was investigated in (Kim et al., 2008). This work adopts a QoS constraint regarding minimum SINR and transmission rate for SU. This algorithm, however, is not enough for CRs. Usually, different SUs transmit data at different rates. Thus, the behaviour and equilibrium points among these competitive SUs with different utilities should be studied and understood. Moreover, the algorithm did not consider a pricing scheme for the CRs.

To ensure fairness in power control, many researchers have proposed different ideas. The concept of linear pricing was abolished as it did not ensure CRs were treated fairly. All CR devices were penalised equally without considering the requirements of each CR. A non-cooperative game was proposed in (Aik Jin and Chee Keong, 2012) where the cost function is dependent on the distances of individual CR from the base stations. The throughput of the system was shown to have improved against the non-cooperative game without pricing but there was no reference to the convergence of the system.

Recently, iterative algorithms have taken centre stage. This utility can be modelled as concave or convex systems (Al-Gumaei et al.). In (Koskie and Gajic, 2005), a power control algorithm (KG) which quantifies the signal-to-interference noise ratio (SINR) based on an iterative algorithm for 3G CDMA networks. This algorithm ensures power is controlled, but it is insufficient for CRs. An adaptive power control scheme is proposed in Aik Jin, and Chee Keong, 2012 which ensures the power is regulated adaptively in the system, but the SINR degrades as the number of radios rises. The algorithm incorporates QoS constraints on the SU but doesn't incorporate the maximum power of the channel in the system. Another iterative algorithm with sigmoid cost function was proposed in (Al-Gumaei et al., 2014), the algorithm also achieves Nash equilibrium as the game comes to rest and convergence achieved. A non-cooperative iterative algorithm which is an improvement on the Nash algorithm for wireless data by including a cost function is proposed by (Junhui et al., 2013). The authors show it ensures power control while improving the capacity of the spectrum. An improved algorithm was proposed by (Talabani et al., 2015) in which a chaos function was included the cost function to aid convergence. The power was reduced by the algorithm, but the algorithm performance in SINR is not efficient.

The aim of power control using iterative algorithm is to lower the power requirement while ensuring faster convergence while guaranteeing the SINR requirements is achieved.

2.6 Summary

CR offers the ability to use licenced spectrum as an unlicensed user. This promising technology may hold the key to other technological progresses due to its ability to learn from stimuli and make informed automated decisions. But for these benefits to come to fore, certain problems such as spectrum sensing and power control will have to be resolved.

Spectrum sensing is the ability for the CR to search through spectrum for PU signals. It also serves as a link to the spectrum for learning purpose. Several techniques have been proposed in literature to solve the spectrum sensing problem, some of which are, energy detection, matched filter, compressive sensing, and cooperative sensing. Cooperative sensing allows several SUs to sense the spectrum at once and the decision on the status of spectrum is done by a predetermined decision technique. This type of sensing provides another layer of performance over conventional narrowband techniques because it easily eliminates the problem of hidden node where the CR fails to detect the PU signals.

The aim of every CR network is to increase throughput. Cooperative sensing when combined with a narrowband offers higher throughput values.

Power control is the process of controlling the level of transmit power of CRs. There are lots of techniques in literature such as cooperative and non-cooperative game theory, load balancing techniques. In cooperative games, the CRs all cooperate and reach an agreement between themselves on what penalty a defaulter should enjoy.

The PU chooses whether to cooperate or not. In non-cooperative game theory techniques, the CRs all see themselves as a competitor and penalty is assigned by the Cognitive Base station. During this research, it is assumed that for power control, every CR competes with the next CR as they all seek to maximise their transmit powers to achieve excellent quality of service.

Chapter Three

Methodology

3. Introduction

In research, methodology generally is a sequence of methods used in resolving the questions raised earlier in the research. It is often of two forms. The qualitative research method or the quantitative research method. Qualitative research method is a model that seeks to identify trends in subject thought and opinions using several structured or unstructured techniques while Quantitative research method emphasizes on the statistical, numerical or mathematical analysis of new or preexisting data using computational techniques.

The focus of this work is on the problems of Spectrum sensing and power control with regards to cognitive radios by generating new models or revising existing models so as to simulate accurate representations of CR within its host spectrum.

This chapter seeks to identify methods in literature which is used extensively in later chapters. It also gives reason as to why such method is used.

3.1 Spectrum sensing in Cognitive Radio

In cognitive radio, the purpose of spectrum sensing is to identify useable spectrum for use, through opportunistic spectrum access. This is the most important in cognitive radio operation. It allows the CR to identify spectrum holes for communications. Spectrum sensing is essentially about sensing and identifying the signals of the primary user. As stated earlier in chapter 2, CR uses the conventional wireless detection techniques with some modifications to allow for the cognitive capability of CRs.

Energy detection is the mode of sensing used in this research. This is because it allows the detection of primary users without knowing the characteristics of the primary user. Primary user detection involves a comparison of received signal against a predetermined threshold. It involves a hypothesis testing where the state H_0 and H_1 represent the absence and presence of the primary user respectively in the presence of noise within the channel. The threshold is usually set after periodic sensing of the host environment to determine the noise level of the spectrum. Essentially, the Energy detector is a power meter that compares the power of signal received. When the response from the search is higher than the noise level, the detector sets its response to H_1 signifying that there is an active PU in the spectrum.

$$Y = \begin{cases} \sum_{i=1}^{I} {n_1}^2 & H_0 \\ \sum_{i=1}^{I} (s_i + n_i)^2 & H_1 \end{cases} \qquad 1$$

Y is the signal received by the CR, n is noise power and s is the primary user signal within the channel. H_0 is the state of which the received stimuli is essentially noise while H_1 means there is a primary user signal included with the noise.

The performance of the energy detector is dependent on three very important variables. These are the Probability of detection (P_d), probability of misdetection (P_m) and the probability of false alarm (P_{fa}).

Probability of Detection (P_d) is a measure that the detector predicts the state of the channel correctly. It is expressed in mathematical term as:

$$P_d = P_r(Y \geq z|H_1) = (s_i + n_i)^2 \; = \; 1 - \; P_m \qquad 2$$

Probability of Misdetection (P_m): The probability that the detector detects the channel as idle while there is an active PU in the channel. This occurs in situations of hidden nodes where fading or other sources of interference may mask the signal of the PU or if the threshold value was set too high.

Probability of false alarm: the probability that the detector detects the channel as busy when the spectrum is idle. This occurs when the threshold level is set too low and noise levels are assumed to be PU signals.

Figure 3.1 shows the relationship between the SNR and the P_d in a given spectrum. It is deduced from the plot that in spectrum where the SNR is excellent, the rate of detecting the PU signal correctly increases. It also shows the rate of success also increases with lower P_{fa}.

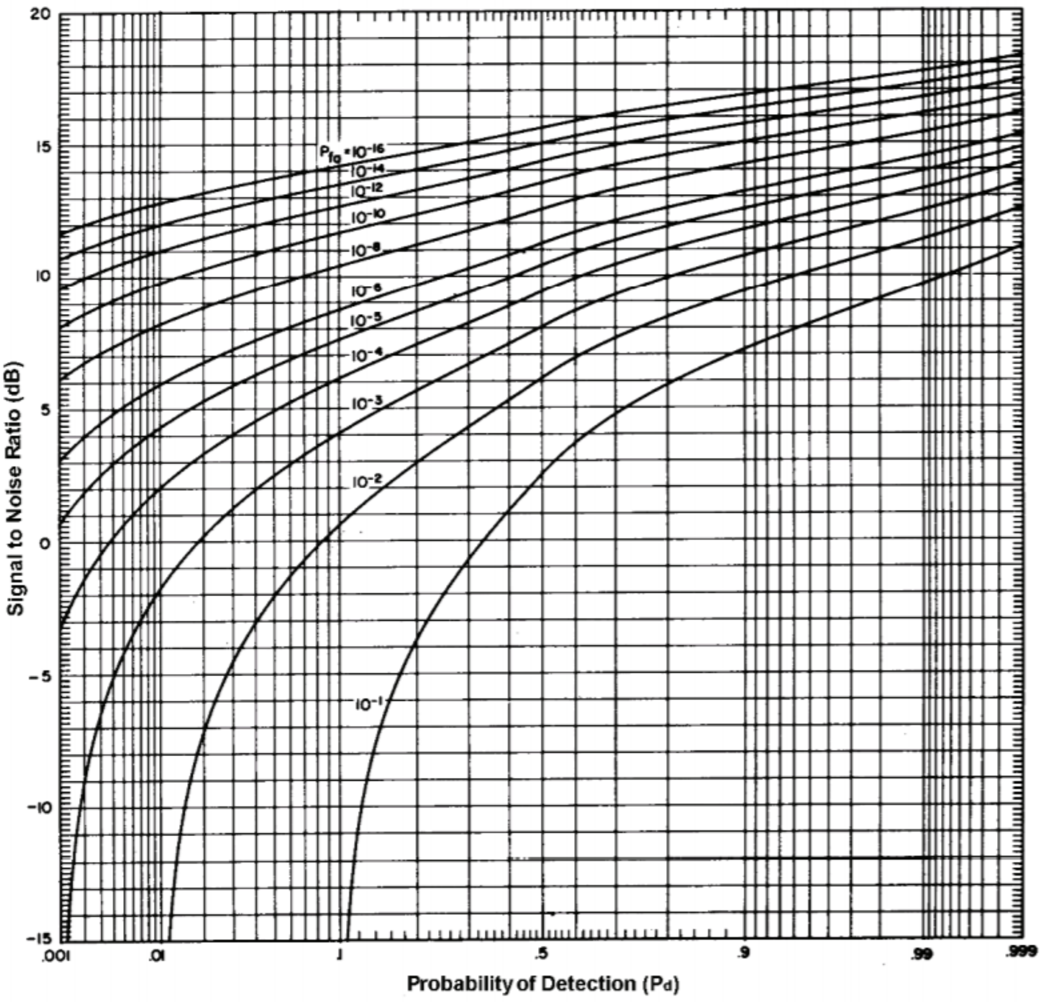

Figure 3. 1 plot of SNR against P_d using P_{fa} as a variable.

While the energy detector is easy to design and detects the channel correctly in most cases, its performance in environments where the noise level varies or where fading, and shading occurs is relatively poor. Since cognitive radios will be employed in areas with low PU transmit power, there was a need to improve the performance.

To improve the performance of PU, Cooperative spectrum sensing based on energy detection was employed.

3.1.2 Cooperative Spectrum sensing

A very promising solution for improving the sensing performance of the SU networks is to exploit cooperation among the secondary nodes. In particular cooperative strategies, exploiting the SUs spatial diversity can be adapted to counteract the channel effects such as multipath and shadowing that causes the hidden node problem (Sreedharan and Sharma, 2011, Kandeepan and Giorgetti, 2012). Cooperative Spectrum Sensing (CSS) has received an increased attention in the last few years, and many different schemes proposed. In this research work, cooperation between the cognitive radios is exploited to increase the chances of detecting incumbent signals and increasing throughput. A survey of cooperative sensing techniques can be found in (Akyildiz et al., 2011). In this review, it shows a plethora issues that should be addressed for cooperative sensing to work efficiently.

Classification of cooperative sensing is carried out by investigating the way the SU share their sensed data and the mode in which the final decision is reached. There are two approaches, the centralised and the distributed.

- Centralized cooperative sensing

In centralised cooperative sensing, the information sensed by the CRs are all sent back to a central location, called the fusion centre. This fusion centre collates all the information from the individual CRs and makes a global decision which is sent back to the CRs for a decision on the channel state (Akyildiz et al., 2011).

- Distributed cooperative sensing

The difference between the centralised and distributed sensing lies in the absence of a specific fusion centre. The decision, in this case, is achieved by communication between individual CRs, and a unified decision is accepted by all radios. This process can be performed iteratively. In this scheme, therefore, the final decision is taken by each SU by a collective decision policy (Akyildiz et al., 2011).

3.2 Power Control in Cognitive Radio

The need to manage transmission power in CR cannot be overemphasized. This is because like every wireless service, controlling the transmission power is a fundamental radio resource management technique as it addresses two fundamental limitations of wireless networks:

- Radio spectrum is a scarce resource. Therefore, the mitigation of interference from devices transmitting in the same spectrum band is critical.
- Mobile wireless devices have significant limitations on the duration of their “talk time,” as the life of their battery is limited. The design of energy efficient wireless networks that optimises battery life is critical (Conti et al., 2011).

Power control is a conventional technique applied in wireless communications to achieve the reasons stated above. Furthermore, the ability to combine power control with other interference mitigation techniques is an added plus. Power control helps improve the performance of wireless systems.

The results from the adoption of power control algorithms regarding mitigating the interference and increasing the network capacity are significant. Although while the benefits of power control techniques seem apparent, the analysis depends critically on assumptions and parameters of the operational environments which must be chosen very carefully.

Power control for mitigation control begins with the knowledge of the Signal-to-Interference (plus Noise) Ratio (SINR). This shows the quality of signal with which data is transmitted within the spectrum. It is assumed that in CR, the state of the SINR in the channel can be estimated by communications and feedback between the CR and the base stations. Mathematically, it can be represented as:

$$\gamma_i = \frac{p_i h_i}{\sum_{j=1, j\neq 1}^{N} p_j h_j + \sigma^2} \tag{1}$$

This formula assumes that the channel gains does not change, and the only changes are adjustments made by the CR because of power control.

Presently, research into power control focuses on reducing transmit power and achieving faster convergence.
In this research work, Game theory was used as the method to model the power components of the CR.

3.1.2 Game theory in Cognitive radio

Power control in cognitive radio defers from the conventional power control in wireless devices because it affects all other radios within the spectrum. That is, when a CR changes its SINR state, it affects not just its SINR but those of other CRs within the spectrum band even though they are all independent of the reference CR. This situation can be efficiently analysed by game theory, *i.e.*, “the study of mathematical models of conflict and cooperation between intelligent, rational decision-makers” as defined in (Myerson, 2013).

Game theory has emerged as an essential tool in the design of future wireless networks. Three indicative examples follow:

- In multi-hop communications, whether a radio should act as a relay (forwarding some data to another node) or not can be directly transformed into a game (Douros and Polyzos, 2011).
- In multichannel networks, game theory can be used to find optimal channel assignments with distributed schemes (Ren et al., 2009).
- In spectrum sharing scenarios, multiple non-cooperative wireless devices compete for spectrum access (Xu and Zhao, 2014). Game theory is a natural choice for deciding upon who is going to transmit and with what power.

In cognitive radios, there is that tendency to increase its power requirements to ensure adequate quality of service (QoS) for transmission without considering the other CRs in the network. This is a typical example of a non-cooperative scenario there for non-cooperative game theory should be applied. Contrary to coalitional game theory, where decisions are based on the formation of teams, in a non-cooperative game, each player makes decisions on its own.

Two important properties of CR devices in the wireless spectrum are *rationality* and *selfishness*. Rationality means that each CR makes decisions with the aim of achieving its QoS objectives. Selfishness means that radios aim to achieve its QoS without a care about how it affects the communication capability of other radios. The CR device has no intention of damaging the QoS of other radios only the aim of ensuring it achieves its own.

To define a non-cooperative game, there's a need to specify the set of players, the strategy to play and the utility function which indicates the satisfaction or dissatisfaction with the state of the game. Since CRs are rational and selfish, they always seek to maximise the profit in their utility functions. A formal definition follows:

Definition 1. *A strategic (or normal form) non-cooperative game* G *with a finite number of players consists of the following triplet: A finite set of players* N = (1, 2….N) *and, for each player* i*, a set of strategies* S_i*, and a utility function* U(.)*.*

Therefore, mathematically it can be represented as:

$$G = [\,N, S, U]$$

A powerful concept for finding a solution in non-cooperative game theory is the Nash Equilibrium (NE) which predicts outcomes of games at a point where it achieves stability (Beibei Wang, 2010). The formal definition follows:

Definition 2*: (NE):* A power vector S= is the NE of a game G. For $\forall_I \in N$ if and only if

$$u_i(p_i^*, p_{-i}) \geq u_i(p_i, p_{-i}),\ \forall p_i \in s_i$$

where p_{-i} is the power of all SUs except SU_i and is p_i^* the NE solution of SU_i.

A NE corresponds to a steady state of a game in the sense that no player has an incentive to change its strategy unilaterally.

Chapter Four

A Sensing -Throughput tradeoff in cooperative sensing for cognitive radios

4.1 Introduction

Cognitive radio which enables the use of spectrum when such spectrum is inactive is proposed as a solution to solving the spectral scarcity. Periodic spectrum sensing is essential for the knowledge of the live status of PU within the spectrum. Previous research has shown that more extended sensing periods improves the sensing reliability. In fixed time frames, more extended sensing periods reduces the time available for transmission. For efficient transmission, a tradeoff between sensing time and transmission time is the general requirement. To improve sensing reliability in situations where the PU signal to noise ratio (SNR) is very low, cooperative sensing is proposed. Some cooperative sensing schemes used in literature include k-out-of-n fusion (Akyildiz et al., 2011), soft combination-based fusion (Ma et al., 2008), weighted combination-based fusion (Khan et al., 2010). Optimization based detection techniques such as iterative algorithm (Peh et al., 2009) and selected cooperation (Peh and Liang, 2007) have also been shown to achieve better detection but has higher complexity. In this chapter, the k-out-of-n algorithm is applied as a detection tool to predict the availability of PU in the spectrum by reformulating the interference probability to PU and SU throughput while using the slotted aloha and back-off counter to model the contention of the cognitive radio systems. The k-out-of-N algorithm has already been shown as the sub-optimal sensing algorithm for hard fusion.

4.2 System Model

The channel model consists of one primary radio coexisting with n SUs within a single cell and one fusion centre that uses decision fusion to detect the presences of PUs cooperatively. This channel is broken into time frames. Each frame has a total duration L, a sensing duration X, a decision duration of S and a transmission duration of L-S-X. The frame duration L is fixed while the sensing period X and decision period S are flexible since they depend on the performance of the radios and the state of the channel which such radios are deployed.

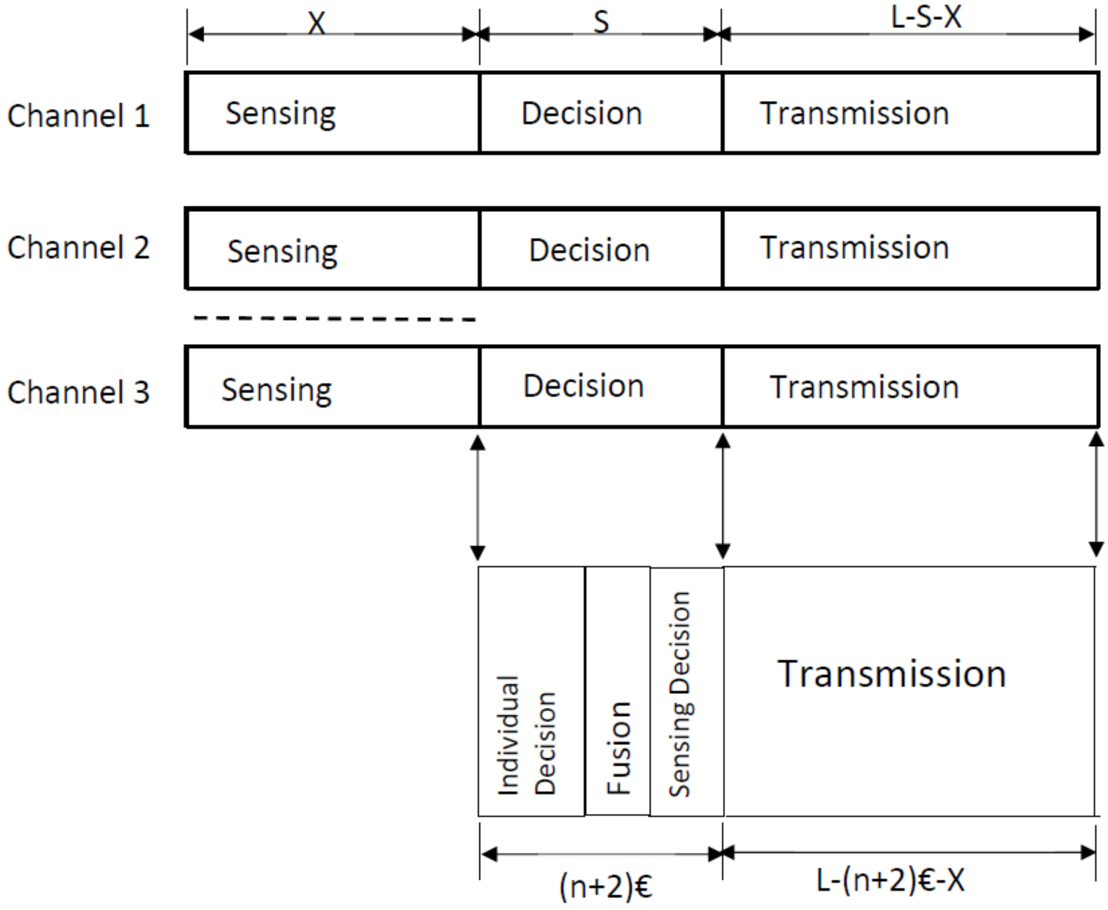

Fig 4.1 The frame- by- frame structure for CRN

In this model, the cognitive radio senses the channel during the allocated period and makes an individual decision based on the signal it receives, sends the decision to the fusion centre. The fusion centre collates the results, analysis it and makes a decision based on a predetermined fusion rule and sends the decision back to the radios. During sensing period, energy detection is performed by the CR and reports the results to the fusion centre. It is assumed that the decision phase is broken into micro time-slots of equal length and that each cognitive radio uses one slot to send its decision to the fusion centre. Since there are n cognitive radios in the channel, n time slots are used. Its also assumed that the fusion centre uses a time slot to process the data received from the individual radios. For the fusion centre to operate with equity and fairness to all SUs, it is assumed it can send its decision as a blanket response to all available radios within one micro time slot. If each time slot has a length of €, the total time used for this process will then be (n+2)€.

The received signal is then filtered with a bandpass filter with bandwidth B, then squared and summed up over the sensing period. The total number of samples over the sensing period is I=2τB and the sampling interval is T_s=τ/I. The decision is made based on the results by the fusion center and transmitted to the SUs. The SUs decides to either transmit or not, based on the information received from the fusion center. This format generally introduces reduced interference to the PUs. The default equations for decision fusion detection technique are given in chapter 2.

Signal detection is performed with energy detection; the detection hypothesis is given by:

$$Y = \begin{cases} \sum_{i=1}^{I} {n_i}^2 & H_0, \\ \sum_{i=1}^{I} (x_i + n_i)^2, & H_1, \end{cases} \qquad (1)$$

Y is the received signal, x_i is the sample of received PU signals by the SUs and n_i is a sample of additive Gaussian noise. H_0 and H_1 are hypothesis for when the PU is absent or present respectively. For large number of samples, applying central limit theory, the probability of detection $P_d(z, I)$ and probability of false alarm $P_f(z, I)$ are given as:

$$P_d(z, I) = P_r(Y \geq z|H_1) = \frac{1}{2} er\,fc\left(\frac{z-I-I\gamma_p}{2\sqrt{2}\sqrt{\frac{I}{2}+I\gamma_p}}\right) \qquad (2)$$

$$P_f(z, I) = P_r(Y \geq z|H_0) = \frac{1}{2} er\,fc\left(\frac{z-I}{2\sqrt{2}\sqrt{\frac{I}{2}}}\right) \qquad (3)$$

z and γ_p denote the detection threshold and PU's SNR received by the SUs respectively while $er\,fc(\bullet)$ is the complimentary error function. It is assumed that the results are independent and identically distributed since the model is a single cell.

At any time, let λ and μ represent the average probability that the channel is busy and an idle channel respectively, then that the channel is busy is P_n= $\frac{\lambda}{\lambda+\mu}$ while the probability of idle channel $P_x = 1 - P_n$.

The *i*th SU makes its individual decision D_i based on the hypothesis shown in (1) above: D_i = 1, when the presence of a PU is observed and D_i = 0 when PU signal is absent. The k-out-of-n rule is applied at the fusion centre (e.g. if k= 1, the OR fusion rule is applied and if k=n, the AND fusion rule is applied). Based on this result, the fusion centre decides that the channel is busy when $\sum_1^n D_i$ ≥ k else the channel is idle.

The overall probabilities of detection $Q_d(k, z, I)$ and false alarms $Q_f(k, z, I)$ are given as:

$$Q_d(k, z, I) = \sum_{i=k}^{n} C^i{}_n \, P^i{}_d(z, I)(1 - P_d(z, I))^{n-i} \qquad (4)$$

$$Q_f(k, z, I) = \sum_{i=k}^{n} C^i{}_n \, P^i{}_f(z, I)(1 - P_f(z, I))^{n-i} \qquad (5)$$

$C^i{}_n$ Represents the number of combinations of n SU transmitting as *i*th SU at a time.

4.3 The Trade-off problem with slotted Aloha

When an idle channel is detected, multiple SUs will contend to access the signal using MAC protocol. A slotted Aloha is used to analyse the impact of access contention on sensing-throughput trade-off and to alleviate multiple SU contention, a binary exponential backoff (BEB) is used to reschedule retransmission. Let W and m denotes the minimum detection window and the maximum backoff stage respectively. When the channel is detected as idle, it is assumed that all SUs will attempt to transmit a packet at once thereby decreasing their backoff counters by 1, and if the channel is detected as busy, all SUs will freeze transmission, and their backoff counters are also frozen till the next frame. Let the conditional probability of collision of packets with transmission from other SUs and PUs be $P^s{}_c$ and $P^p{}_c$ respectively.

Transmission is assumed to be at the beginning of every idle slot with identical probability,τ_s. When a channel is detected as idle, all SU attempt to transmit and a transmission can only collide with the transmission of other n-1 SUs since there are only n SU in the channel. Therefore, the probability that a packet transmitted by an SU will collide with a packet from another SU is given by:

$$P^s{}_c = 1 - (1 - \tau_s)^{n-1} \qquad (6)$$

In some instance, the fusion centre could decide that a channel is idle while such channel has a live PU present, this is known as Missed Detection. In this case, when the SUs transmits, such packets are bound to collide with those of the PUs. The conditional probability that a transmitted packet will collide with a PU transmission is given as:

$$P^{p}{}_{c} = P_b \,.\, (1 - Q_d(k, z, I)) \qquad (7)$$

Since $P^{s}{}_{c}$ and $P^{p}{}_{c}$ are statistically independent, the aggregated conditional collision probability p for each packet transmitted by the SUs can be derived as:

$$p = P^{s}{}_{c} + P^{p}{}_{c} - P^{s}{}_{c} \bullet P^{p}{}_{c} \qquad (8)$$

Under saturation conditions, the average transmission probability at the beginning of back off slot is given as:

$$\tau_s = \frac{2(1-2p)}{(1-2p)(W+1)+pW\,(1-(2p)^m)} \qquad (9)$$

To compute the throughput of the system, there must be some form of transmission. When the channel is detected as idle, it is assumed the CRs attempt to transmit, and since there are n radios, the overall probability that at least one SU is transmitting during the transmission period:

$$P_{one} = 1 - (1 - \tau_s)^n \qquad (10)$$

It is assumed that there is interference to the PU only when there is a missed detection, while at least one SU is transmitting. Their interference probability to the system is given as:

$$T_{Int}(k, z, I) = P_n \,.\, \big(1 - Q_d(k, z, I)\big) \,.\, P_{one} \qquad (11)$$

$$= P_n \,.\, \big(1 - \textstyle\sum_{1=k}^{n} C^{i}{}_{n}\, P^{i}{}_{d}(k, z, I)(1 - P_d(z, I))^{n-1}\big).\,(\,1 - (1 - \tau_s)^n) \qquad (12)$$

The aim of spectrum sensing is for SUs to be able to transmit successfully without interfering with the PU. This means that the channel was successfully detected, and the decision transmitted by the fusion centre is idle. The probability that an attempt to transmit a packet was successful is given by:

$$p_a = n\tau_s\,(1-\tau_s\,)^{n-1} \tag{13}$$

The conditional probability of successful transmission is the probability of successful attempts conditioned by the number of attempts. Therefore, the probability that the transmission was successful is given as:

$$P_s = \frac{P_{one}}{P_a} = \frac{n\tau_s\,(1-\tau_s\,)^{n-1}}{1-(1-\tau_s)^n} \tag{14}$$

It can be deduced that based on the conditions stated above, a successful transmission only occurs when the channel is correctly detected as idle, and only one SU transmits at a given transmission period. The aggregated secondary throughput is:

$$T\,(k,z,I) = P_x\,.\left(1-Q_f(k,z,I)\right)\,.P_s\,.C(I) \tag{15}$$

$$= P_x\,.\left(1-\sum\nolimits_{k=1}^{n} C^i{}_n\,P^i{}_f(k,z,I)(1 - P_f(z,I))^{n-1}\right).\frac{n\tau_s\,(1-\tau_s\,)^{n-1}}{1-(1-\tau_s)^n}\,.\frac{L-(n+2)€-X}{L}.R \tag{16}$$

$C(I)$ is the normalised throughput within each successful transmission period.

Most research works use the detection probability as a constraint for the sensing-throughput trade-off optimisation problem. Since interference protection to the PUs is critical for the deployment of CRs, the interference probability has been used as the constraints to solve the throughput maximisation problem. The sensing-throughput trade-off optimisation problem can be represented as:

$$\max_{k,z,I}\,T(\,k,z,I),$$

$$\text{s.t. } T_{Int}(k,z,I) \leq \bar{T}_{Int} \tag{17}$$

This optimisation problem can be resolved using various optimisation solvers.

4.4 Solving the optimization

The optimization problem shown above holds the solution to the sensing-throughput problem. To solve the optimization problem, the best option is to find a solution for a single fusion rule then run it for other fusion rules to arrive at an optimal solution. This is possible since the fusion rule is a real integer. Supposing for a given fusion rule k_a, the optimal number of samples I_a and its corresponding detection threshold z_a mazimises the throughput while restricting the interference caused to below the given interference threshold, $\bar{T}_{Int}$. Then the optimisation problem can be rewritten as:

$$\max_{k,z,I} T(k, z, I),$$

$$\text{s.t. } T_{Int}(k_a, z_a, I_a) \leq \bar{T}_{Int} \qquad (18)$$

if $T_{Int}(k_a, z_a, I_a) = \bar{T}_{Int}$, it is easy to see that if another threshold z_b is chosen for the given fusion rule and optimal sample size, such that $z_b \ll z_a$, the fusion centre will likely detect the channel as busy. This shows that the probabilities of false alam and detection decreases with respect to the detection threshold. Also, when the probability that the channel is detected as busy increases, the transmission probability of the network reduces. Further deductions can be made by finding the first derivative of the probability that at least one SU transmits (10),

$$P_{one} = 1 - (1 - \tau_s)^n$$

$$\frac{dP_{one}}{d\tau_s} = n.(1 - \tau_s)^{n-1} \qquad (19)$$

From the derivative, since n is a real number, the value is always going to be higher than 0. A smaller threshold will, therefore, result in a decrease in transmission probability and hence lower the interference in the channel.

$$T_{Int}(k_a, z_b, I_a) < T_{Int}(k_a, z_a, I_a) \qquad (20)$$

If it is assumed that, at optimal point, the total interference to the channel is equal to the interference caused to the primary users, therefore;

$$\bar{T}_{Int} = P_{one}.\ P^p{}_c \qquad (21)$$

The optimal τ_s can then be calculated for a given value of $\bar{T}_{Int}$ and a known k_a with the formular below:

$$\frac{\bar{T}_{Int}}{P^{p}{}_{c}} = 1 - (1 - \tau_s)^n \tag{22}$$

To solve the tradeoff problem, a search algorithm is used and presented below:

Algorithm:

```
Input n, B, k, I
Determine $\tau_s$, z and T for all values of I, k using equation (21), (7), (9), (16)
Set $T^{n+1} = T^n$ if $T^{n+1} \geq T^n$
else break if $T^{n+1} < T^n$
compare T and set corresponding K as $K_{opt}$ for maximum $T^{n+1}$
```

4.5 Simulations and analysis

The impact of the access contention on sensing-throughput tradeoff problem is evaluated. Twenty SUs are randomly located within a single-hop area with a transmission rate of 1Mbps. The total frame duration is 20ms, and the sampling interval is 1μs. W and m are assumed to be 16 and 4 respectively. The channel is idle or busy with identical probability of 0.5. The total interference to the channel is assumed to be 0.1 and the length of one micro frame is 0.1ms. The SNR value is varied from -22dB to -6dB. To analyze the effect of increasing the number of secondary users, the number of cognitive radios are taken as 20, 25, 30, 35, 40 and 45 while $\gamma_p = -15dB$.

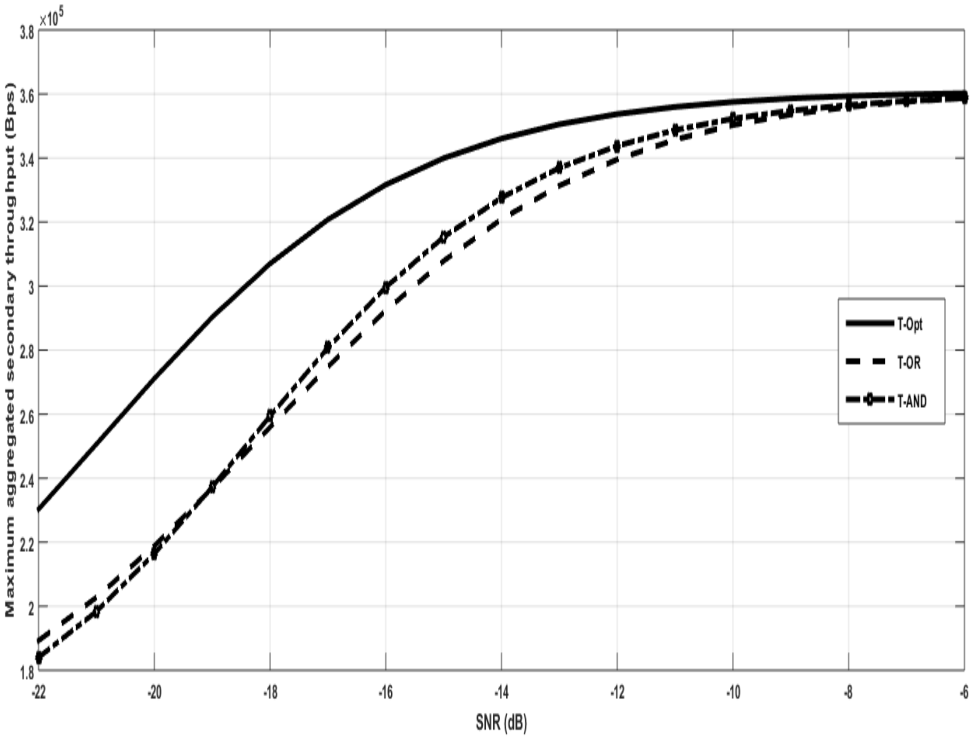

Figure 4.2 Aggregated Secondary throughput against SNR n=20

The maximum aggregated secondary throughput with SNR is shown in figure 4.2. T-opt is the aggregate throughput achieved by plotting the throughput using the optimum k of m values. The figure also shows the throughput achieved by applying the fusion rules. The -OR- fusion rule is implemented by setting k=1 since the fusion centre decides that the channel is busy when any single SU reports it as busy. The -AND-fusion rule is implemented by setting k=n. The fusion centre only detects the channel as busy if all the SUs detect the channel as busy. Deduction from the graphs shows that at lower SNR values, the performance degrades substantially. This degradation is due to the difficulty in detecting the primary user signal hence a more significant number of collisions. This is more pronounced when the fusion rules are applied, at -22dB, the optimum k-of-n algorithm outperforms the fusion rule by almost a ratio of 2:1. This gap in performance is rapidly covered as the SUs move to environments with good primary user signal. As seen in the plot, they all converge towards a fixed point.

Figure 4.3 depicts the period spent sensing the channel by the SUs. This figure investigates the best times required to detect the presence of PUs within the channel at different SNRs. With the goal of achieving a substantial level of throughput, the period spent sensing is required to be short. This allows for a more extended period of transmission. It is initially assumed that half the time of a frame is used for sensing, the value of X is gradually varied up to 10,000 micro seconds. When the optimized throughput value is achieved, the time spent sensing is plotted for the given SNR value. From the plot, it is deduced that time spent in spectrum with low PU SNR. This is because it takes longer time to decide if such signal is PU or noise. As the PU SNR improves, lower time is expended on sensing hence the improvement in throughput as noticed earlier in figure 3.2.

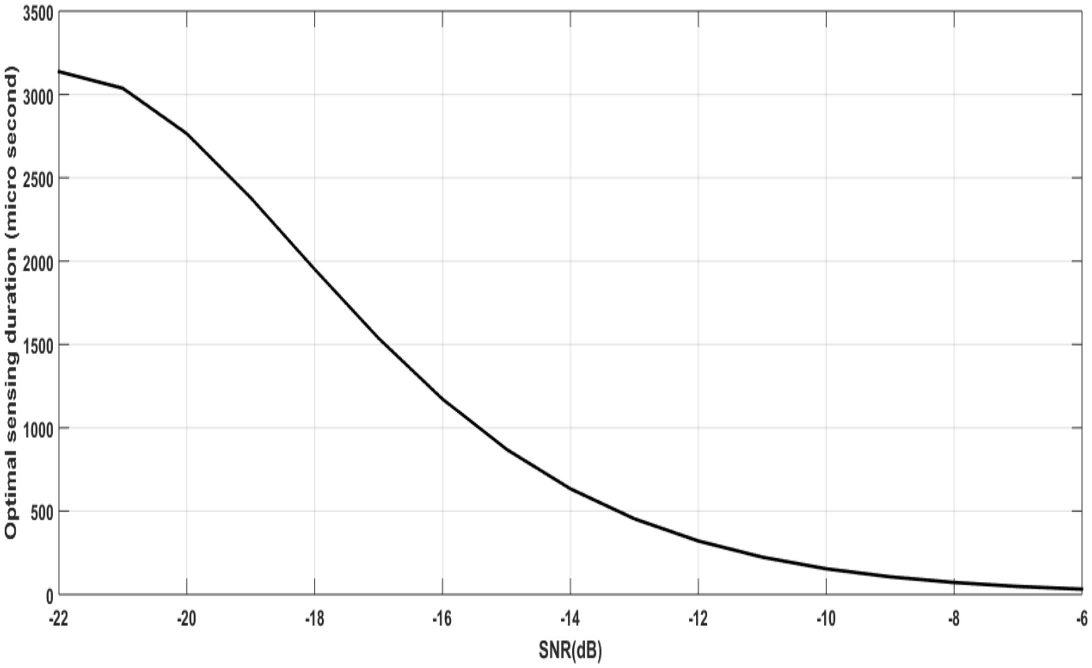

Figure 4.3 Optimal sensing duration against SNR n= 20.

Figure 4.4 depicts the aggregate throughput of the SUs plotted against the sensing time at $\gamma_p = -15dB$. This is a measure to investigate the performance of the model when more time is spent sensing. Again, the sensing period is varied to a maximum of 10ms and, the throughput plotted for the optimal k, the AND fusion rule and the OR fusion rule.

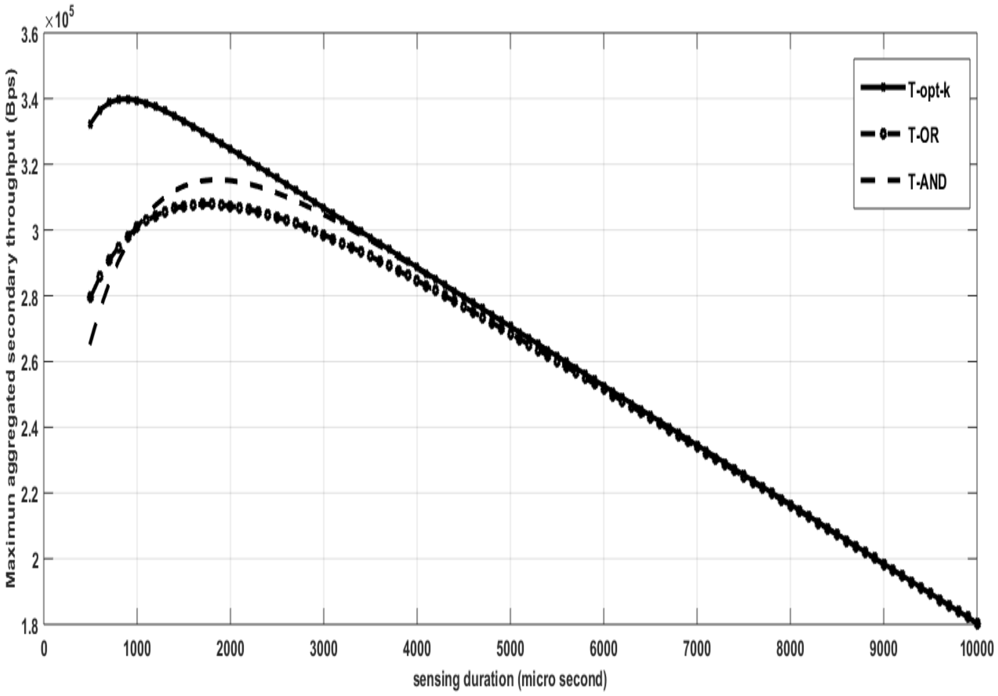

Figure 4.4 Throughput vs sensing duration $\gamma_p = -15dB \ and \ n = 20$.

As the period spent sensing increases, the performance of all rules converges to the same. This shows that, if much time is spent in the sensing phase, the decision rule exhibited by the fusion centre does not matter. This is because it becomes easier to identify PU signals. Therefore, every SU within the cell would report same decisions. The drawback here is that there is a reduction in the transmisson period, thereby reduction in throughput. In the figure, almost 50% of the throughput has been lost by 10ms.

Figure 4.5 shows the achievable aggregated throughput when the number is varied from 20 to 45, and a comparison is made against the earlier stated fusion rules. When the number increases, the level of contention increases and the rate of collision of packets also increases. This means the interference in the channel increases. This impacts the throughput negatively. As seen in figure 4.5, as the number of SU increases, the throughput reduces as packets are lost to the collision.

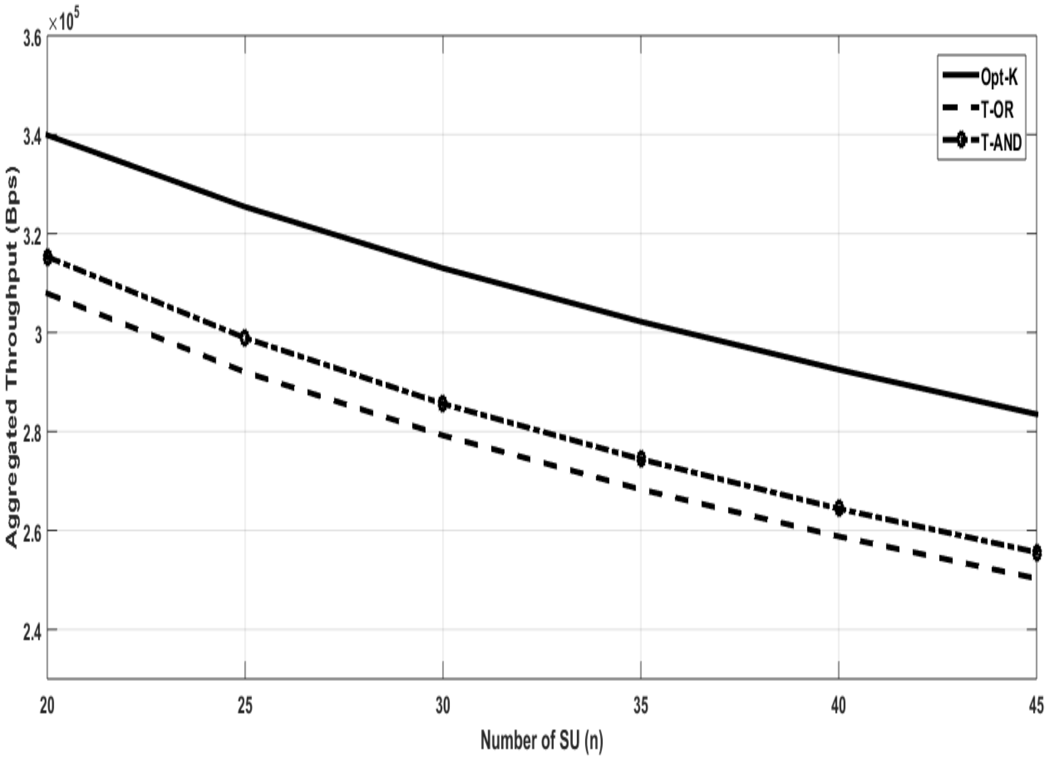

Figure 4.5 Aggregated throughput against number of radios at $\gamma_p = -15dB$

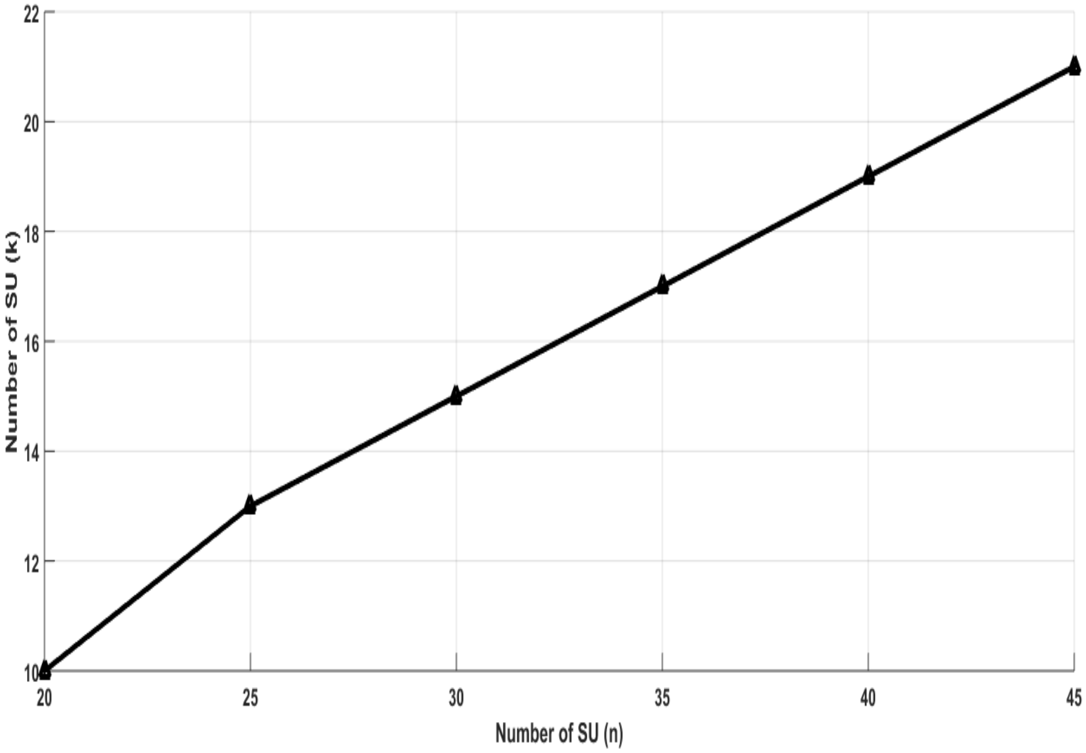

Figure 4.6 Number of SUs required for Optimum Throughput at $\gamma_p = -15dB$

The number of SU decisions required to achieve optimum throughput is investigated in figure 4.6. The percentage of SUs required to detect the presence of PUs correctly gradually reduces from 50% at 20 SUs to 46% at 45 SUs. It can be deduced that the fusion centre can make the correct sensing decision when it receives correct data from 50% of the SUs within the coverage area.

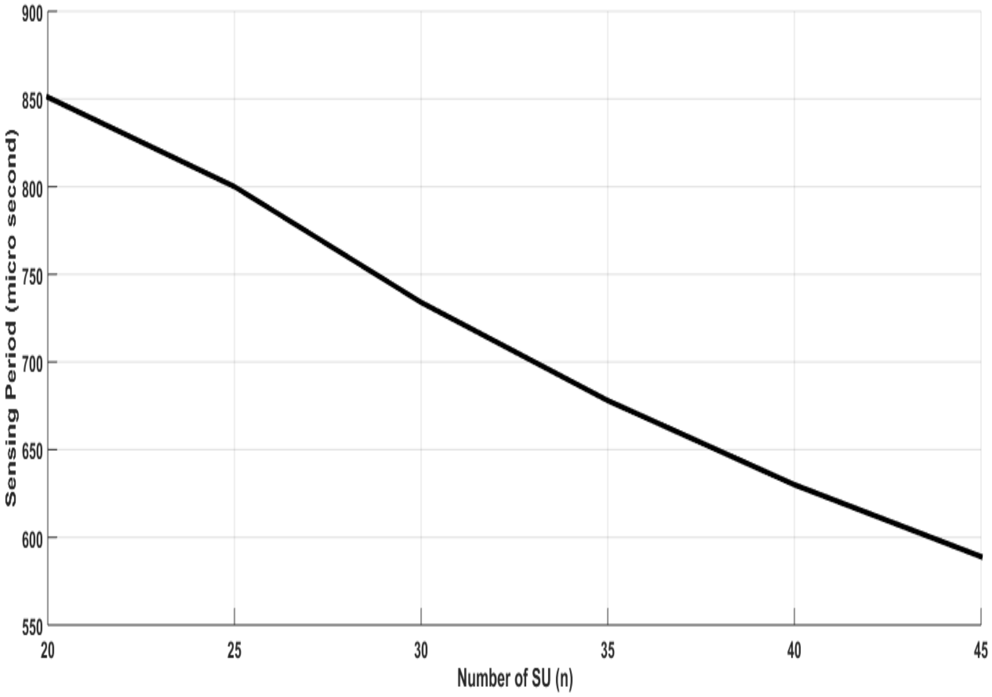

Figure 4.7 Sensing period required by radios at $\gamma_p = -15dB$

It is also noticed that when the number of SUs is also increased, the time spent for sensing could be reduced. This is because the problems such as hidden PU nodes are reduced as there will always be an SU that identifies the PU. This could help if the collision rate can be reduced. If packet collision rate can be reduced, there could be an increase in the throughput achieved. One possible way of doing this will be to increase the size of the contention window. Figure 4.8 shows the graph when the contention window is increased from 16 to 32. It is observed that the value of aggregated throughput shows a marked increase. The problem here is with the increase of the window; it does not offer any means to solve the throughput lost to collisions between SU-SU transmission or SU-PU collision. There is also a high chance of false alarm as SU may detect contending SU and report it as PU signals.

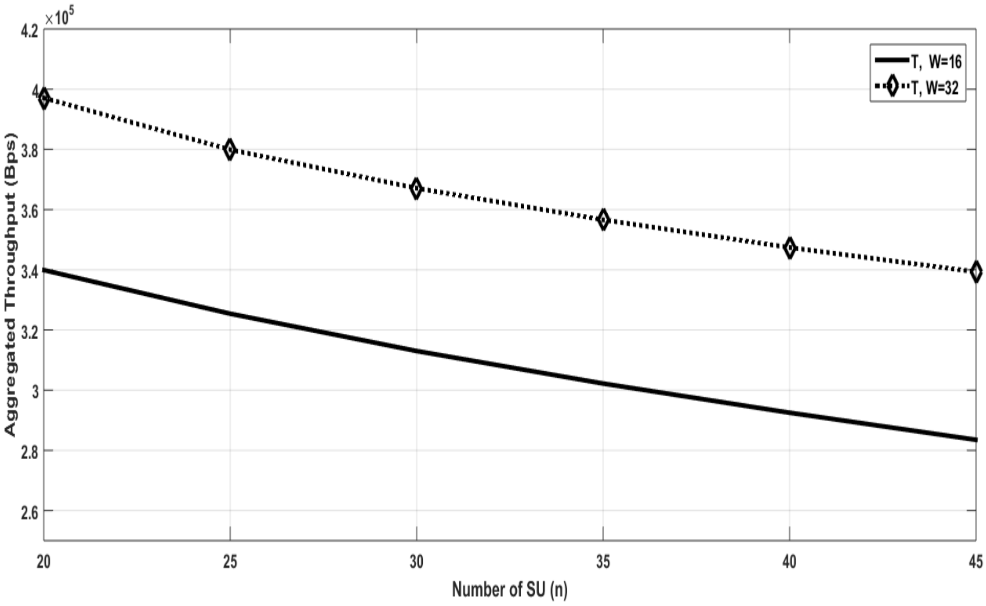

Figure 4.8 Aggregated throughput against number of SUs at $\gamma_p = -15dB$ when contention window is increased.

4.7 Summary

A sensing-throughput is presented in this chapter using cooperative sensing. The chapter uses the k-of-n fusion decision criteria to detect the presence of PUs within a channel using energy detection technique.

The fixed frame is used for sensing and transmission, so maximisation of such frame is critical to achieving substantial throughput. By exploiting slotted aloha together with a back-off counter, the throughput of the channel is investigated.

Since interference to PU is key to the deployment of Cognitive Radios, the interference introduced to the channel is used as constraints to solve the throughput maximisation problem. It can be deduced that for optimal performance, the fusion centre only requires the decision of less than 50% of the SUs within the channel depending on number of SUs withing the channel.

Chapter Five

Non-Cooperative Power Control Game for Cognitive radio Internet-of-Things

5.1 Introduction

The demand for wireless service is currently increasing at a tremendous rate as stated earlier in chapter one but with this demand comes significant challenges. The primary challenge of providers is to provide excellent service irrespective of the increasing demand.

As these new services continue to increase, inefficient utilisation of spectrum is a significant problem for the providers. Dynamic spectrum management tools are being investigated to address this problem.

The major problem with deploying these dynamic spectrum access devices is that of mitigating the interference introduced to the spectrum by these devices. It should be stated that PUs were licenced bands without the intention of having dynamic users or SUs within their spectrum. CRs seeks to improve their performance by increasing their transmit powers. This increase in transmit power ensures CR can meet its quality of service, but damaging interference is introduced to PUs.

Power control has been introduced to prevent this damaging interference to PU. It seeks to limit the transmit power by CR while ensuring that the quality of service of the system (both CRs and PUs) are kept at acceptable levels.

5.2 System Model

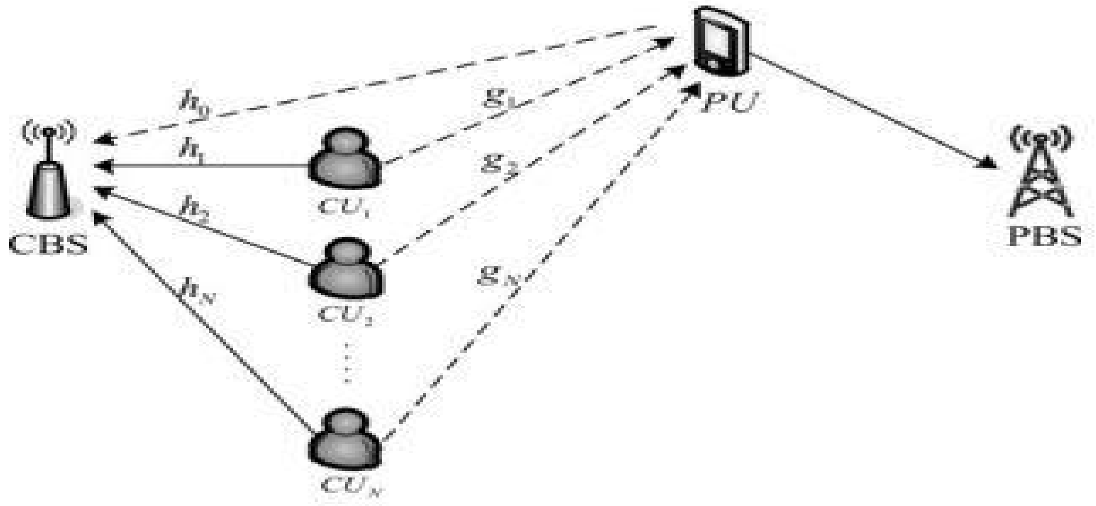

Figure 5.1 Model of CR network

The network investigated here involves a single cell scenario where *N* SUs with CR terminals are operating in a network with a Cognitive Base Station (CBS) together with one PU along with its Primary Base station (PBS). It is assumed that there is no channel gain between the SUs and the PBS, but there are some gains from the PU to the CBS denoted by h_i as shown in the Figure 1. The link gains from SUs to CBS are given by h_i, (i = 1……*N*) and the link gains g_i represents the gains from SU to PU. These gains show some form of interference from one device to another.

We focus on the uplink power control and assume that our network is a closed system. This means that the cell can only be associated with the predetermined devices and no new device can join the game.

The link gains are related to the path distances from the CBS by (Zhu et al., 2010):

$$h = Ad^{-n} \tag{1}$$

Where *A* is a constant gain factor and d is the distance from the CBS. If the power of the i^{th} SU is given by p_i and the power of the PU is denoted by p_0, then SINR of the i^{th} SU is given by (Guanglong et al, 2015):

$$\gamma_i = \frac{p_i h_i}{\sum_{j=1,j\neq 1}^{N} p_j h_j + p_0 h_0 + \sigma^2} \tag{2}$$

where σ^2 is an additive white Gaussian noise with zero mean and variance. To protect the SU and for a QoS, a SINR threshold is included such that:

$$\gamma_i \geq \gamma_i^{tar} \tag{3}$$

In (3) γ_i^{tar} is the SINR threshold for a QoS. If equation (3) is not violated, the system will guarantee the required QoS.

For the PU quality of service to be guaranteed, the interference (I_t) introduced by the CR must be lower or equal to the interference threshold (I_{th})of the spectrum but never above it.

$$I_{th} \geq I_t \tag{4}$$

$$I_t = p_i h_i \tag{5}$$

For this cell, the total interference on the reference CR (i) from all other radios and PU given:

$$I_{i(p-i)} = \sum_{j=1, j\neq 1}^{N} p_j h_j + p_0 h_0 + \sigma^2 \qquad (6)$$

The table below shows the other required setup of the game.

Table 5.1 formulation of a non-cooperative game.

Set of players	*I* = (1,2……*N*)
Strategy of players	*P* = $p_1 \times p_2 \times \ldots\ldots \times p_N$
Utility of players	$u_i(p_i, p_{-i}) = a_i \log(\gamma_i - \gamma_i^{tar}) + b_i\sqrt{p_i^{max} - p_i}$

The utility function is chosen such that there is an SINR requirement (γ_i^{tar}) for the CRs, such that it always seeks to achieve for successful transmission and a maximum allowable power constraint on the CR. These values are predetermined and known to the base station which relays them to the CR. The maximum power constraint stops any radio from surpassing the maximum power limit on the spectrum. This ensures that the maximum interference introduced to the PU is always below the required threshold. a_i and b_i are positive weighting factors which could be adjusted to adaptively control the power.

In iterative algorithms, the iterative power algorithm is deduced from the utility function. The iterative algorithm involves a manipulation of the first derivative of the utility function concerning the power of the reference CR.

$$\frac{\partial u_i}{\partial p_i} = \frac{a_i}{\gamma_i - y_i^{tar}} \times \frac{h_i}{I_{i(p-i)}} - b_i \frac{1}{2(\sqrt{P_i^{max} - P_i})} \qquad (7)$$

Setting the value of $\frac{\partial u_i}{\partial p_i} = 0,$ and making the γ_i the subject of formula, the equation becomes;

$$\gamma_i = y_i^{tar} + \frac{2a_i\, h_i}{b_i\, I_{i(p-1)}} \sqrt{P_i^{max} - P_i} \qquad (8)$$

Substitute $\gamma_i = \frac{p_i h_i}{I_{i(p-i)}}$ into the equation. This is just another variation of equation 2.

Then making p_i the subject of formula, the equation becomes:

$$p_i = \frac{I_{i\,(P_{-i})}}{h_i}\, y_i^{tar} \;+\; \frac{2a_i}{b_i}\sqrt{P_i^{max} - p_i} \qquad (9)$$

$$p_i^{m+1} = \frac{p_i^{(m)}}{\gamma_i^{(m)}}\gamma_i^{tar} + \frac{2a_i}{b_i}\sqrt{p_i^{max} - p_i^{(m)}} \qquad (10)$$

By equation 10, and to ensure that the iterative algorithm does not void the power constraint, the iterative algorithm can be written as:

$$p_i^{(m+1)} = \begin{cases} \frac{p_i^{(m)}}{\gamma_i^{(m)}}\gamma_i^{tar} + \frac{2a_i}{b_i}\sqrt{p_i^{max} - p_i^{(m)}} & p_i^{(m+1)} < p_i^{max} \\ p_i^{max}, & p_i^{(m+1)} \geq p_i^{max} \end{cases} \qquad (11)$$

The algorithm in 11 above will continue to iterate until the game comes to rest when convergence and Nash equilibrium is achieved. Moreover, the lower part of the algorithm puts a maximum power constraint on the CRs.

5.2.1 Nash Equilibrium of Game

As stated in chapter one, the Nash equilibrium of a non-cooperative game is that point where the players can no longer change the state of the game no matter the strategy they play. The Nash Equilibrium is known as the solution to the non-cooperative game.

At this point, the game reaches a state of convergence and all the players have played their strategy and can no longer influence the outcome of the game.

The criterion for analysing the Nash equilibrium of a game is given as:

Theorem 1: (existence): *At least one NE exists for the proposed game G if, for all i ∈ N(Li et al., 2011)*

- The transmission power p_i is a non-empty, convex and compact subset of some Euclidean space.
- The utility function $u_i(p_i, p_{-i})$ is continuous and quasi-concave in p_i

The first condition is met as the initial power levels for all CR are non-empty.

The second condition involves comparing the second derivative of the utility function to ensure that it is quasi-concave as the utility function is already continuous. The second derivative of is;

$$\frac{\partial^2 u_i(p_{i,}p_{-i})}{\partial p_i^2} = a_i \frac{-h_i^2}{(y_1 - y_i^{th})^2 \; I^2(P_{-1})} - b_i \frac{1}{\sqrt[4]{(p_i^{max} - p_i)}^3} \qquad (12)$$

As the second derivative shows, $\frac{\partial^2 u_i(p_{i,}p_{-i})}{\partial p_i^2} > 0$ which means the utility function is concave in p_i. This proves the algorithm has a valid Nash equilibrium.

5.3 Power Control adaptation for Cognitive Radios for the Internet-of-Things (IoT)

Internet technology initially based on human-to-human (H2H) communication is now seeing a paradigm shift with the inclusion of objects as machines or devices that can sense and communicate with each other. With such devices expected to surpass 50 billion by 2020 (Ali et al., 2015), machine-to-machine (M2M) communication is expected to be an essential element in future networks. Internet-of-Things (IoT) would be able to connect these different devices offering a whole range of new services. Therefore, a future network has to cater for various M2M requirements such as spectrum, power and cost. With a massive volume of devices anticipated to be connected, spectrum scarcity is a constraint that will influence the quality-of-service (QoS). Small cell design, the interconnection of the cellular network to other wireless networks and cognitive radio (CR) are some of the solutions that can address this problem (Tragos and Angelakis, 2013). Since CR offers a solution to increase the spectrum efficiency by allowing secondary users (SU) to access the licensed spectrum provided it does not cause interference or degrade the required quality of service (QoS) for the primary user (PU). It is increasingly seen as a viable solution for M2M in IoT (Aijaz and Aghvami, 2015b, Shigueta et al., 2014). However, as such opportunistic spectral access by CRs is likely to introduce some level of interference to the PUs and lower the QoS, the primary functions of a CR network is to provide transmission opportunities for SUs, lowering interference to the PUs and simultaneously ensuring an optimal QoS for all users. Maintaining adequate power control is therefore crucial for realising a CR network.

As the deployment of IoT would be across heterogeneous environments, e.g. factories, inaccessible and confined areas such as structural monitoring, free and urban spaces, this opens up various challenges for CR deployment. Diverse operating environments affect the wireless signal propagation which varies power received due to the isotropic power loss, reflection, refraction, diffraction and scattering. The combined effects of which are quantified as the power loss exponent *n*. Presently to our best knowledge, no study has investigated power control in CR in these diverse environments. The power loss exponent is generally taken as a fixed value of 4 assuming as the worst case in the cost function (Zu et al., 2012). Path loss exponent is a measure of how fast the signal attenuates as a function of distance. It is different for these environments in which the CR network would be deployed for which the values are given in Table 5.2. This chapter investigates power control in CR-IoT within these different environments and focuses on the underlay scenario where the PUs and SUs transmit simultaneously in the network.

Table 5.2 Path loss Exponents for different Environments (Miranda, J. et al., 2013)

Environment	Path loss Exponent, n	Path loss Exponent used
Line of sight, In Buildings	1.6 – 1.8	1.6
Free Space	2	2
Factory with Obstructions	2 - 3	3
Shadowed urban cellular radio	3 – 5	4

5.4 CR-IoT Network Model

The deployment of IoT across different environments require the use of adequate CBS with different ranges for transmission. These may include cognitive sensors (Vijay et al., 2015) deployed within homes with a range below 40m to central hubs in factories or sensors on streets and traffic lamps where the range could be ~ 500m. In this research, we consider a single cell scenario where *N* SUs with CR terminals are operating in a network with a CBS together with one PU along with its Primary Base station (PBS). It is assumed that there is no channel gain between the SUs and the PBS, but there is a gain from the PU to the CBS denoted by h_i as shown in the Figure 5.2. The link gains from SUs to CBS are given by h_i, (i = 1……N) and the link gains g_i represents the gains from SU to PU.

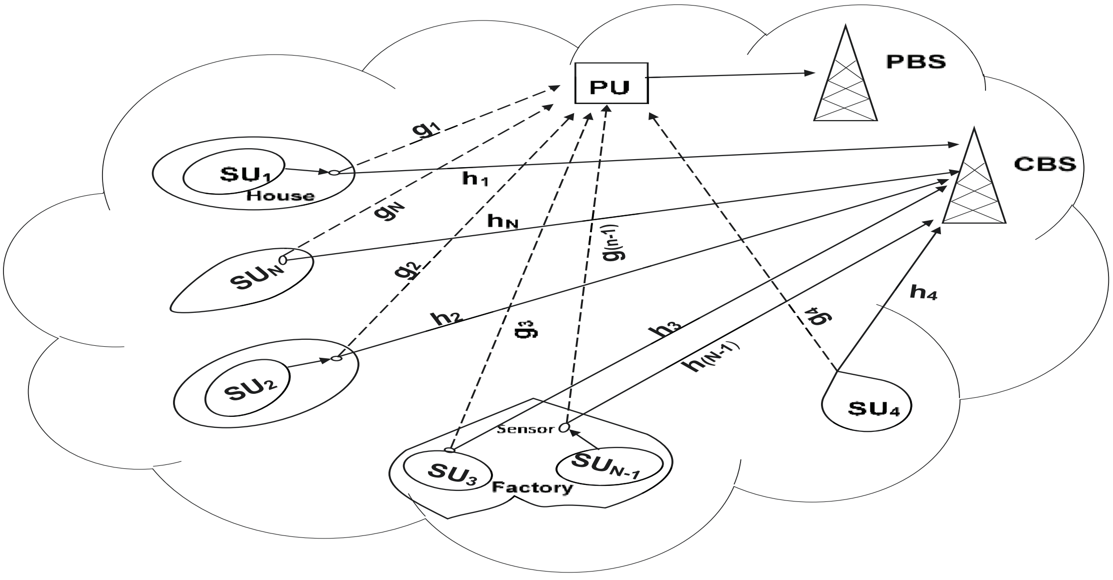

Figure 5.2. Model of the CR-IoT network

5.5 Simulation and Analysis for IoT

Simulations are taken in Matlab® R2015a for typical single cell network parameters. The CR-IoT devices are placed with fixed distances of 20m, 60m, 90m, 130m, 190m, 220m, 290m and 350m from the CBS. This should cover the operational distance of most CR deployed IoT devices such as wearable devices which should have a range under 50m to handheld two-way radios in factories. The noise power variance σ^2 = 5 x10^{-15} W. The PU transmission power p_o = 0.07 W and the SUs have an initial transmission power of p_i = 5 x 10^{-10} W. The maximum allowable transmission power of the i^{th} CR is p_i^{max} = 0.5 W. The SINR threshold is specified as γ^{tar} = 7dB and $2a_i/b_i$ = 3 x 10^{-4} as the initial value for iterations. The channel gains are given by (1), where A= 7.5 x10^{-3} and n = [1.6, 2, 3, 4] where each of the values represents the power exponents for various environments in Table 5.2. The transmit power of CR enabled IoT devices will be essential for the success of such technology. This is because CR devices will seek to improve its performance to optimal levels by increasing the transmitted power without regards to other users. The average transmitted power of a CR is crucial to the QoS for both the PU and SU. If the average power is too high, it introduces interference into the network which in turn causes a degradation to the QoS of the PU, if the CR transmits low power, its own QoS may be affected if the signals have a lower signal-to-noise ratio (SNR) for the required bit-error rate (BER) resulting in dropped calls and or failed data transmission. As battery life for IoT devices is limited, there is a need to ensure optimal transmission while preserving battery life in such devices. Figure 5.3 shows the average transmit power of the i^{th} SU as it varies with the environment within which the CR network is based.

The simulation shows different powers levels required for efficient transmissions while operating in different environments. This is because power degradation due to propagation losses are accounted for in the power loss exponents which the transmitted power has to overcome. It can be deduced from the plots that the proper selection of the power loss exponent is crucial for adequate power transmission and effective battery life in IoT devices. The IoT device operating in line-of-sight (LOS) doesn’t need to transmit with the power loss exponent for an urban cellular radio as this will result in higher transmitted power than what is required thereby reducing battery life. CR-IoTs should be able to adaptively select the power loss exponent based on its operational environment during sensing or initial link-up. Within the right environment, the CR transmit power may be reduced without affecting the QoS or the available power may be used to accommodate more SUs without causing disruptive interference to the PUs.

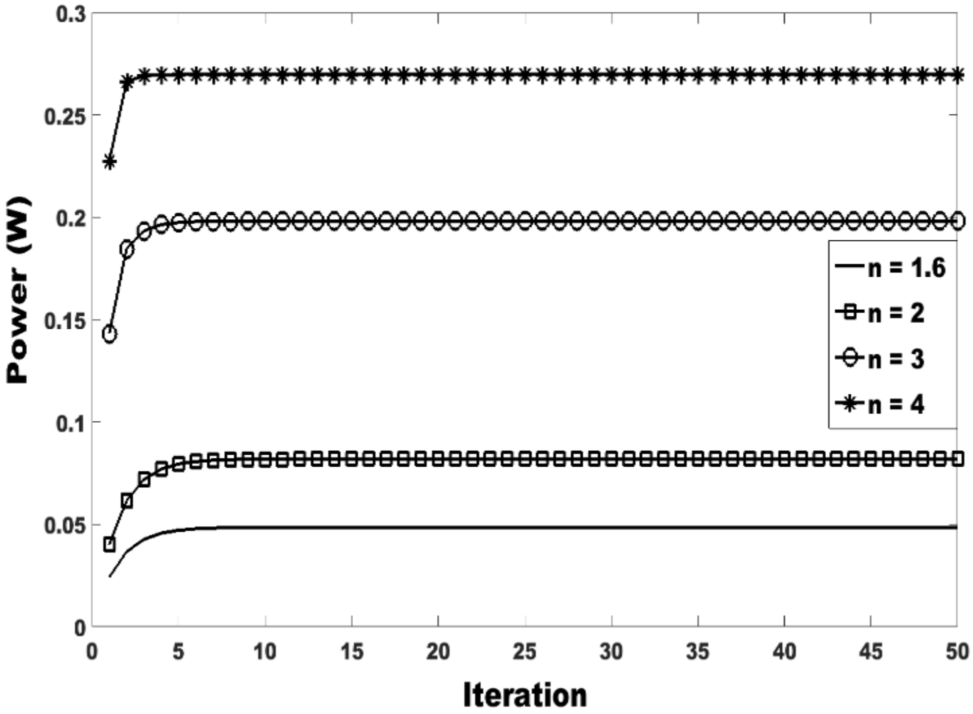

Fig. 5.3 Average Power required by the i^{th} cognitive Radio

There is a risk that reducing transmit power may result in failed transmission as the IoT devices may not have sufficient power to reach the required SINR for efficient transmission. In Figure 5.4, the average SINR of the SUs in the different environments are plotted. The plot shows that based on the fixed distance of IoTs devices in the network and for the correct path loss exponent, the performance of all the radios were all above the target SINR required to guarantee the QoS for both the PU and SU. This means that if the correct path loss exponent for the IoT device is selected, the non-cooperative game cost function via the iterative algorithm ensures the required QoS is met.

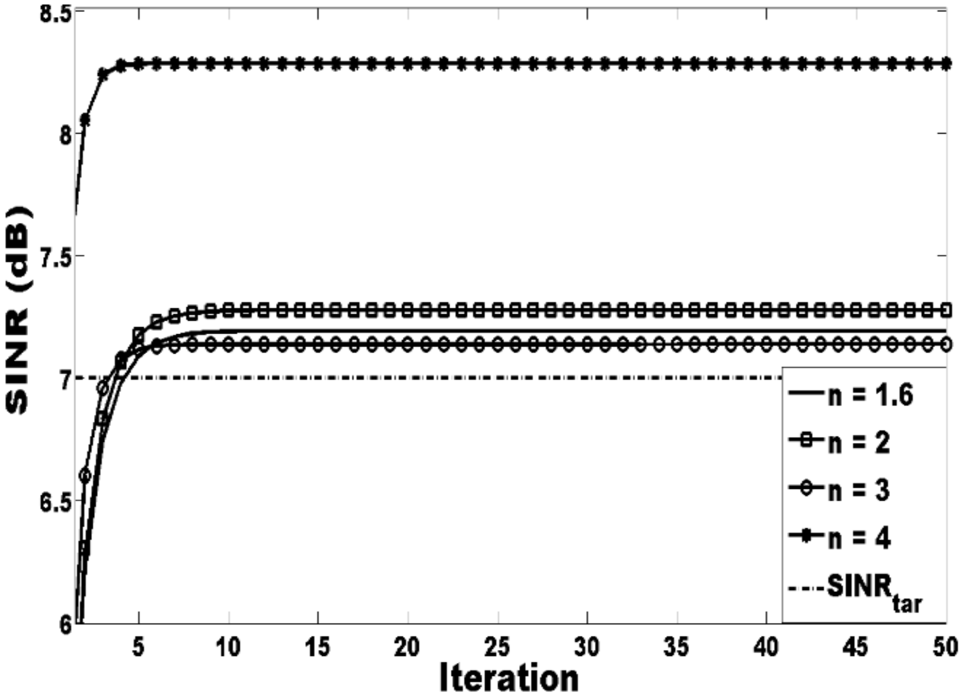

Figure 5.4 Average SINR of the i^{th} CR

Frequently, a single value of *n* as 4 is chosen irrespective of the operating environment of the IoT devices. This does not always guarantee an improved performance of the CR IoT network. IoT devices will be deployed over different environments. Therefore, the PU can be within any distance from the CBS. The effect of varying the PU distances over a range of 10m-150m on SINR is investigated for different environments, and its variation is plotted in Figure 5.5. This figure seeks to investigate the SINR constraint failure point for the simulated model. It is observed that the target SINR is achieved at distances of almost 30 m, 45 m, 70 m and 65 m for *n* = 1.6, 2, 3 and four respectively. If the PU is placed any distance lower than these points, the SINR constraints and the model SU cannot transmit successfully. As the distance increases between the CBS and the PU, the user case of *n* values crosses the target SINR to ensure acceptable QoS as seen in Figure 5.4. The increase in PU and CBS distances is because the IoT devices with higher *n* transmit at higher powers as compared to lower values of *n* as shown earlier. Thereby increasing the PU distances for the target SINR. After the crossover, the SINR increases at the fastest rate for *n* = 4 than for others.

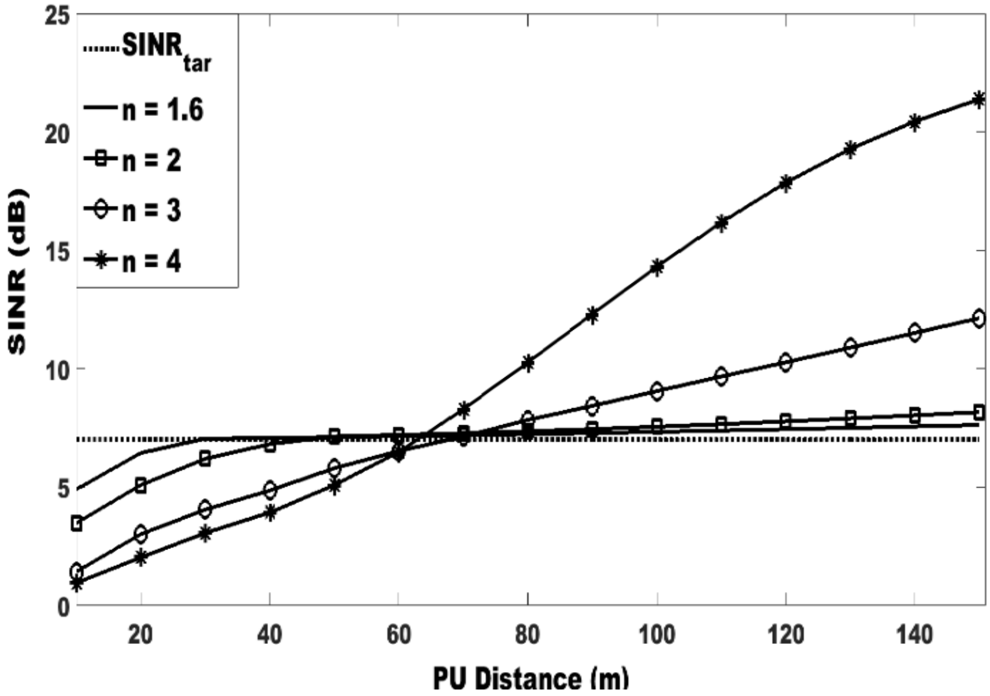

Fig. 5.5 Average SINR vs PU distances with fixed CR IoT distances

In Figure 5.6, the variation in power required for optimal transmission by the *i^th^* IoT device at various distances is given.

This shows the rate at which the transmit power of the *i^th^* CR increases concerning the distance of the *i^th^* SU for each environment. It can be seen that the power required to transmit signal increases at a faster rate as *n* increases. This is to ensure that the signal reaches the CBS without failure to overcome the effects of higher propagation losses. If the SU continues to transmit assuming a path loss exponent of *n* = 4 while being in the environment for *n* = 1.6, though the QoS may be met for both PU and SU, it would be transmitting at much higher power levels than required leading to excessive power usage and battery power drain.

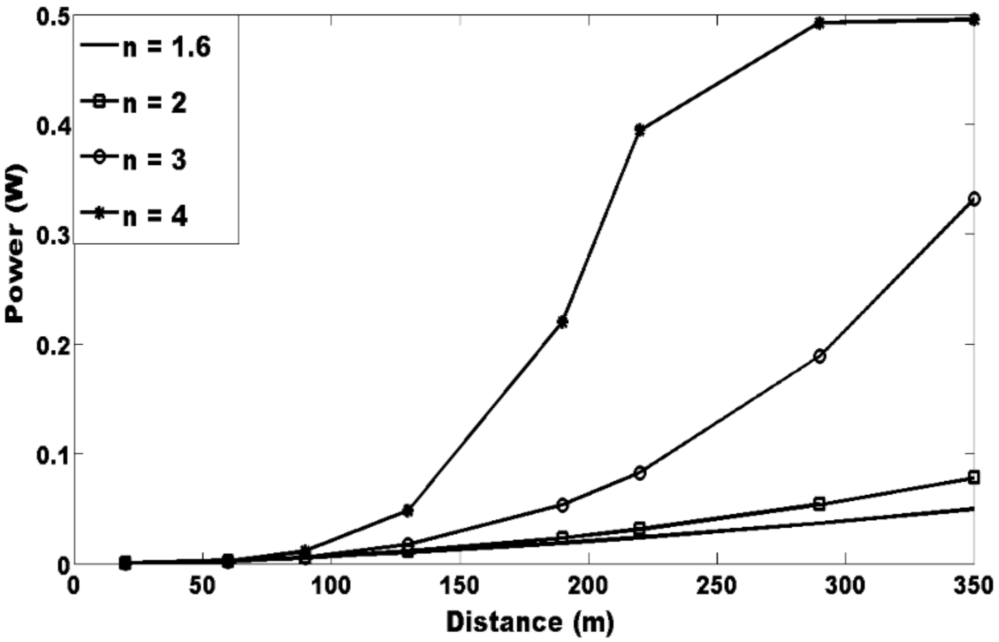

Fig. 5.6 Average Power of the i^{th} CU against Distance for each environment

5.6 Summary

Optimal power control in M2M for CR deployment is critical to realise the anticipated services in IoT. The environment where the CR operates is vital as different power levels are required to achieve efficient transmission. A CR should, therefore, be able to detect the best channel properties to ensure optimal performance at all times thereby improving the use of the spectrum. Environments with higher propagation losses will require higher transmit power to ensure the required QoS than those with lower losses. These diverse environments that affect wireless propagation can be modelled into the non-cooperative game cost function with an accurate power loss exponent relevant for IoT deployment, which will reduce battery usage, and is critical for IoT services as these are likely to be deployed on low/ultra-low power sensor networks. It can be deduced from the simulations above that CR-IoT devices will require adaptive power control based on the characteristics of its operational environments.

Chapter Six

Throughput in Interweave Cognitive Radio Networks

6.1 Introduction

The introduction of opportunistic spectrum access is intended to increase the efficiency of spectrum usage by allowing the reuse of licensed spectrum by unlicensed users. Cognitive Radios was initially expected to access the spectrum when the primary users are absent from the spectrum. An access technique known as an overlay spectrum access. However, with progress In research, cognitive radios have been shown to be able to access the spectrum while the incumbent signal is still occupying the spectrum. This technique is known as underlay spectrum access.

With the introduction of opportunistic access devices, the spectral usage is expected to grow above average. The challenge, therefore, is to improve the throughput of these cognitive radio devices.

To improve the throughput of cognitive radio systems, a spectral access technique which combines the two, which was earlier stated is recommended. This technique is known as the interweave access technique. In interweave cognitive radios, when the spectrum is detected as idle, the cognitive radio accesses the spectrum and transmits at full power. When the primary user returns, the cognitive radio has to ensure that its access to the spectrum is such that the quality of service of the primary user is not hindered. This is often achieved by reducing the transmit power of the secondary user. To achieve this, power control is often carried out. With the aid of power control, the cognitive radio readjusts its parameters such that its transmissions do not infringe on the performance of primary users.

6.2 Model of the Network

The frame-by-frame structure used in chapter 5 is used once again in this chapter. The difference is that it is assumed that the detection is carried out in a distributed manner, all decisions are made by individual CR so there is no decision phase.

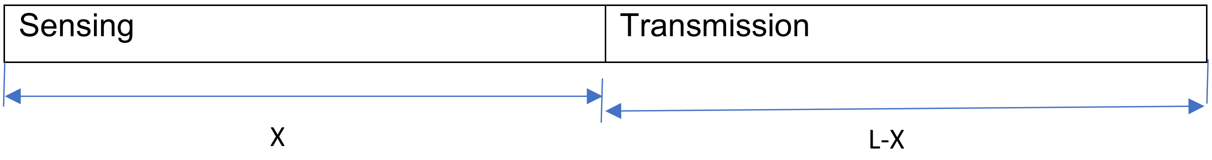

Figure 6.1 CR data Frame

Energy detection is used as the detection technique of choice. Let's consider a single cell cognitive radio network that operates in a closed system and no new cognitive radio can join the network like that in chapter 5. It is assumed that there is no channel gain between the SUs and the PBS, but there are some gains from the PU to the CBS denoted by h_i as shown in the Figure 1 of chapter 5. The link gains from SUs to CBS are given by h_i, (i = 1……N) and the link gains g_i represents the gains from SU to PU. This gain shows some form of interference from one device to another. It is also assumed that the SU on joining the network receive the detection threshold from the CBS. The maximum allowed transmit power in the channel is also given by the CBS. It is also assumed that there is no fading in the channel. Let the probability of the channel being busy be identical to the probability of idle and be represented as P_x.

The SU SNR is given as

$$\gamma_i = \frac{p_i h_i}{\sum_{j=1,j\neq 1}^{N} p_j h_j + p_0 h_0 + \sigma^2} \qquad (1)$$

The SUs in the network perform spectrum sensing and collects the spectrum statistics. The received signal is then compared to the threshold received from the CBS.

$$Y = \begin{cases} \sum_{i=1}^{I} {n_i}^2 & H_0, \\ \sum_{i=1}^{I} (x_i + n_i)^2, & H_1, \end{cases} \qquad (2)$$

The sensing- power modelled is performed in the format shown in the flow chart shown in figure 6.2

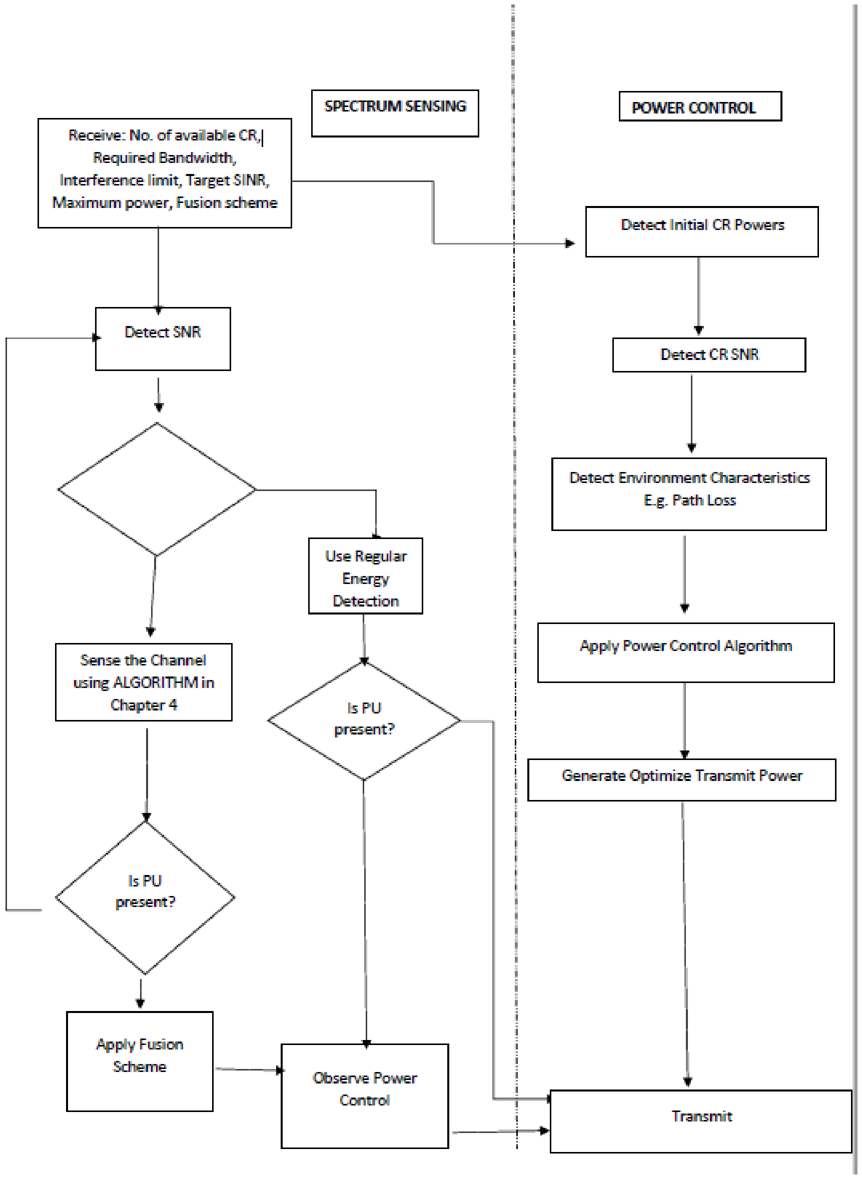

Figure 6.2 Flow chart of the interweave sensing

After performing sensing and decision are made, the CR sets its SNR and begins to transmit. It is assumed that transmit power control is performed at all times to keep the interference introduced into the channel to the barest minimum. This power control is to ensure that the channel will always be safe for the PU to come into it at all times.

In every sensing performed by ED, the probability of detection and false alarm cannot be avoided. Therefore, the probability of detection and false alarm are:

$$P_d(z,I) = P_r(Y \geq z|H_1) = \frac{1}{2} er\,fc\left(\frac{z-I-I\gamma_p}{2\sqrt{2}\sqrt{\frac{I}{2}+I\gamma_p}}\right) \qquad (3)$$

$$P_f(z,I) = P_r(Y \geq z|H_0) = \frac{1}{2} er\,fc\left(\frac{z-I}{2\sqrt{2}\sqrt{\frac{I}{2}}}\right) \tag{4}$$

Based on figure 6.1, the normalised throughput is:

$$G = R.(\frac{L-X}{L}) \tag{5}$$

Where R is the rate of transmission, X is the sensing period and L is the total frame time.

With the expressions of $P_d(z,I)$ and $P_f(z,I)$ known, the throughput of an interweave CR can be based on the sensing period is:

$$T = G.P_x.[C_i(1-P_d(z,I)) + C_b\left(1-P_f(z,I)\right)] \tag{6}$$

C_i is defined as the throughput of the cognitive radio in the absence of PU and C_b is the throughput of the SU in when the PU is active.

From equation one above, it is deducted that in the absence of PU, the P_o component in the SNR equation becomes zero, so the SNR becomes

$$\gamma_i = \frac{p_i h_i}{\sum_{j=1,j\neq 1}^{N} p_j h_j + \sigma^2} \tag{7}$$

The Shannon formula for capacity is used for throughput of cognitive radio as

$$C = log_2(1+\gamma_i) \tag{8}$$

The throughput is for when the channel is idle is given as then:

$$C_i = log_2(1+\frac{p_i h_i}{\sum_{j=1,j\neq 1}^{N} p_j h_j + \sigma^2}) \tag{9}$$

Moreover, the throughput for busy channel is:

$$C_b = log_2(1+\frac{p_i h_i}{\sum_{j=1,j\neq 1}^{N} p_j h_j + p_0 h_0 + \sigma^2}) \tag{10}$$

The aggregate throughput from equation becomes;

$$T = G.P_x.[log_2\left(1+\frac{p_ih_i}{\sum_{j=1,j\neq 1}^{N}p_jh_j+\sigma^2}\right)\left(1-P_d(z,I)\right)+\ log_2\left(1+\frac{p_ih_i}{\sum_{j=1,j\neq 1}^{N}p_jh_j+p_0h_0+\sigma^2}\right).\left(1-P_f(z,I)\right)] \quad (11)$$

For continuity, the non-cooperative game in chapter five is used for the power control.

The iterative power update formula is

$$p_i^{(m+1)} = \begin{cases} \frac{p_i^{(m)}}{\gamma_i^{(m)}}\gamma_i^{tar} + \frac{2a_i}{b_i}\sqrt{p_i^{max}-p_i^{(m)}} & p_i^{(m+1)} < p_i^{max} \\ p_i^{max}, & p_i^{(m+1)} \geq p_i^{max} \end{cases} \quad (12)$$

All conditions in chapter five remain the same.

6.3 Analysis and Simulations

The parameters for the simulation are given below.

Table 6.1 Parameters for simulation

Probability of Detection	$P_d(z,I)$	0.9
Probability of False Alarm	$P_f(z,I)$	0.1
Initial transmit power of CR	p_i	5×10^{-10} W
PU transmit power	p_o	0.07 W
Maximum allowed power	p_i^{max}	0.5 W
Target SNR	γ^{tar}	7dB
Noise power	σ^2	5×10^{-15} W
Attenuation constant	A	7.5×10^{-3}
Number of Sus	n	4
Transmission rate	R	10^6

Figure 6.3 below shows the simulated throughput of the Overlay and interweave network. Since overlay spectrum access occurs when the cognitive radio identifies holes and only accesses the spectrum when the spectrum is idle, C_i is used for the simulation.

From the figure, the improvement in throughput when cognitive radios employ power control is immense. Additional throughput may be significant in the case of broadband and TVWS spectrum.

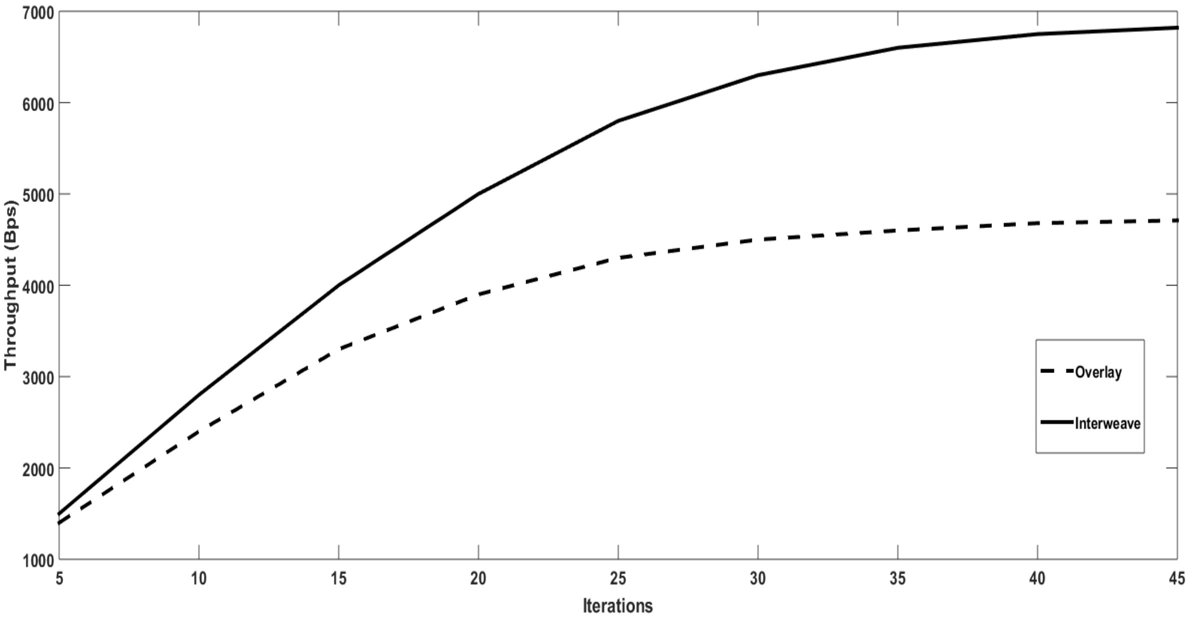

Figure 6.3 Comparison of underlay and interweave throughout

6.4 Summary

The interweave is a variation of CR access mode where the CR employs both the overlay and the underlay techniques. In this mode, the CR transmits at full capabilities when the PU is idle but at reduced capability when the the PU becomes active rather than vacate the spectrum. It can be observed from the graph that there is an increased throughput to be achieved when system is on interweave mode, but there is also an increased chance of causing damaging interference to the PU.

Chapter Seven

Evaluation

7.1 Introduction

The work reported in this thesis investigated the problems of spectrum access in cognitive ratio with emphasis on spectrum sensing and power control. In chapter 5, a non-cooperative power control algorithm based on game theory is proposed. This algorithm leverages on the path loss characteristics of different environment to reduce the transmit power of CRs within the game. This in turn improves coexistence between CRs and Pus, as lower transmit power introduces lower interference to the system thereby guaranteeing the quality of service is preserved.

This chapter evaluates the performance of the proposed algorithm by comparing its performance against two other power control algorithms.

The first algorithm is proposed in Koskie and Gajic (KG), 2005, and its iterative formula is given as:

$$p_i^{(m+1)} = \frac{p_i^m}{\gamma_i^m}\gamma^{tar} - \frac{b_i}{2a_i}\left(\frac{p_i^m}{\gamma_i^m}\right)^2 \qquad 1$$

The second algorithm is presented in Junhui et al, 2013 and will be termed as the revised SIR (RSIR). The iterative formula is given as:

$$p_i^{(m+1)} = \frac{p_i^m}{\gamma_i^m}\gamma^{tar} - \left(\frac{a_i}{b_i}\frac{p_i^{(m)^2}}{\gamma_i^{(m)2}}\right) \qquad 2$$

Both algorithms have shown significant performance levels in literature and evaluation will be carried out based on the following parameters.

1. Average power across all CRs: This informs about the power introduced into the network which can be used to deduce the interference introduced to the PU.
2. The rate of convergence: A good power algorithm should be able to achieve Nash equilibrium at a faster rate. This is to ensure protection to the PU. During the stage of the game before convergence is achieved, there is a period of chaos which all radios seek to transmit at optimum levels disregarding other CRs within the network.

3. Average SINR of the CRs: this is the measure of the successful transmissions. Certain target SINR must be achieved to ensure that CR transmissions successfully reaches the receiver.

These parameters will be recorded over three different scenarios created by varying different number of CRs within the network.

7.2 Results and Discussions

In this evaluation, the model is again a single cell network with an area of 50m by 50m. The positions of the CRs with respect to the base station is uniformly and randomly generated. These positions are used to generate the channel gain with the attenuation formula as shown in chapter 5. Pathloss exponent of 4 is used in both KG and the RSIR while the Non- cooperative game (NCG) model proposed in chapter 5 uses 2. The three scenarios are modelled as underlay networks as the PU and SUs share the network together (Scenario 1, 5 SUs. Scenario 2, 10 SUs. Scenario 3, 20 SUs.)

Table 7.1 Average Power of CRs

Average Power	NCG	KG	RSIR
Scenario 1 (10^{-3}w)	2.5	8.2	11
Scenario 2 (10^{-4}w)	5.1	9	14
Scenario 3 (10^{-5}w)	4.2	8	9

Table 7.1 shows the average power required by the SUs to transmit signals within the network after NE is achieved. From the table, it can be observed that the power requirement of the proposed algorithm is far lower than that of the other two algorithms. Such improvements on the others is replicated again in scenario 2 and 3.

Table 7.2 shows the SNR of the SUs in the different scenarios. In the first scenario, all algorithms transmit efficiently but as the strain of more CR devices join the network in scenario 2, KG begins to fail its QoS requirement even though it needs lower power to transmit than RSIR as shown earlier in table 7.1. By scenario 3, only the proposed NCG is still able to guarantee that quality of required in a CR network.

Table 7.2 Average SNR of SUs

SNR (dB)	NCG	KG	RSIR
Scenario 1	7	7	7
Scenario 2	7	6.8	7
Scenario 3	7	6.6	6.9

Table 7.3 shows the rate of convergence of each algorithm. This is a measure of the number of iterations it takes the game to achieve NE. It is further observed that the NCG takes the shortest period to achieve equilibrium. In the first scenario, its performance was more than three times better than the KG though the gap closes in the other scenarios.

Table 7.3 Rate of convergence

No of Iterations	NCG	KG	RSIR
Scenario 1	32	108	51
Scenario 2	25	73	39
Scenario 3	21	48	27

It should be noted that the rate of convergence of all the algorithms show a marked improvement when the number of CRs.

7.3 Summary

This chapter shows an evaluation of the power control game algorithm proposed in chapter 5. It evaluates the performance of the algorithm by comparing its performance against other algorithms while measuring key performance indicators like the average power required by SUs, the average SNR and the rate of convergence. The results show that the algorithm will be able to offer suitable coexistence between CRs and PUs as it outperformed the other existing algorithms in every area. It offers low power, stays within the required SNR requirement while ensuring a fast convergence.

6.1 Conclusions

The work reported in this thesis investigated the problems behind the slow implementation of cognitive radios. Cognitive radios, a device which will help improve spectrum usage efficiency by opportunistic access. The study provides an excellent overview of cognitive radios and the challenges to designing it. It further gives an overview of spectrum sensing, delving into narrowband sensing techniques and cooperative sensing as a means to solve problems suffered by conventional sensing techniques. It also looked into transmission power management this showed an overview of power management techniques used in cognitive radio systems to protect the licensed users from interference. The research also showed that the problem of implementing cognitive radios is wrought with loads of complexities, but by breaking them into smaller units, it is easier to create models to solve them.

To investigate spectrum sensing, the channel is modelled as a series of frames which over which the cognitive radio senses the channel, reaches a decision based on test statistics and then transmits on the channel if results show the channel as available. Slotted Aloha is used to derive the probability of transmission, and the throughput generated. The optimal k-of-n and optimal sensing time are found using a search algorithm.

To attend to the power control problem for cognitive radios, game theory is applied. Since in the network, cognitive radios will compete to send transmission without caring about the state of other cognitive radios, a non-cooperative game model is adopted in the research. The game is used to investigate the transmit power of cognitive radio devices based on fixed distances from the cognitive base station. The power control game was extended to accommodate cognitive radio based Internet-of-things devices. This device will be devices operating in short distances from their base stations, therefore, the need to use the appropriate path loss exponent.

The interweave cognitive radio systems involve cognitive radio systems that will operate both as overlay and underlay systems. They will be required for improved throughput in cognitive radios thereby increasing the overall efficiency of the operational spectrum.

6.2 Future Works

During the literal review, many problems were discovered. The thesis focused mainly on the spectrum sensing and power control in cognitive radio systems with the aim of improving the throughput of secondary users in the licensed spectrum.

Cognitive radio is paraded as an enabling technology for machine-to-machine communications devices such as internet-of-things. Which this research was able to postulate a way to handle the power control problem in cognitive radio based Internet-of-things devices. Future works from this chapter will involve the implementation of a power control system on field programmable gate array (FPGA). Such design should incorporate an adapting form which will be able to select the adequate path loss for the operational environment.

The IEEE802.22 standard allows Cognitive radios to be able to operate in the television white space (TVWS) due to its excellent propagation qualities. With current research focused mainly on databases for detection, a spectrum sensing algorithm which incorporates power control to ensure that the stringent requirement in TVWS are met.

Chapter 8

Conclusions, Recommendations and Future work

8.1 Conclusions

The work reported in this thesis investigated the problems in cognitive radios. Cognitive radios, a device which will help improve spectrum usage efficiency by opportunistic access. The study provides an excellent overview of cognitive radios and the challenges to designing it. It further gives an overview of spectrum sensing, delving into narrowband sensing techniques and cooperative sensing to solve problems suffered by conventional sensing techniques. It also investigated transmission power management, this showed an overview of power management techniques used in cognitive radio systems to protect the licensed users from interference. The research also showed that the problem of implementing cognitive radios is wrought with loads of complexities, but by breaking them into smaller units, it is easier to create models to solve them. Specifically, the main contributions of this thesis are summarised as follows:

- A novel cooperative sensing algorithm is presented in chapter 3 to investigate spectrum sensing and improve the throughput of the CRN. The channel is modelled as a series of fixed-time frames which over the cognitive radio senses the channel, reaches a decision based on test statistics and then transmits on the channel if results show the channel as available. The aim of this chapter was to improve the throughput of cognitive radio network investigating the loss of transmitted packets due to collision. To model this collision based cognitive radio network, slotted aloha, a collision-based model was implemented with a back-off counter to regulate the transmission of CR in the channel. Using probability, an optimisation to maximise the throughput is generated. As Interference mitigation is one of the major requirements of CR networks, the Interference limit is used as constraints to solve the optimisation problem. The optimal k-of-n values are gotten, and an optimal sensing time found using a search algorithm. It was discovered that the algorithm could guarantee optimum throughput values when at least 50% of the SUs correctly predict the state of the channel using energy detection.

- A novel power control algorithm is developed in chapter 5. To attend to the power control problem for cognitive radios, game theory is applied. Since cognitive radios will compete to send transmission without caring about the state of other cognitive radios, a non-cooperative game model is adopted in the research. The game is used to investigate the transmit power of cognitive radio devices based on fixed distances from the cognitive base station. The power control game was extended to accommodate cognitive radio-based Internet-of-things devices. This device will be devices operating in short distances from their base stations, therefore, the need to use the appropriate path loss exponent. With the right pathloss exponent applied in the appropriate environment as against the blanket value of 4 used in literatures, the transmit power of CR devices can be reduced. This reduction could be used to increase the capacity of the network, or to save battery life.

The interweave cognitive radio systems involve cognitive radio systems that will operate both as overlay and underlay systems. They will be required for improved throughput in cognitive radios thereby increasing the overall efficiency of the operational spectrum. As transmission is continued whether it is a white space or not, the additional time spent in the spectrum when the PU returns gives an improvement in throughput.

Chapter 7 is a validation chapter that compares the power control model in chapter 5 against two commonly used algorithm. Evaluation was carried out using 3 key performance indicators of average power, average SNR and rate of convergence. The indicators showed that the power control algorithm outperforms the other algorithms.

8.2 Recommendations

This research work has made great strides in CR as it has proposed means to improve the already vast archives of power control in cognitive radios. The idea suggested here if successfully implemented can greatly improve the transmit power problem in cognitive radios. Exploiting the pathloss exponent of adequate operational environment could offer new levels of success in search for viable power control in CR. Based on the performance of the model against other power control algorithm, it is recommended that the power control model based on environmental properties be adopted and means to improve on the model here be investigated.

Throughput in cognitive radios is a major concern as the optimum time to spend sensing and transmitting is a problem. The results indicate that throughput increase can be achieved when less than 50% of SUs report to the fusion centre with the correct detection result. It further shows the best possible sensing period for the spectrum. Based on the results I recommend this spectrum sensing-throughput algorithm for adoption.

8.3 Future Works

During this research, it was discovered that the impact of mobile CR devices is not covered in literature. Most research allocate positions to the SUs (including this work) and as such, it is not really known what happens when a SU moves from one point to another. What happens when an SU moves from the coverage area of one CBS to another? Is there some form of handshake? What is its impact on the other cognitive devices if it leaves after NE has been achieved? Does the game resume? How is the PU protected if a CR moves from a different location to its spectrum? If for one reason or another, the CR device is expected to change characteristics such as frequency, access technique and others in an instant, what is the impact it has on the existing CR network? All these have not really been covered in literature hence will provide a starting point for further research.

In furtherance of the work in this thesis, the CR must develop means to adequately determine environmental characteristics for adequate coexistence. In this research it is assumed that such details come from the CBS, how does the CR determine it is a line-of-sight setup and not an open space?

In theory it is easy to design interweave CRs but, how does the CR keep track of PU activity in the spectrum? If the SU was transmitting at full power in a spectrum, and the PU suddenly becomes active, how does the SU stop transmission before any harm is caused to the PU? If constant spectrum sensing is to be carried on such spectrum, can CR handle the computational complexity needed to analyse such data? Can there be ways to reduce it? In most researches, it is assumed the PU has low or no activity within the spectrum, but what if it’s not the case?

These questions all provide an avenue for future investigation to improve the work presented in this thesis.

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