Power Management in Cognitive Radio Networks

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Abstract

Power Management in Cognitive Radio Networks

Mahmoud Khasawneh

Recently, the demand for wireless networks resources is exponentially increasing over the world. This is because of the large increment in the web-services. In wireless networks, there are limited resources that can be used by different users for their data transmission to achieve their requirements of quality of service (QoS). The limitation of the available resources and the increment of the demands of these recourses lead to spectrum scarcity problem. To overcome spectrum scarcity problem, Federal Communications Commission (FCC) has already started working on the concept of spectrum sharing. In spectrum sharing the spectrum could be shared between both unlicensed (secondary users, SUs) and licensed (primary users, PUs) users, provided the SUs respect PUs rights to use the spectrum exclusively.

Cognitive technology is considered as a promising technology for spectrum exploitation dynamically. By integrating the capability of the cognitive technology in the traditional wireless networks, the spectrum scarcity problem can be solved. Spectrum sensing and trading are considered as the two main functionalities of cognitive radio technology. Much power is consumed in broadcasting the spectrum sensing results. The issue of power trading is considered as a new research topic in the area of cognitive radio network wherein licensed users lease their spectrum channels to unlicensed users in terms of power levels to use for their data transmissions.

In this work, we manage the power in wireless networks by applying the concepts of the cognitive technology. In particular, we manage the power firstly in the spectrum sensing process specially in the way of exchanging the sensing results; we utilize the concepts of clustering, sureness, voting, and cooperation to develop a model that decreases the power consumed in exchanging the sensing results between the sensing nodes (SUs).

Secondly, the power is managed in the spectrum trading and access functionalities. The users in the wireless networks use different power values in their data transmission; in order to manage these values dynamic power management models are developed. Then the Game Theory is applied to develop a new model for better power management, which leads to a Nash equilibrium (NE). In our proposed work, the licensed users (primary users PUs) trade the unused spectrum to unlicensed users (secondary users SUs). For this sharing paradigm, maximizing the revenue by trading the power is the key objective of the PUs, while that of the SUs is to meet their requirements and obtain service from the rented spectrum. These complex conflicting objectives are embedded in our power trading models.

Acknowledgement and/or Dedication

All praises be to "ALLAH" Almighty who enabled me to complete this task successfully and my utmost respect to His last Prophet Mohammad (S.A.W.). This thesis would have never been completed without the will and blessing of Allah, the most gracious, the most merciful. AL HAMDU LELLAH.

First of all, I thank my family for their constant moral support and their prayers. They are the people who are the closest to me and suffered most for my higher study abroad. Their support was invaluable in completing this thesis.

Next, my gratitude to my supervisor Prof. Anjali Agarwal, whose constant encouragement and guidelines at each step made this thesis possible. I am very grateful for her motivation and support throughout this endeavor. Deepest thanks also to my thesis examiners, Dr. Roch Glitho and Dr. Dongyu Qiu whose valuable comments improved the contents of my thesis. Moreover, I would also like to express my appreciation to Dr. Marzia Zaman and Dr. Venkat Narasimhan, who are a full researcher of Cistel Technology Inc. Ottawa, Canada. They were my advisors in this research work as an industrial partner for the MITACS – Accélération Québec Funds to whom I am grateful for providing me the financial support.

I dedicate this thesis to my aunt Tamam who sadly passed away in September 2012. She looked forward to see me finishing my Master's and PhD degrees and becoming a university professor.

During my stay in the university, I have made some great friends, especially, Sadeq, Fawaz, Ahmed, Suhaib, Ahmad, Mohammed, Abdel Rahman, Tareq, Rafat, Moayad, Masud, Mahmoud, Yousef, and Ismail. It will not be out of place to thank them for their support and encouragement.

Last but not least, I will not forget my research mate, Saed Alrabaee, who effectively contributed towards this project and provided very creative and constructive ideas and kept motivating me even after he finished his Master’s degree.

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Chapter 1: Introduction

Nowadays, people want to access the internet anywhere and anytime. This desire results in the increment of the spectrum demand. Meanwhile, the web-based applications are rapidly increasing. However, the spectrum resources are limited. Therefore, limitation in spectrum resources and high spectrum demand lead to spectrum scarcity problem.

In most countries over the world, spectrum is allocated to the licensed users exclusively. However, if the licensed users do not use this spectrum, it will be considered as used while it is actually unused (wasted). Recent spectrum utilization measurements have shown that the usage of spectrum is concentrated on certain portions of the spectrum while significant amounts are severely under-utilized. The Federal Commission Communication (FCC) chart shows that as in Figure 1.1 [1].

In order to increase the spectrum utilization in an efficient way, new spectrum sharing models must be produced. FCC allows sharing the spectrum among both types of users, i.e. the unlicensed users and licensed users while the unlicensed users respect the licensed users' rights.

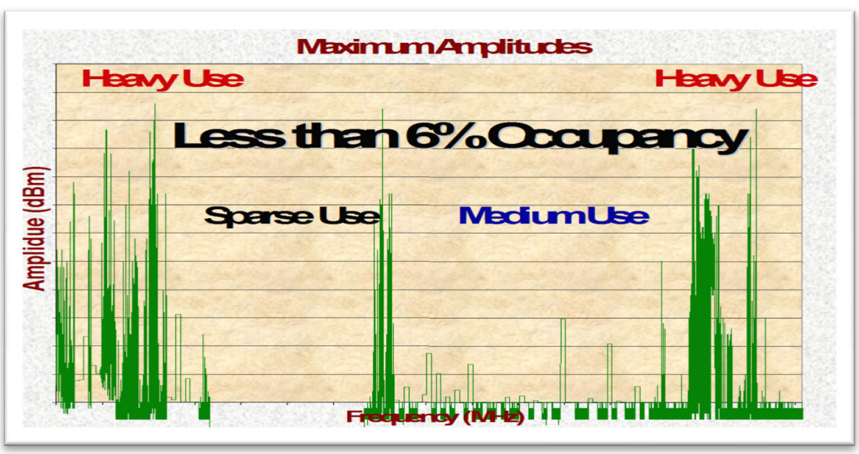


Figure 1.1: Spectrum Utilization [1].

Many solutions have been introduced to overcome the spectrum scarcity problem. Dynamic spectrum access (DSA) is one of them, wherein the spectrum is dynamically utilized. It enables users to adjust communication parameters (such as operating frequency, transmission power, and modulation scheme) in response to the changes in the wireless environment [2-4].

DSA enables implementation of Cognitive Radio (CR) that brings a promise to increase spectrum utilization at a minimum cost by using licensed spectrum whenever spectrum owners do not use it. Cognitive radio brings a revolution in the field of wireless networks because of its characteristics which grant the unlicensed users the opportunity to utilize the spectrum bands of licensed users when they are not in use.

Two types of users are defined in CR: the licensed users which are referred to as primary users (PUs) and unlicensed users which are referred to as secondary users (SUs). The PUs get the spectrum bands from their service providers and then they have the ability of using the bands whenever they want while the SUs detect the absence/presence of PUs in their spectrum bands in order to use them.

Power is consumed when the spectrum is used by any type of user. This value of power should be in an acceptable range such that it does not affect the performance of the whole system. The spectrum owners (i.e. PUs) use the full capabilities of their frequency bands, while the secondary users (SUs) can use partial or full capability of the frequency bands of the PUs. The SUs can use low power levels to transmit over the frequency bands of the PUs. However, if they want to use the capabilities of the frequency bands, they should pay for that.

Spectrum trading is the process of leasing the frequency bands of PUs to SUs wherein the SUs pay for the usage of the bands, while the PUs allow SUs to use proper power levels to achieve the quality of service (QoS) of SUs and to not harm other users in the network. Meanwhile the PUs achieve high revenue from this lease.

The big challenge in CR is how to develop a model that represents the spectrum trading process. Any developed model should take the different goals of different users' types in consideration and make a balance between these conflicting goals.

Game theory is a tool widely used in wireless networks and in CR networks as well. More balancing between the different aims of the different users (i.e. PUs and SUs) in the CR network is achieved by applying the game theory.

Our main focus is to develop a model that balances these conflicting goals, and then apply the game theory concepts on the developed model so that a higher level of balance is achieved.

1.1 Cognitive Radio (CR)

The principle of Cognitive Radio (CR) was firstly mentioned and explained by Joseph Mitola [1]. Cognitive Radio is defined as an efficient technology that allows more users to use the available spectrum. It is a radio that can change its transmitter parameters based on interaction with the environment in which it operates. Two characteristics are identified from the previous definition, which are the cognitive capability and the reconfigurability [1]. Cognitive capability represents the ability of the radio technology to capture or sense the information from its radio environment. Through this capability, the spectrum portions that are unused at specific location or time can be identified, while the reconfigurability enables the radio to be dynamically programmed due to the radio environment.

As most of the spectrum is assigned to specific users which are called primary users (PUs), the most important challenge is to share the licensed spectrum between licensed users (PUs) and unlicensed users which are called secondary users (SUs).

Cognitive radio techniques provide the capability to use or share the spectrum in an opportunistic manner. The SUs have to detect the unused spectrum bands which are known as spectrum holes and this process is called spectrum sensing. Spectrum sensing is recognized as the basic functionality provided by CR. In the spectrum sensing process, the SUs should keep monitoring the channel(s) that are owned by the PU(s) and once one of them is free, the SUs can start using it. Despite the high power levels consumed during the spectrum sensing process, the spectrum sensing results should be accurate which helps the SUs in using the free frequency bands of PUs.

Our focus in spectrum sensing process is on how to find an efficient method to collect the results of the spectrum sensing process that reduces the consumed power during the process the sensing results exchange.

Another functionality provided by CR is the spectrum management wherein the SUs share the spectrum with the PUs in such a way that attains the above conflicting users' goals. It consists of many different issues such as: spectrum access, spectrum trading, and power control.

Spectrum access refers to the technique that is used by the users to access the frequency channels. An important issue arises here which is the interference level that should be in an accepted range to not harm the different existing users. The accepted range of the interference is defined depending on the spectrum access technique used by the spectrum owners (PUs) and spectrum buyers (SUs). Two different spectrum access techniques are defined in CR and based on them the spectrum trading process is defined. The first one is the underlay access technique wherein the SUs coexist with the PUs in the same channels, while the PUs use higher power level to transmit their data, SUs use lower power levels. In the second access technique which is the overlay access technique one type of users (i.e. SUs or PUs) fully use the spectrum channel (s) at a specific time.

Spectrum trading is recently recognized as one of the most important issues of spectrum management in cognitive radio networks, wherein the spectrum owners (PUs) try to lease some of their frequency bands to the secondary users (SUs) to use for their data transmission.

Each type of the users has different objectives through the trading process. On the PU side, they always look for achieving a higher profit from leasing their channels, while the SUs try to use the spectrum to achieve a higher Quality of Service (QoS) while at the same time paying less for that. The QoS on the SUs side is to achieve an efficient data rate to transmit their data transmissions while not harming the PUs and other SUs with a high interference.

The third issue in the spectrum management is the power control. It refers to the way in which both users (PUs and SUs) use proper power levels to transmit over the different spectrum channels. These power levels should be precisely chosen to avoid high interference level, which may lead to high noise with less spectrum utilization.

Power trading is considered as a new issue [22] to be addressed in CR network wherein the spectrum management and power control issues are merged together. The main focus of this thesis is to develop new approaches that consider the objectives of the different users and balance them.

1.2 Game Theory

Mathematical models and techniques developed in economics to analyze interactive decision processes, predict the outcomes of interactions, to identify optimal strategies [6]. Game theory techniques were adopted to solve many protocol design issues (e.g., resource allocation, power control, and cooperation enforcement) in wireless networks [6]. By using game theory, we can find many solutions for many issues appearing in a cognitive radio network (CRN), such as in spectrum sensing, power control, spectrum sharing, and spectrum trading.

The basic and one of the most important elements in the game theory is the notion of a game. In each game there are three components that represent the game which are the players, their action sets, and the payoffs.

1. Players: a set of rational actors who have their own interests.
2. Strategies: a set of actions that have to be applied by the players to achieve their interests.
3. Payoff/Utility: the outcome from playing the game.

In cognitive radio networks, the players are the users which are the PUs and the SUs. Each type of players (i.e. PUs or SUs) has its own strategy to choose, (which can be, for example, the assigned bandwidth, the spectrum price, power level to be used for data transmission, and so on) in order to achieve his payoff which could be high profit, high efficiency, less delay, low jitter, and so on.

By applying the concepts of the game theory, a balance is achieved between the different users of the network. The users always choose actions that do not affect the other users. The best actions used by the different users result in a balance point which is called a Nash Equilibrium (NE). It represents an outcome that results from the simultaneous maximization of individual payoffs.

There are many types of games that can be classified as cooperative or non-cooperative game. In a non-cooperative game, the interests of the rational players are in conflict, and each player has different strategies to apply in order to maximize its payoff, so each player plays in a selfish way. Therefore, the solution for that is a Nash Equilibrium (NE) where no user can unilaterally improve its payoff [6]. On the contrary, in a cooperative game the players have mutual benefits to cooperate, where each player will cooperate using its strategies to achieve its interests. Meanwhile, it cooperates in helping the other players to achieve their interests too.

Two games are widely applied in CR networks which are the Bertrand game, and the Stackelberg game. In Bertrand's game a player changes its behavior if it can increase its profit by changing its price, on the assumption that the other players' prices will remain the same and their outputs will adjust to clear the market. Stackelberg game is a one game mode that is used in CR area to represent the relation between the different types of users. Here one type of players (PUs) is assumed to be the leader of the game and the other players (SUs) are the followers who react to leader's action. The players (PUs and SUs) do not choose their actions simultaneously, only the leader (PU) performs an action and the followers (SUs) choose their actions based on their leader's action. This leads to an agreement that achieves both players' goals.

1.3 Motivation

Many factors motivate us to do a research in the area of cognitive radio networks mainly in spectrum sensing and spectrum management by power trading.

The main motivation in spectrum sensing is that most of the work that is done focuses on the physical issues of the spectrum sensing related to sensing of the vacant spectrum channels, where the distribution of these sensing results from the different SUs is power consuming. More efficient ways should be developed wherein less power is consumed during collection of the sensing results.

The main motivating factor is controlling the spectrum by power trading, which is less researched in the area of cognitive radio networks (CRN). The power levels are assumed as a highly sensitive issue during the data transmission over the spectrum channels, because if proper power levels are not used a high interference will affect the different existing users in the wireless network. Another factor is the limitation in the available spectrum with the rapid increase of the spectrum demand. In the past, the spectrum is assigned to a specific number of users for a long time period, but currently due to a large number of applications and users who want to use the spectrum, the users must coexist with the other users over the same or nearby channels and they will need suitable power values to transmit over these channels. Therefore, the issue of controlling these power levels arises. Since we trade the power between two different types of users (PUs and SUs), we need some tool to balance the goals of both of them, and game theory is one of the best choices to do that.

1.4 Problem Statement

The cognitive radio technology allows SUs to operate on the unused parts of the spectrum allocated to PUs. Due to the nature of radio networks, the users have the ability to sense the licensed channels. Therefore, different SUs may sense the same channel(s), which opens the door for using different power levels between SUs on one side and between PUs (spectrum owners) on the other side. For Secondary users, the power is consumed during the sensing and trading processes while for the primary users, the power levels will be traded but without causing a high interference that might reduce the data rate of their data transmissions. Therefore, the issues of power management in sensing and trading processes need to be considered. The problem can be divided into two parts: the first part is to find an efficient approach for spectrum sensing process that helps in reducing the consumed power during the results exchanged among the SUs. The second part is to obtain a dynamic model to trade the power between the PUs and SUs and applying the game theory for further enhancement.

1.5 General System Overview

This section presents the general form and assumptions of the system that is considered in this research. Figure 1.2 illustrates the network overview. There are two types of users in the network: primary users (PUs) $\{PU1 \ldots PU_N\}$, and secondary users (SUs) $\{SU1 \ldots SU_M\}$. PUs have licenses to access the spectrum, which they obtain from their service providers. SUs try to find vacant spectrum bands in order to use them for their data transmission. SUs buy the licenses from the PUs to start transmitting their data by using the whole capabilities of the spectrum channels, in other words, in a specific time and over a specific spectrum band, more than one user could be exist. Each PU divides its frequency band into different equal sized channels which have the same capabilities. Each channel has a unique ID within the PU range. SUs deal directly with PUs in order to rent some frequency channels from. We assume that SUs can sense the PUs' spectrum accurately, and all of them are trusted nodes.

There is a common pre-defined control channel that is used as a communication channel for many purposes as follows:

- To send the spectrum sensing results between the different SUs in the spectrum sensing phase.

- To send the channel request and response messages between the SUs and PUs in the negotiation through the spectrum trading phase.
- To send the assigning channel information from PU to SU in the spectrum allocation phase.

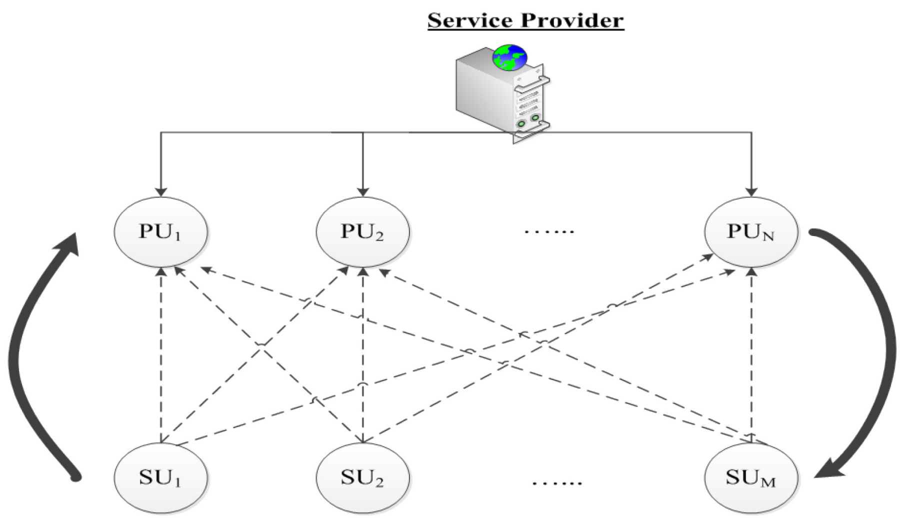


Figure 1.2: Network Overview.

The size for each channel is measured by hertz, while the channel capacity which represents the bandwidth or the data rate is represented by bits/sec. In order to measure the maximum rate (capacity) for each channel to be rented by a SU, we will use Shannon`s capacity law. Signal to Noise Ratio (SNR) value is important in doing the calculations of the channel capacity.

1.6 Objectives and Contributions of the Proposed Research

This section demonstrates the objectives and the contributions of this research.

1.6.1 Research Objectives

The general and principle objective of this research is to develop new methods and models in spectrum sensing and trading in order to increase the number of users that use the spectrum which results in more efficient utilization of the spectrum through power management. New mechanisms and methodologies are proposed that will consider interactions between the different users in the system which is able to handle the changes in the wireless environment.

The proposed work is based on two parts which are the spectrum sensing and spectrum trading functionalities of CR.

1.6.1.1 Research Objectives in Spectrum Sensing Phase

In spectrum sensing functionality, the proposed research aims at developing a model that achieves the following objectives:

- To reduce the power consumed in exchanging the results of the spectrum sensing phase.
- To improve the methods used in the spectrum sensing phase.
- To make the utilization of the spectrum more efficient.
- To reduce the time of the spectrum holes detection.
- To reduce the number of messages to be exchanged so only the helpful messages will be exchanged.

1.6.1.2 Research Objectives in Spectrum Trading Phase

Spectrum trading phase is assumed to be a major part in CR, where the proposed research aims in developing new models that attain the following objectives:

- To allow the users to use proper power levels for their transmissions; these power levels should not harm other users in the system.
- To increase the number of users that uses the spectrum.
- To consider the requirements of the SUs in CR networks.
- To enhance the efficiency of the spectrum utilization.
- To identify the different conflicting objectives of both types of the users in the CR networks.
- To make a balance between the conflicting objectives of the PUs and SUs by applying the game theory concepts.

1.6.2 Research Contributions

Cognitive Radio is considered to be a rich area for research, and much research has been done in this area. Most of the research that has been done in the spectrum sensing process was in developing different methods and approaches that consider the physical conditions of the sensed system. However, few researchers have discussed the issue of exchanging the sensing results between the SUs. Our goal in spectrum sensing is to reduce the power consumed during exchange of sensing results. In spectrum management functionality, few researchers have considered the issues of power trading and management in CR systems. Our goal in power trading is to propose complete models that help the PUs in trading their unused spectrum to SUs.

With these goals in mind, this research contributes in the following aspects of CR networks:

1- Proposing a new method of exchanging the spectrum sensing results which involves the merging of different spectrum sensing techniques and some general aspects from our life together (for example voting, cooperation, and sureness) to reduce the power consumed during the sensing process.

2- Developing a model that represents the power trading process in detailed steps.

3- Developing a power trading model by applying the game theory approach which takes the different users' requirements in consideration. This model helps each user to attain its own goals and achieves a balance between these goals in a way that no user can attain more utility over the other users.

1.7 Thesis Organization

The rest of the thesis is organized as follows. Chapter 2 describes detailed information about cognitive radio and how to apply the approaches of the game theory in CR networks. Moreover, a literature review of the research that has been done in the related areas of spectrum sensing and spectrum management is described. Our developed model for exchanging the spectrum sensing results is presented in detail and its performance evaluation is shown as well in Chapter 3. The developed models in spectrum trading process and their performance evaluation are shown in Chapter 4. Game theory concepts are also applied to the spectrum trading model in this chapter. In Chapter 5, the conclusion of the research is presented and some suggestions for future work are shown.

1.8 Summary

In this chapter, an overview has been presented on the cognitive radio and game theory. The objectives and contributions of the thesis have been presented as well. These objectives and contributions can be summarized as follows:

- Introducing the general concepts of the CR.
- Introducing the general concepts of game theory.
- Proposing a new method in spectrum sensing phase.
- Proposing a new model that shows the power trading process in detail.
- Combining the game theory concepts in the proposed model to develop a new scheme that shows the equilibrium points between the different users in the CR network.

Chapter 2: Background and Literature Review

In this chapter the issue of power management is addressed, with reviewing the researches that have been done in this area until now. The two most important functionalities of the cognitive radio (CR), which are the spectrum sensing and the spectrum (power) trading are described in detail. Applying game theory in spectrum (power) trading in CR networks is also explained.

Many researchers have developed different approaches in spectrum sensing and spectrum trading processes by using different tools, game theory being one of them. In this chapter we review them and use their work as a base for our approaches.

This chapter is organized as follows: first, the spectrum sensing functionality and the different applied methods are presented. Next, spectrum management is demonstrated. After that, spectrum (power) trading is described in detail. Applying the concepts of game theory in CR networks is shown. The chapter is concluded with a summary.

2.1 Spectrum Sensing

The PUs use the assigned bands of spectrum for their data transmission for a specific time and over a specific geographical area. These bands are divided into channels which have ability to carry data. When the PUs do not use these bands (channels), they create spectrum holes as in Figure 2.1. The purpose of SUs is to detect these spectrum holes in order to use them for their data transmission.

There are two ways to detect the spectrum holes. The first one is to detect the primary users that are receiving data. The second one is to detect the primary users that are transmitting data. In reality, however, it is difficult for a cognitive radio to have a direct measurement of a channel between a primary receiver and a transmitter. Therefore, the researchers in CR networks focus more on detection of the transmitter.

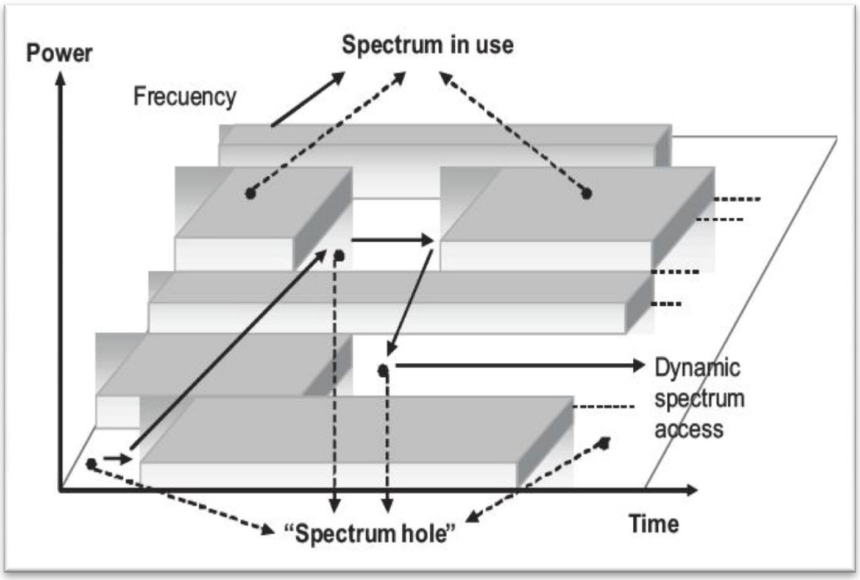


Figure 2.1: Spectrum Holes Concept [2]

Generally, the spectrum sensing techniques can be categorized as transmitter detection, cooperative detection, and interference-based detection [2] as in Figure 2.2.

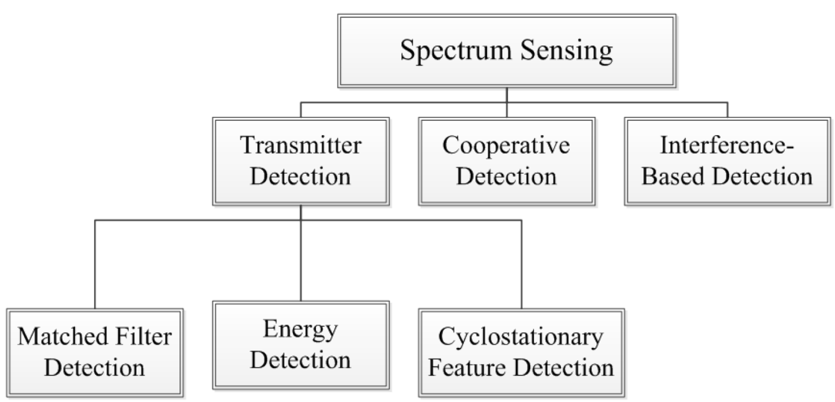


Figure 2.2: Classification of Spectrum Sensing Methods [2]

2.1.1 Transmitter Detection

In transmitter detection, the PU transmitter presence in its spectrum band is determined. Three schemes generally used for the transmitter detection are matched filter detection, energy detection and cyclostationary feature detection [2].

2.1.1.1 Matched Filter Detection

When the information of the primary user's signal is known to the secondary user, the optimal detector in stationary Gaussian noise is the matched filter since it maximizes the received signal-to-noise ratio (SNR) [2]. Figure 2.3 represents this technique where the received signal is sampled at time equal to T. These sampled signals are compared with a threshold value in order to make the final decision of the spectrum. The main advantage of this method is that it requires less time to achieve high processing gain due to coherency. However, the big disadvantage of this method is that it requires a priori knowledge of the primary user's signal such as the modulation type and order, the pulse shape, and the packet format. Hence, if this information is not accurate, then the matched filter performs poorly.

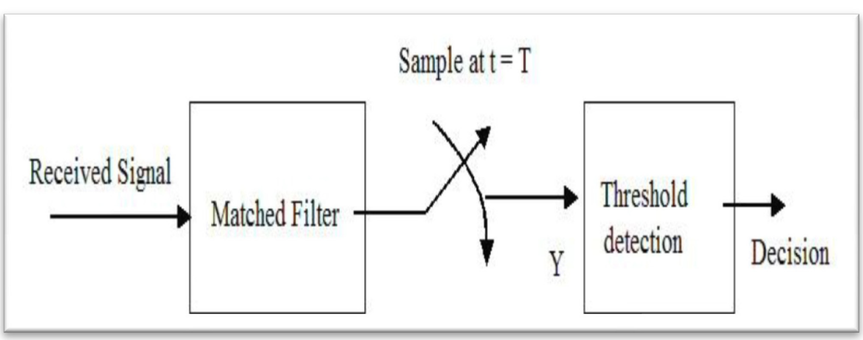


Figure 2.3: Matched Filter for Signal Detection [2]

2.1.1.2 Energy Detection

If the receiver cannot gather sufficient information about the primary user signal, for example, if the power of the random Gaussian noise is only known to the receiver, the optimal detector is an energy detector [2]. In order to measure the energy of the received signal, the output signal of band-pass filter with bandwidth W is squared and integrated over the observation interval T. Finally, the output of the integrator, Y, is compared with a threshold to decide whether a licensed user is present or not, as in Figure 2.4. However, the performance of energy detector is susceptible to uncertainty in noise power. In order to solve this problem, a pilot tone from the primary transmitter is used to help improve the accuracy of the energy detector in [2]. Another shortcoming is that the energy detector cannot differentiate signal types but can only determine the presence of the signal. Thus, the energy detector is prone to the false detection triggered by the unintended signals [2].

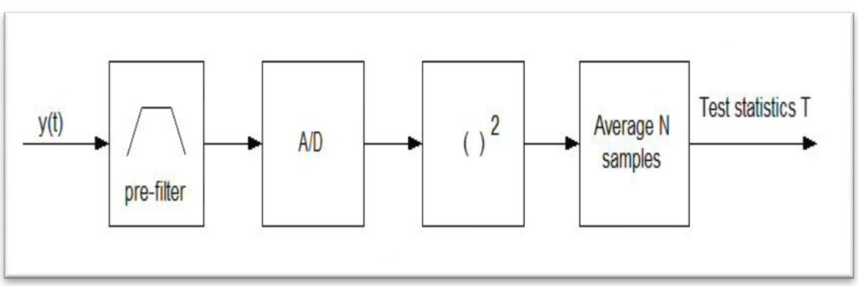


Figure 2.4 Energy Detection Method [2]

2.1.1.3 Cyclostationary Feature Detection

An alternative detection method is the cyclostationary feature detection [2]. Modulated signals are in general coupled with sine wave carriers, pulse trains, repeating spreading, hopping sequences, or cyclic prefixes, which result in built-in periodicity. These modulated signals are characterized as cyclostationary since their mean and autocorrelation exhibit periodicity. These features are detected by analyzing a spectral correlation function. The main advantage of the spectral correlation function is that it differentiates the noise energy from modulated signal energy, which is a result of the fact that the noise is a wide-sense stationary signal with no correlation, while modulated signals are cyclostationary with spectral correlation due to the embedded redundancy of signal periodicity. Therefore, a cyclostationary feature detector can perform better than the energy detector in discriminating against noise due to its robustness to the uncertainty in noise power [3]. However, it is computationally complex and requires significantly long observation time. For more efficient and reliable performance, the enhanced feature detection scheme combining cyclic spectral analysis with pattern recognition based on neural networks is proposed in [3]. Distinct features of the received signal are extracted using cyclic spectral analysis and represented by both spectral coherent function and spectral correlation density function. The neural network, then, classifies signals into different modulation types.

2.1.2 Cooperative Detection

Many factors affect the transmitter detection method which leads to reducing the efficiency of this method. With the transmitter detection, the secondary users cannot avoid the interference due to the lack of the primary receiver's information. Moreover, the transmitter detection model cannot prevent the hidden terminal problem. A secondary user transmitter may not be able to detect the primary user transmitter due to the shadowing. Consequently, the sensing information from other users is required for more accurate detection. The cooperative detection method is used to allow the secondary users to share their sensing results among other SUs which help in increasing the accuracy rate of the spectrum sensing results.

Cooperative detection can be implemented either in a centralized or in a distributed manner [4, 5]. In the centralized method, a central point, which may be one SU or a base station, plays a role in gathering all sensing information from the secondary users and detecting the spectrum holes. On the other hand, in distributed solutions each SU detects the spectrum holes and then exchanges the observations among all the secondary users.

Despite the big advantages provided by the cooperative detection technique, it has some disadvantages such as the traffic overhead resulting from the exchange of the spectrum sensing results among the different SUs in the network.

2.1.3 Interference Based Detection

The interference temperature model accounts for the cumulative radio frequency energy from multiple transmissions and sets a maximum cap on their aggregate level. As long as the secondary users do not exceed this limit by their transmissions, they can use this spectrum band. However, the most important issue is how to define this maximum cap of interference.

In [5], a direct receiver detection method is presented, where the local oscillator (LO) leakage power emitted by the RF front-end of the primary receiver is exploited for the detection of primary receivers. In order to detect the LO leakage power, low-cost sensor nodes can be mounted close to the primary receivers. The sensor nodes detect the LO leakage power to determine the channel used by the primary receiver and this information is used by the unlicensed users to determine the operation spectrum.

The SUs use any of the above methods for spectrum sensing. However, failure in spectrum sensing results might cause substantial interference for those who use the spectrum. On the other hand, wrong results of the spectrum sensing lead to inefficient spectrum utilization. The probability of getting correct sensing results is low, if the spectrum sensing is made by each secondary user individually. If the cooperation concept is applied among the different secondary users (SUs), this probability will be increased.

Cooperative spectrum sensing helps in achieving a higher accurate correct decision ratio. It alleviates the negative impacts on performance caused by multipath fading and shadowing [4]. It allows the secondary users to share their initial decisions about the vacant spectrum bands and then make their final decisions. Every participating user first detects the spectrum using any spectrum sensing method of transmitter detections methods such as matched filter, energy detection, or cyclostationary feature detection [5], and then they exchange their detection decisions. Despite the advantages of the cooperative spectrum sensing, it leads to power consumption. Mostly, for battery-operated mobile terminals, the power resource is limited. Few researchers have suggested solutions for this problem. In order to decrease reporting power consumption, a censoring scheme is studied in [7] and [8] by ignoring uninformative test statistics or local decisions. In [9], a time scheduling scheme is shown to decrease the number of local decisions.

In the above works, all secondary users' decisions are forwarded to a specific one receiver directly, but the distance between some SUs and the receiver might be long which might corrupt the sensing results and they become incorrect. On the other hand, their (i.e. some SUs) decisions are valuable for improving the spectrum sensing performance, since the increment in the number of participating SUs in the sensing will increase the accuracy of the sensing results. In order to guarantee correct transmission of their decisions to the receiver, more power is needed due to signal distortion and fluctuation with the communication distance increment. Moreover, if this receiver becomes inactive and the secondary users do not recognize that, they will continue sending their decisions without getting any reply which consumes more power and leads to low spectrum sensing efficiency.

In traditional broadcast scheme, each SU transmits its decision to all the SUs which has many disadvantages such as it consumes too much power in transmitting and receiving the spectrum sensing results, and takes more time too.

These two disadvantages motivate us to develop an approach that helps in reducing the power consumed during the exchanges of spectrum sensing results, by merging the concepts of the different spectrum sensing methods.

This research presents a new method of exchanging the results of spectrum sensing by combining the advantages of the different spectrum sensing methods, using the clustering concept, and general concepts from our life such as voting and sureness.

2.2 Spectrum Management

After the spectrum is sensed and the spectrum holes are defined by the SUs in the network, each SU wants now to start accessing the spectrum. The spectrum management is referred to as the way of sharing the spectrum between the primary and secondary users in such a way that do not harm each of them and sustaining a balance between them. There are three models to represent the spectrum sharing which are:

1- Public Commons Model

The radio spectrum is open to anyone for access with equal rights; this model currently applies to the wireless standards (e.g., WiFi and Bluetooth radio) operating in the license-free ISM (Industrial, Scientific, and Medical) band.

2- Exclusive Usage Model

The radio spectrum can be exclusively licensed to a particular user; however, spectrum utilization can be improved by allowing dynamic allocation and spectrum trading by the spectrum owner.

3- Private Commons Model

Different users in a cognitive radio network (e.g., primary, secondary, tertiary, and quaternary users) can have different priorities to share the spectrum.

Secondary users can access the spectrum using an underlay or overlay approach. In the underlay approach a secondary user spreads the transmission over a large bandwidth using low transmission power (e.g., ultra-wideband [UWB] transmission). In the overlay approach a secondary user accesses the spectrum in the frequency or time domain. While power control is crucial for underlay access, spectrum opportunity identification and synchronization are important for overlay access.

The private commons model is the model that represents the spectrum sharing model in cognitive radio networks. It is clear from this model that there are two techniques used to access the spectrum which are: underlay and overlay access techniques. Underlay technique is assumed as a horizontal sharing model, where the PUs and SUs have the equal opportunities to access the spectrum as in WLANS in ISM (industrial, scientific, medical) band. SUs choose the channel(s) with low traffic. PUs and SUs coexist in the system and use the band simultaneously, where SUs use low power levels that do not make interference to the PUs which owns the spectrum channels.

Overlay technique is recognized as a vertical sharing model, where the SUs have less preference over PUs, and the SUs cannot send while PUs are using the spectrum, they have to wait until the PUs are not using their channels and sense the spectrum holes, then they can send. The SUs must vacate the spectrum as fast as possible once a PU is detected.

2.2.1 Spectrum and Power Trading

Spectrum trading is the process of leasing spectrum from the licensed user (s) that own the spectrum to unlicensed users in such a way where predefined rules control the process.

Many objectives that could be satisfied from the spectrum trading process are:

- Allow the spectrum owners (PUs) to achieve some profit.
- Allow the unlicensed users (SUs) to use the spectrum for their data transmissions.

- Increase the efficiency of the spectrum utilization.

The most important concerns that appear in spectrum trading are:

1- Pricing: The value or worth of the spectrum to both the entities (i.e. the PUs and SUs) is determined.

2- Competition/Cooperation PUs or/and SUs. The competition between the PUs helps the SUs to get good spectrum bands with low prices while the cooperation between the PUs give them the opportunity to set a specific price and not to decrease this price in all circumstances as it happens in real market.

Recently, many researchers paid their attention to the economic aspect of dynamic spectrum sharing, which is also referred to as spectrum trading. In [10], authors discussed the concept of spectrum trading in the context of different spectrum sharing models, and outlined different forms of spectrum trading, the related research problems, and the different solution approaches. In [11], authors studied the spectrum trading with multiple PUs selling spectrum opportunities to multiple SUs. In spectrum trading, pricing is a major issue that determines the value (or worth) of the spectrum to the spectrum seller and buyer. In [12], an integrated pricing, allocating, and billing system was proposed for cognitive radio networks. In [13], a joint power/channel allocation scheme was proposed that used a distributed pricing strategy to improve the network's performance. The authors in [14] proposed different models of spectrum sharing and presented the issue of spectrum trading in these different models. While the authors in [15] discussed the spectrum trading process with presence of multiple PUs offer the spectrum and SUs require the spectrum. The game theory concepts have been applied in the context of CR networks. Pricing is assumed to be one of the most important issues in spectrum trading. In [16], the authors proposed a model that comprises three main issues which are the allocation scheme, the price of the offered channels and the way of collecting the rent value from the renting SUs. In [17], the performance of the network is improved by using a distributed pricing strategy which is the base of a joint channel allocation scheme. In [18], a new model of bandwidth auction is considered as a solution to the dynamic spectrum sharing problem. In [19], the problem is formulated as that there are many users who use spread spectrum signaling to share the spectrum, and the solution was by developing an auction mechanism. In [20], multiple PUs and SUs use the auction mechanism for the spectrum sharing purposes. In [21], a power control solution based on a game theoretical framework for wireless data networks is presented. It is helpful in a heavily loaded network. In [22] the authors propose a power to price model in the presence of competing PSPs. In that model a new network element (TCA) is introduced to be responsible for power and price calculations. However, the previous work [22] done in 2011 is considered as the first attempt to trade the power in cognitive radio networks (CRN).

The drawbacks of this model are: first, TCA cannot provide service for free; therefore a cost should be paid by PUs to get TCA's services which were not considered in PSPs' profits calculations. Second, more overhead and time will be consumed due to the communication between the TCA and PSPs.

This research trades the power wherein the PUs sell their spectrum bandwidth to the SUs by allowing them to use power levels for their data transmission.

2.3 Game Theory in CR

The concepts of game theory were initially raised in economy, which can be defined as following. Mathematical models and techniques developed in economics to analyze interactive decision processes, predict the outcomes of interactions, and to identify optimal strategies [23].

Many researchers have studied the power control problem in wireless networks and have tried to develop different models by using game theory concept. In [24] the authors used non-cooperative game approach to model the power control problem in wireless networks wherein the utility function of the players (users) is defined as a ratio of throughput to transmission power value. A few motivations are proposed in [25] to apply game theory concepts in CR networks. In [26] a pricing function is set by authors in order to attain more capable solution for the power control issue. The authors in [27] and [28] tried to use the concept of the signal to interference ratio (SIR) to define the utility function of the spectrum users. In [29] the existence of both types of users (PUs and SUs) was discussed under interference temperature constraints. The authors in [30] have chosen an exponential function of price among the different secondary users to model the power control issue. In [31], both SUs and PUs are considered as game players where they make their own decisions. The utility function of PU is to get money by allowing the SUs to use the spectrum channels without harming other users by a high interference value which is greater than a threshold value called interference cap (IC). However, none of these models [26-31] consider the issue of maximizing the profit of the spectrum owner (i.e. PU) and specifying the best value of the transmission power to be used by the SU.

This research proposes a new model wherein the game theory concepts are used to play a game between the PUs from one side and SUs from another side. The PUs aim in achieving high profit from leasing its spectrum to SUs that aim in using proper power level to use the spectrum for their data transmission.

2.4 Summary

Power management is a challenging problem in cognitive radio network. Spectrum sensing is the first step in CR and if it is properly done, the next steps will be correctly done. The SUs always want to use a good mechanism in sensing the spectrum, so they can get accurate sensing results. However, this mechanism should not consume too much power and should give accurate sensing results.

Spectrum trading is an interesting but a challenging topic in CR networks. Many characteristics can be used to evaluate available channels. These characteristics include noise, interference level and wireless link errors. Combining these factors in a decision function is a challenging problem. New approaches should be developed to combine these factors together in order to achieve the different objectives of the users in the system. Trading the power is assumed as a new idea in CR networks, wherein the channels` owners lease power level to unlicensed users.

Game theory is assumed to be an effective tool to be used in CR networks in order to improve the spectrum trading (i.e. power trading) process. It helps in accomplishing a balance between the different users of the network.

Chapter 3: Power Management in Spectrum Sensing

In this chapter a new mechanism is proposed as a solution for the power consumption issue of the spectrum sensing functionality in Cognitive Radio networks (CRN). Moreover, this mechanism meets the different requirements of both the users in the network (PUs and SUs) defined later in section 3.1. It helps to reduce the power consumed during the exchange of spectrum sensing results, and enhances the spectrum utilization.

This chapter is organized as follows: firstly the requirements of both types of users are clearly identified. Next, the general assumptions of the system are declared. Following this, the developed model in spectrum sensing process is presented in detail. It is further explained how efficient the model is in reducing the consumed power among the SUs during exchange of the spectrum sensing results. Next, the performance of the new mechanism is evaluated under a simulation scenario. The chapter is concluded with a summary.

3.1 System Requirements

The first step in cognitive radio networks is the spectrum sensing, wherein each SU explores the channels that are assigned for a specific PU and uses its own techniques in order to determine the absence or presence of the PU.

The requirements of the system users (PUs and SUs) are separately defined for each type of users.

3.1.1 PU's Requirements

Each PU is assigned many channels to communicate with other nodes in the network. Each PU works as transmitter and receiver at the same time and the same channel could be used to send and receive data. Each channel has a signal power level that, during the communication, cannot be exceeded by the transmitter as well as the receiver.

3.1.2 SU's Requirements

Each SU would like to use any channel that is assigned to any PU in the network. To do so, it senses all channels of each PU to detect if the PU that owns the sensed channel is using it or not. As mentioned before there are many techniques used to sense the channels of the PUs. In our model we assume that each SU uses the energy detection technique to sense all the channels of all the PUs. The sensing time will be affected by the distance between the sensing node and the sensed node. The spectrum sensing is subjected to the probability concepts. There are many types of probability including the detection probability and the miss probability that are taken into account during the spectrum sensing.

The detection probability is defined as the probability to sense a free channel while it is really free. On the contrary, the miss probability is to sense a free channel while it is busy in reality. We assume that the distributed cooperative sensing scheme is applied in our model, so each SU has to have a matrix containing the status of the sensed channels.

3.2 General Assumptions

A system model is developed to meet the requirements identified in the previous section. This model is developed for a general network shown in Figure 1.2. The M SUs are grouped in J clusters based on geometric locations, wherein each cluster contains R SUs such that $\sum_{j=1}^{J} R_j = M$. In each cluster, one SU is randomly chosen to be the cluster head (CH). The remaining SUs are named cluster nodes.

There are some general design assumptions to be specified that represent the first step in the model design, and are as follows:

- *K* channels are assigned for each PU in advance from its Service Provider (Base Station).
- Each channel has a unique ID in the system.
- A common predefined channel is used as a communication channel between the different users of the system.
- Each PU may have different number of channels.
- The size of the channel is measured in *Hertz*.
- The data rate (Bandwidth) is measured in bits/sec (*bps*).
- Both types of the users (i.e. PU or SU) could coexist and use the spectrum channels at a specific time.

3.3 The Model

The proposed model is developed based on three main aspects which are: the sureness, the clustering, and the cooperation. Clustering means to divide the SUs into groups and choosing one of the cluster nodes as a cluster head (CH) that manages the communication among the different clusters' nodes. Sureness means that each SU has to be sure of its spectrum sensing results before forwarding it to other SUs in the same cluster. Meanwhile the cluster head has to be sure of its cluster's decision before forwarding it to other clusters. The cooperation means that all SUs cooperate together by exchanging their sensing results.

In the proposed model, the energy detection method is used by all SUs to detect the presence or absence of the PU in its spectrum band, i.e. to make the initial decision about the PUs' bands, where two hypotheses are used to represent that as follows:

$$z_0 : \text{Spectrum is idle}$$

$$z_1 : \text{Spectrum is busy}$$

SUs measure the signal strengths in all the channels, and by using the energy detection method the SUs make the initial decision about the presence/ absence of a PU in its reserved channels. If the decision in a SU is z_0 then 0 will be stored in a Spectrum Sensing Matrix (SSM) for the corresponding channel of that PU which is being checked; otherwise 1 will be assigned. On each cluster node (SU_m) the spectrum sensing matrix, which contains the initial decisions of all the channels of different PUs, has the following format:

$$SSM_m = \begin{bmatrix} Z_{11} & Z_{12} \cdots & Z_{1k} \\ \vdots & \ddots & \vdots \\ Z_{i1} & \cdots & Z_{ik} \end{bmatrix} \quad \text{such that} \quad 1 \leq m \leq M, \quad 1 \leq i \leq N, \quad 1 \leq k \leq K$$

where, each row represents the SU's initial decisions about all channels of each PU. The first row represents the initial decisions about all channels (from 1 to K) of PU_1, while the second row represents the channels of PU_2 and so on. The values of SSM_m entries are initially unknown i.e. before the SUs start sensing the spectrum all the entries of SSM_m are equal to ∞. We define a function called Initial Decision Function (IDF) that is used by each SU to update its SSM. It has the following format:

```
Boolean IDF (float ReceivedSignalStrength)
{
    FOR PU_i = 1 to N
            FOR CHANNEL_k = 1 to K
                    Get(Threshold_ik)
                    IF(ReceivedSignalStrength > Threshold_ik)
                            Z_ik= 1
                            Return true
                    ELSE
                            Z_ik= 0
                            Return false
            ENDFOR
    ENDFOR
    }
```

Next Decision Function (NDF) represents all the decisions made by the cluster nodes except the initial decision. It works same as IDF.

After each SU fills its copy of the SSM, in each cluster, the cluster nodes send their sensing results to their CHs. Next, the clusters' decisions are forwarded to the other clusters through the

CHs communication. After that, each CH collects other clusters' decisions, and finally CH forwards all the clusters' decisions to its clusters nodes.

Each cluster head (CH) is responsible for collecting the cluster nodes' decisions and making the cluster decision. In our model, each CH maintains a Cluster Decision Matrix (CDM) that has the following format:

$$\mathrm{CDM_j} = \begin{bmatrix} \mathrm{CD}_{11} & \mathrm{CD}_{12} \cdots & \mathrm{CD}_{1k} \\ \vdots & \ddots & \vdots \\ \mathrm{CD}_{i1} & \cdots & \mathrm{CD}_{ik} \end{bmatrix} \text{ such that } \quad 1 \le j \le J \ , \ 1 \le i \le N \ , \ 1 \le k \le K$$

where, each row represents the cluster decision about all the channels of each PU. The first row represents the cluster's initial decisions about all channels (from 1 to K) of PU_1, while the second row represents the channels of PU_2 and so on. The values of $\mathrm{CDM_j}$ entries are initially unknown i.e. before the SUs start sensing the spectrum all the entries of $\mathrm{CDM_j}$ are equal to ∞. We define a function called Cluster Initial Decision function (CID) that is used by each CH to update its CDM. It has the following format:

```
Boolean CID (Array SSM)
{
    Integer No_ofSUsSayThisChannelIsBusy;
    Integer No_ofSUsSayThisChannelIsIdle;
    FOR PUi = 1 to N
            FOR CHANNELk = 1 to K
                    Get(Zik)
                    IF(Zik = 1)
                     {
                            No_ofSUsSayThisChannelIsBusy++;
```

```
                    IF(No_ofSUsSaySThisChannelIsBusy>(M/2))
                      CDik=1;
                    ELSE
                      CDik=0;
                }
            ELSEIF(Zik = 0)
                {
                    No_ofSUsSayThisChannelIsIdle++;
                    IF(No_ofSUsSayThisChannelIsIdle >(M/2))
                      CDik=0
                    ELSE
                      CDik=1
                }
        ENDFOR
    ENDFOR
    }
```

Cooperation is the second concept that the proposed model relies on wherein all SUs take other SUs' decisions in consideration when making their final decisions.

The third concept that is used in the developed model is the sureness. There are two levels of sureness, the first level is in each SU (i.e. each SU has to be sure of its initial decision before forwarding it to its cluster head). The second level is in each CH (i.e. each CH has to be sure of its cluster decision before forwarding it to other cluster heads). Spectrum sensing is periodically made which means every sensing round all SUs including the CHs re-sense the spectrum and update their matrices with the new sensing values. At the first round of the sensing phase, all SUs and CHs sureness values are true. This means that the SUs will send their initial decision to their CHs and the CHs will send their decisions to other CHs. Each SU sets its sureness value as follows: at each spectrum sensing round, the SU gets the decisions of all clusters via its CH, and then compares its decision with the other clusters' decisions. If more than 50% of the clusters' decisions are similar to its decision, then it sets its sureness value to be true, otherwise it is false. In other words, if the sureness value of a SU is true at the beginning of the sensing round and by the end of the sensing round more than 50% of the clusters' decisions are same as its decision, then its sureness value remains true, otherwise the SU loses it sureness and it cannot send their sensing results in the next round of sensing. Simultaneously, each CH sureness value is set too by using the same way. If the sureness value of a SU or CH is false, it stops transmitting its sensing results but keeps sensing the spectrum and tracking the majority of all the SUs. As soon as it gets its sureness value back, it restarts sending its sensing results.

Each CH makes the cluster decision based on the majority voting mechanism. Each CH counts the number of the SUs whose their sensing results are 1 (i.e. spectrum is busy) and simultaneously counts the number of the SUs whose sensing results are 0 (i.e. spectrum is idle). After that the CH makes the cluster's decision where the number of SUs which have the same sensing results should be greater than 50% of the total number of SUs in that cluster. The same mechanism is applied to SUs in making their final decisions where more than 50% of clusters' decisions should have the same decision as their initial decisions.

When a CH receives other CHs' decisions, it maintains a decision matrix (D) which has the following format:

$$D = \begin{bmatrix} D_{11} & D_{12} \cdots & D_{1k} \\ \vdots & \ddots & \vdots \\ D_{i1} & \cdots & D_{ik} \end{bmatrix} \quad \text{such that} \quad 1 \leq i \leq N, \quad 1 \leq k \leq K$$

where, first row represents the system decision that has been collected from all clusters about all the channels of PU_1, and so on. D matrix is sent by each cluster head to its cluster nodes where each cluster node uses this matrix to find its next decision. After that the SU uses its next decision to update its sureness value.

Low accuracy rate of spectrum sensing results when the number of cluster nodes that are sure decreases while the sensing is repeatedly made. In order to solve this problem, a rule is configured on each CH. Every CH checks the number of cluster nodes that participates in the spectrum sensing round, at least more than half of them should participate in order to take the cluster decision, otherwise, a notification message is sent to all cluster nodes to send their sensing results. The algorithm of the proposed scheme is summarized in Table 3.1.

Table 3.1 The Algorithm of Cluster based Sureness Sensing Mechanism

Initialize
  SSM=Spectrum Sensing Matrix
  CDM=Cluster Decision Matrix
  D=Decision matrix
Define
  IDF= Initial Decision Function
  CID=Initial Decision of the cluster
  NDF=Next Decision Function which is all the decisions except the initial decision

For round R
For SU m
    Sense the spectrum to obtain the signal strength
    Execute IDF
    Update SSM_m
    While (SU_msureness)
        Forward SSM to CH
    Endwhile
    If(SU_m = = CH)
        Check if more than half of SUs are sending their SSMs
        Receive SSM from sender SUs of its cluster
        Execute CID
        Update CDM_j

```
        Receive  CDM from other CHs
        Execute  NDF
        Update D
        If ( NDF = =CID)
              CHsureness =TRUE
        Else
              CHsureness =FALSE
        EndElse
        While (CHsureness)
             forward  CDM to CHs
    EndIf
EndFor
 For SU m
      Execute NDF
      If(NDF==IDF)
             SUsureness = TRUE
      Else
            SUsureness = FALSE
      EndElse
  EndFor
Endfor
```

3.4 Model benefits

In the proposed mechanism, we show that more power saving is achieved compared to the broadcast scheme. It reduces the number of messages to be exchanged between the sensing nodes (SUs), therefore decreases the power consumed.

The authors in [10] propose a model wherein a central point (a SU) takes care of sensing the spectrum and deciding the presence or absence of PUs in the spectrum, which results in a lower sensing accuracy rate. More time may be spent in making the final decision of the spectrum and forwarding the decision to other SUs, thus decreasing the efficiency.

Each SU works as a transmitter and a receiver simultaneously. Therefore, power is consumed in transmitting and receiving the spectrum sensing results; P represents the total consumed power. It has two components: the power consumed in the transmission phase ($P_{sender(total)}$) and the power consumed in the receiving phase($P_{receiver(total)}$). The following equation is used to represent this:

$$P = P_{sender(total)} + P_{receiver(total)} \tag{3.1}$$

In the transmission period the power is consumed by exchanging the spectrum sensing results from the cluster nodes to its CH, CH to other CHs, and CH back to its cluster nodes which can be computed as follows:

$$P_{sender(total)} = \sum_{j=1}^{J}\sum_{r=1}^{R} P_{SU_r \rightarrow CH_j} + J(J-1)P_{CH\rightarrow CH} + \sum_{j=1}^{J} P_{CH_j \rightarrow SU_{farthest}} \tag{3.2}$$

We assume that same value of power is needed by each SU to transmit. In the receiving period, the power is also consumed in receiving the spectrum sensing results. Most of the time the CHs are ON and consuming power while the cluster nodes consume a small level of power in a small time which can be neglected, so most of the power is consumed by CHs in receiving other clusters' decisions which can be represented as follows:

$$P_{receiver(total)} = J(J-1)P_{receiver} \tag{3.3}$$

where $P_{receiver}$ represents the power consumed by the receiver.

Number of messages to be exchanged among the sensing nodes (SUs) is comparison with the broadcast model. In the broadcast model, each SU sends the sensing decision to all the other SUs, therefore the total number of messages exchanged is represented in the following equation:

$$\#\text{ of Messages} = M(M-1) \tag{3.4}$$

In our proposed model, the number of messages depends on the sureness value of the sensing nodes. The worst case (i.e. the maximum number of messages exchanged) is when the sureness value of all the sensing nodes is true, therefore all cluster nodes send their SSMs to their cluster head and all the cluster heads send their CDMs to the other cluster heads and it is represented by the following equation:

$$\# \text{ of Messages} = 2 * \sum_{j=1}^{J} \sum_{r=1}^{R} SU_r \rightarrow CH_j + J(J-1) \quad (3.5)$$

The complexity of the number of messages in the broadcast model is $O(M^2)$, while it is $O(M)$ in our proposed model.

3.4.1 An example: A scenario

This section provides an example to clarify the mechanism and shows in detail the results exchange of the spectrum sensing process and power saving.

Consider nine SUs that form three clusters as in Figure 3.1, with the following information:

- SU_3 is the Cluster head (CH_1) in the cluster 1 (C_1).
- SU_8 is the Cluster head (CH_2) in the cluster 2 (C_2).
- SU_{13} is the Cluster head (CH_3) in the cluster 3 (C_3).
- SU_{15} is the farthest node in the network for the broadcast model.
- SU_5 is the farthest node in the cluster 1 (C_1).
- SU_{10} is the farthest node in the cluster 2 (C_2).
- SU_{15} is the farthest node in the cluster 3 (C_3).
- There are three PUs in the network, where one channel is owned by each PU. Therefore, SSM is a 3x1 matrix.
- The decision about the presence/absence of PU_1, PU_2, or PU_3 in C_1 is made in two rounds of information exchanges.
- The consumed power in transmitting the sensing results between the SUs is equal to 0.7 watts where the power range depends on the network card used on the physical layer as in [11].

- The consumed power in receiving the information from the other SUs is equal to 0.5 watts ($P_{receiver}$).

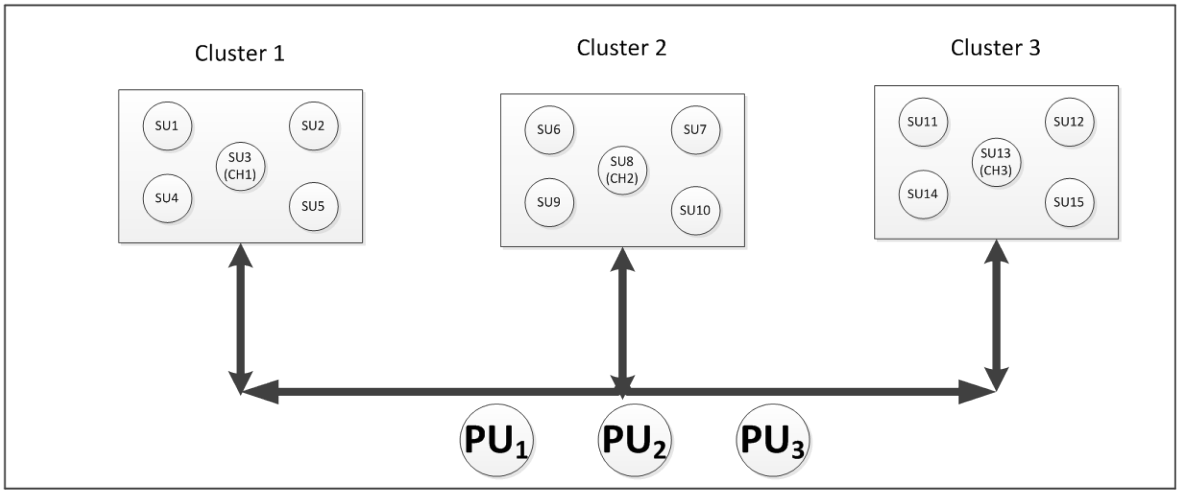


Figure 3.1: An example of the Proposed Scheme

The steps of performing the spectrum sensing process are shown below in detail.

At the beginning the SSM of each SU is as following:

Cluster 1 (C_1)				
SU_1	SU_2	SU_3 (CH_1)	SU_4	SU_5
$SSM_1 = \begin{bmatrix} 0 \\ 0 \\ 0 \end{bmatrix}$	$SSM_2 = \begin{bmatrix} 0 \\ 1 \\ 0 \end{bmatrix}$	$SSM_3 = \begin{bmatrix} 0 \\ 1 \\ 1 \end{bmatrix}$	$SSM_4 = \begin{bmatrix} 0 \\ 1 \\ 0 \end{bmatrix}$	$SSM_5 = \begin{bmatrix} 0 \\ 1 \\ 0 \end{bmatrix}$

Cluster 2 (C_2)				
SU_6	SU_7	SU_8 (CH_2)	SU_9	SU_{10}
$SSM_6 = \begin{bmatrix} 0 \\ 1 \\ 1 \end{bmatrix}$	$SSM_7 = \begin{bmatrix} 0 \\ 1 \\ 0 \end{bmatrix}$	$SSM_8 = \begin{bmatrix} 0 \\ 1 \\ 1 \end{bmatrix}$	$SSM_9 = \begin{bmatrix} 0 \\ 1 \\ 1 \end{bmatrix}$	$SSM_{10} = \begin{bmatrix} 0 \\ 1 \\ 1 \end{bmatrix}$

Cluster 3 (C_3)				
SU_{11} $\mathrm{SSM}_{11} = \begin{bmatrix}1\\0\\1\end{bmatrix}$	SU_{12} $\mathrm{SSM}_{12} = \begin{bmatrix}0\\1\\1\end{bmatrix}$	SU_{13} (CH_3) $\mathrm{SSM}_{13} = \begin{bmatrix}0\\1\\1\end{bmatrix}$	SU_{14} $\mathrm{SSM}_{14} = \begin{bmatrix}0\\1\\1\end{bmatrix}$	SU_{15} $\mathrm{SSM}_{15} = \begin{bmatrix}0\\1\\0\end{bmatrix}$

In each cluster, the cluster's nodes send their SSMs to their cluster heads, where each cluster head collects the SSM, makes the initial cluster decision function and updates cluster decision matrix as follows:

Cluster 1 (C_1)				
SU_1 $SSM_1 = \begin{bmatrix}0\\0\\0\end{bmatrix}$	SU2 $\mathrm{SSM}_2 = \begin{bmatrix}0\\1\\0\end{bmatrix}$	SU_3 (CH_1) $CDM_1 = \begin{bmatrix}0\\1\\0\end{bmatrix}$	SU_4 $\mathrm{SSM}_4 = \begin{bmatrix}0\\1\\0\end{bmatrix}$	SU_5 $\mathrm{SSM}_5 = \begin{bmatrix}0\\1\\0\end{bmatrix}$

Cluster 2 (C_2)				
SU_6 $\mathrm{SSM}_6 = \begin{bmatrix}0\\1\\1\end{bmatrix}$	SU_7 $\mathrm{SSM}_7 = \begin{bmatrix}0\\1\\0\end{bmatrix}$	SU_8 (CH_2) $CDM_2 = \begin{bmatrix}0\\1\\1\end{bmatrix}$	SU_9 $\mathrm{SSM}_9 = \begin{bmatrix}0\\1\\1\end{bmatrix}$	SU_{10} $\mathrm{SSM}_{10} = \begin{bmatrix}0\\1\\1\end{bmatrix}$

Cluster 3 (C_3)				
SU_{11} $\mathrm{SSM}_{11} = \begin{bmatrix}1\\0\\1\end{bmatrix}$	SU_{12} $\mathrm{SSM}_{12} = \begin{bmatrix}0\\1\\1\end{bmatrix}$	SU_{13} (CH_3) $CDM_3 = \begin{bmatrix}0\\1\\1\end{bmatrix}$	SU_{14} $\mathrm{SSM}_{14} = \begin{bmatrix}0\\1\\1\end{bmatrix}$	SU_{15} $\mathrm{SSM}_{15} = \begin{bmatrix}0\\1\\0\end{bmatrix}$

After that each cluster head forwards its SSM to other clusters' heads, collects the other clusters decisions and finds the matrix D which represents the final decisions of all the system nodes.

Cluster 1 (C_1)				
SU_1	SU_2	SU_3 (CH)	SU_4	SU_5
$SSM_1 = \begin{bmatrix}0\\0\\0\end{bmatrix}$	$SSM_2 = \begin{bmatrix}0\\1\\0\end{bmatrix}$	$D = \begin{bmatrix}0\\1\\1\end{bmatrix}$	$SSM_4 = \begin{bmatrix}0\\1\\0\end{bmatrix}$	$SSM_5 = \begin{bmatrix}0\\1\\0\end{bmatrix}$

Cluster 2 (C_2)				
SU_6	SU_7	SU_8 (CH)	SU_9	SU_{10}
$SSM_6 = \begin{bmatrix}0\\1\\1\end{bmatrix}$	$SSM_7 = \begin{bmatrix}0\\1\\0\end{bmatrix}$	$\mathrm{D} = \begin{bmatrix}0\\1\\1\end{bmatrix}$	$SSM_9 = \begin{bmatrix}0\\1\\1\end{bmatrix}$	$SSM_{10} = \begin{bmatrix}0\\1\\1\end{bmatrix}$

Cluster 3 (C_3)				
SU_{11}	SU_{12}	SU_{13} (CH)	SU_{14}	SU_{15}
$SSM_{11} = \begin{bmatrix}1\\0\\1\end{bmatrix}$	$SSM_{12} = \begin{bmatrix}0\\1\\1\end{bmatrix}$	$\mathrm{D} = \begin{bmatrix}0\\1\\1\end{bmatrix}$	$SSM_{14} = \begin{bmatrix}0\\1\\1\end{bmatrix}$	$SSM_{15} = \begin{bmatrix}0\\1\\0\end{bmatrix}$

Finally each cluster head forwards D matrix to its cluster's nodes to check their accuracy about their initial decisions.

Cluster 1 (C_1)				
SU_1	SU_2	SU_3 (CH)	SU_4	SU_5
$SSM_1 = \begin{bmatrix}0\\0\\0\end{bmatrix}$	$SSM_2 = \begin{bmatrix}0\\1\\0\end{bmatrix}$	$D = \begin{bmatrix}0\\1\\1\end{bmatrix}$	$SSM_4 = \begin{bmatrix}0\\1\\0\end{bmatrix}$	$SSM_5 = \begin{bmatrix}0\\1\\0\end{bmatrix}$
Sureness=F	Sureness=T	Sureness(SU)=T Sureness(CH)=F	Sureness=T	Sureness=T
Cluster 2 (C_2)				
SU_6	SU_7	SU_8 (CH)	SU_9	SU_{10}
$SSM_6 = \begin{bmatrix}0\\1\\1\end{bmatrix}$	$SSM_7 = \begin{bmatrix}0\\1\\0\end{bmatrix}$	$D = \begin{bmatrix}0\\1\\1\end{bmatrix}$	$SSM_9 = \begin{bmatrix}0\\1\\1\end{bmatrix}$	$SSM_{10} = \begin{bmatrix}0\\1\\1\end{bmatrix}$
Sureness=T	Sureness=T	Sureness(SU)=T Sureness(CH)=T	Sureness=T	Sureness=T

Cluster 3 (C_3)				
SU_{11}	SU_{12}	SU_{13} (CH)	SU_{14}	SU_{15}
$SSM_{11} = \begin{bmatrix}1\\0\\1\end{bmatrix}$	$SSM_{12} = \begin{bmatrix}0\\1\\1\end{bmatrix}$	$D = \begin{bmatrix}0\\1\\1\end{bmatrix}$	$SSM_{14} = \begin{bmatrix}0\\1\\1\end{bmatrix}$	$SSM_{15} = \begin{bmatrix}0\\1\\0\end{bmatrix}$
Sureness=F	Sureness=T	Sureness(SU)=T Sureness(CH)=T	Sureness=T	Sureness=F

In the next round of the spectrum sensing process, the SUs, which are sure of their initial decisions (i.e. sureness =T), will send their spectrum sensing.

In cluster 1 (C1), all SUs except SU_1 will send their new SSM to the cluster head. In cluster 2 (C2), all SUs will participate in the second round of spectrum sensing process. While in cluster 3 (C3), SU_{11} and SU_{15} will not send their new SSM to their cluster head.

Then, the consumed power in the first round is computed by using equation (3.2) as follows:

$$P_{sender(total)} = \sum_{j=1}^{J}\sum_{r=1}^{R} P_{SU_r \rightarrow CH_j} + J(J-1)P_{CH\rightarrow CH} + \sum_{j=1}^{J} P_{CH_j \rightarrow SU_{farthest}}$$

$$= \sum_{j=1}^{3}\sum_{r=1}^{5} 0.7 + 3(3-1) * 0.7 + \sum_{i=1}^{3} 0.7$$

= 37.8 watts

$$P_{receiver(total)} = J(J-1)P_{receiver}$$

$$= 3(3-1)0.5$$

= 3 watts

While the power consumed in the broadcast model in [10-14] is represented by the following equation:

$$P_{broadcast} = M(M-1)P_{sender} + M(M-1)P_{receiver} \quad (3.6)$$

And in the previous example the total power consumed in the broadcast model is computed by using equation number (3.6) as follows:

$P_{broadcast}$ = 147+105

= 252 watts.

It is obvious that the proposed scheme enhances the system performance by reducing the power consumed in the spectrum sensing process which will be illustrated in the next section.

Another thing to compare is the total number of messages exchanged. In the broadcast model, it is computed by using equation (3.4) as follows:

$$\# \text{ of Messages} = M(M-1)$$

= 15(15-1)

= 210 messages

In our model, it is computed by using equation (3.5) as follows:

$$\# \text{ of Messages} = 2 * \sum_{j=1}^{J}\sum_{r=1}^{R} SU_r \rightarrow CH_j + J(J-1)$$

$= (2 * \sum_{j=1}^{3} \sum_{r=1}^{5} \mathrm{SU_r} \rightarrow CH_j) + 3(3-1)$

= 30 messages

3.5 Performance Evaluation

This section presents the performance evaluation of the developed model and the efficient power savings that could be achieved.

In order to compare our scheme with other schemes, the traditional broadcast scheme is simulated as well. We compare the transmission and the receiving power consumption in our scheme with the broadcast scheme. Table 3.2 shows the simulation parameters.

Table 3.2 Simulation Parameters

Parameter	Value
Number of PUs	3
Number of clusters	[1,100]
Number of channels of each PU.	5
Transmission power	0.03 watt
$\mathbf{P_{receiver}}$	0.1 watt

We used MATLAB to simulate the two models i.e. sureness cluster-based and broadcast models. The transmission and receiving power consumption of our proposed scheme are shown in Figures 3.2, 3.3 and 3.4. To demonstrate the energy efficiency of our proposed scheme, we define the Transmission Power Consumption Ratio (TPCR) as follows:

$$\mathrm{TPCR} = \frac{\text{Our model transmission power}}{\text{Broadcast transmission power}}$$

Also in same way, we define the Receiving Power Consumption Ratio (RPCR),

$$\mathrm{RPCR} = \frac{\text{Our model Receiving power}}{\text{Broadcast Receiving power}}$$

In the traditional broadcast model, TPCR and RPCR values are 1.

Figure 3.2 illustrates the difference between the conventional scheme in spectrum sensing which is the broadcast scheme and our proposed scheme. It is clear that our model helps in reducing the consumed power in transmitting the results of the spectrum sensing process in comparison with the broadcast model under the same network circumstances. Note that TPCR in the broadcast model is equal to 1.

In Figure 3.3, the transmission power efficiency performance of the proposed method is simulated with different numbers of SUs. It can be observed that the transmission energy consumption decreases with the increase of the number of SUs in comparison with the broadcast method. Note that TPCR in the broadcast model is equal to 1. Simultaneously, the transmission power ratio declines with the increase of clusters.

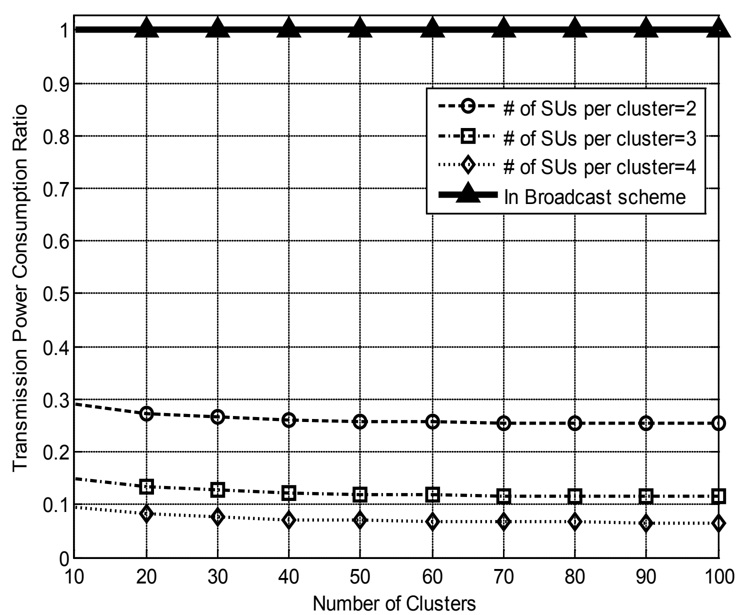


Figure 3.2: Comparison of the Consumed Transmission Power in the Broadcast Scheme and our Scheme.

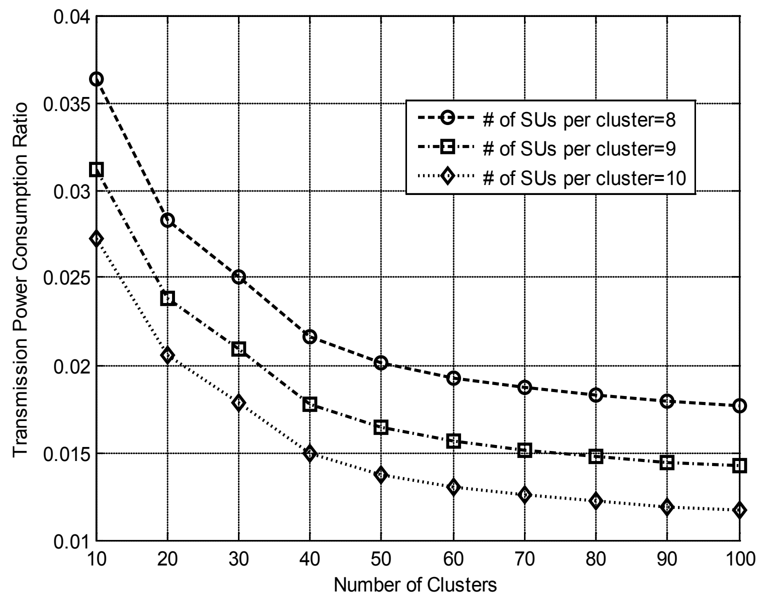


Figure 3.3: Transmission Energy Performance for different Clusters

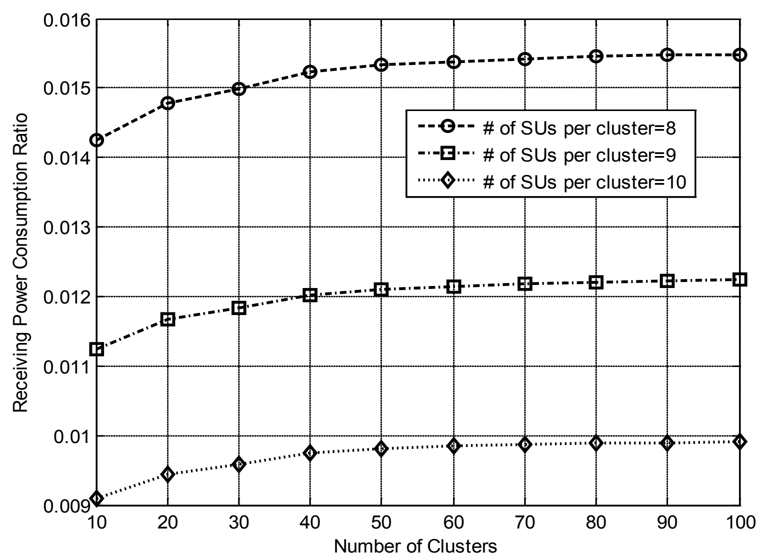


Figure 3.4: Receiving Energy Performance for different Clusters

Figure 3.4 shows the receiving power performance of our proposed method, where it is simulated with the same system parameters. It can be seen that the receiving energy consumption decreases with the increase of the number of SUs in comparison with the broadcast method. Note that RPCR in the broadcast model is equal to 1.However, the receiving power consumption ratio increases slightly with the increase of clusters due to more additional cluster heads are required; however this power consumption seems to be very small in comparison with the conventional broadcast method.

The maximum consumed power by a SU, if it is as a cluster node, depends on the size of spectrum sensing matrix (SSM). It increases when the number of the PUs and their channels to be detected increase. On the other hand if a SU works as a cluster head, the maximum consumed power depends on two factors that are the number of SUs which form the cluster and the total number of the clusters.

3.6 Summary

In this chapter, an efficient spectrum sensing scheme was developed. This scheme helps in decreasing the power consumption in transmitting and receiving the results of spectrum sensing. The transmission and receiving power consumption of our proposed method has been derived and compared with that of the conventional broadcast method. Simulation results show significant decrement of transmission and receiving power consumption.

Chapter 4: Spectrum Management by Power Trading

In this chapter, the process of power trading is addressed in detail and the different conflicting objectives of the PUs and the SUs are met by developing two different models. The PUs aim to attain revenue by leasing their unused spectrum bands to unlicensed users (SUs) that aim to meet their requirements of Quality of Service (QoS) with less payment. Firstly, a new model is developed that helps the PUs to gain profit with considering the desire of SUs to utilize the vacant channels of PUs. The second mechanism applies the game theory tool and considers the conflicted objectives of the users to achieve a balance between both system users. These two separate mechanisms (models) that were proposed as solutions for the challenges of the power trading issue in cognitive radio are evaluated. Meanwhile, by evaluating the game theoretic approach, it is shown how to get the Nash equilibrium point which is considered as the balance point of both users.

This chapter is organized as follows: firstly, the requirements of both types of users are clearly identified. Then, a power trading model without game theory is described in detail. Next, this model is analyzed to show its efficiency. After that the game theoretic power trading approach is explained and then it is valuated and shown how a Nash equilibrium point (NE) is achieved. The chapter is concluded with a summary.

4.1 System Users Requirements

After the SUs sense the channels and specify the unused channels and before starting to use the channels, a negotiation between the SUs and PUs has to take place in order to achieve the goals of each user in the network and balance these goals. Our system is shown in Figure 1.2.

4.1.1 PU's requirements

Each PU saves the properties of its channels and the channels` requests from the different SUs. The properties of the channels are: channel ID, channel's range, channel's initial price, maximum allowed power, and channel's data rate.

During the communication between the PUs and the SUs, which could be initiated by the PU or the SU, a PU generates a response message that contains the requested channel ID and the price of the requested channel and the maximum allowed power level for the requesting SU(s) to use. Each PU has an initial price function that is used to calculate its profit.

The PUs continue the negotiation with the SUs until both of them reach a solution that satisfies the requirements of both sides. The PUs always want to increase their profit by renting their unused channels to the SUs.

A PU can change the price of its channels due to different network conditions. If only a few SUs request a channel, the PU starts to reduce the price of that channel to make it more attractive to the SUs. When one channel is not used by the PU and none of the SUs request it, the PU has to adjust the price of that channel.

Before assigning a channel to a SU, a PU should check if the power level of this SU over this channel does not interfere with other channels in the network.

There is neither competition nor cooperation among different PUs to maximize their profits. The PUs try to set the best price of the offered spectrum.

During the negotiation phase, each PU has to store the received requests from different SUs and keep track of its channels i.e. maintain a database that shows the status of its channels. This database is used for statistical calculations.

The PUs use their spectrum channels if and only if they have data to be transmitted, therefore the traffic type of PUs is sporadic.

4.1.2 SU's requirements

The SUs send the channels' requests to the PUs using a request message that contains the requested channel ID and the desired bandwidth that meet its quality of service (QoS). The QoS of a SU can be represented as one of the two characteristics, which is the high data rate in terms of bits per second or proper power levels in terms of watts. Each SU should make a balance between its wanted QoS and the efficient time of using the channel. These QoS requirements (data rate, power level) might be changed over time corresponding to the changes of status of the network such as traffic load, spectrum demand, and spectrum cost. Each SU, during the negotiation, may ask the PU for more information about its channels.

Each SU has its own mechanisms to check if the selected channel(s) satisfies/satisfy the SU's desired QoS. Also, each SU has to estimate the time to use a channel because it cannot use the channel for a long duration. The SU has to give the channel back to the original owner. This time is specified by the SU depending on its requirements and on the negotiation between the spectrum owner (PU) and the SU.

A timer associated with each rented channel has to be defined; the value of this timer decrements after assigning the channel to a SU. When this value approaches zero, the PU sends a reminder to the SU that the renting period is nearing its end and whether an extension to the rent is required or not.

The SUs use the PUs' spectrum channels after renting them if and only if they have data to be transmitted; therefore the traffic type of SUs is sporadic.

4.2 Power Trading Approach without Game Theory

4.2.1 The Model

In this part, our proposed model is demonstrated. Initially each PU contacts its service provider to obtain a frequency band, $F_{PU_j}, j = 1 \dots N$, at a cost of $Cost_{F_{PU_j}}$, in order to be used for data transmission, which is divided into K number of channels which are equal in size and properties channels as following:

$$K = \frac{F_{PU_j}}{\text{channel size}} \tag{4.1}$$

PUs pay the frequency price, $Cost_{F_{PU_j}}$, to their service providers. This price is used to set the initial price of *i^th^* channel, $IP_{C_i}^{PU_j}$. The following equation shows that:

$$IP_{C_i}^{PU_j} = \frac{Cost_{F_{PU_j}}}{K} \tag{4.2}$$

Each PU knows the maximum data rate, $B_{maximum}$, that can be achieved by transmitting over its channels, therefore each channel data rate, B_{C_i}, can be specified by dividing the overall data rate by the number of channels.

Each PU maintains Channels Properties Table (CPT) which is used to save all the channels properties. This table contains the following: channel ID, channel range in hertz, initial price of the channel, maximum allowed power value which shows the maximum limit of power to be used over a channel, and the channel data rate in bits per second. All these values can be calculated using the previous equations, while the maximum allowed power is predefined for all PU channels.

After the PU initiates these values and stores them in the CPT, different SUs start sending their spectrum requests messages to PUs depending on their spectrum sensing results. Each PU uses another table to save these channels' requests, which is called Channels Requests Table (CRT). This table contains the following: the request ID, SU ID, Channel Served, the ID of the assigned channel, and the final price of the channel, where request ID is an auto generated number that represents the number of the request. Served entry represents the serving status for the SU with the associated channel; it is represented by using two bits such that it has one of three values (0, 1, or 2). If served value is 1, it means that a channel is assigned to a SU and is in use now. While 2 means the assigned channel is released, 0 means this request is not served until now and no channels are assigned. Channel final price represents the channel price which the SU will pay for the PU. This value is computed after the negotiation between the PUs and SUs is made. This negotiation is made based on the different objectives and requirements of the PUs and SUs. PU is always looking for a high profit from leasing its channel(s) and not to let the SUs use high power levels which will interfere with other users in the network, while SU does not want to pay much for renting channels but to get good channels that satisfy its QoS.

SU starts negotiation by sending a request message to PUs that have unused band, this message contains the desired bandwidth, $\mathrm{B_{desired}}$, to be used to transmit its data wherein this value must not exceed the maximum data rate of all PU channels together as following:

$$\mathrm{B_{desired}} \leq \mathrm{B_{maximum}} \tag{4.3}$$

Once a PU receives this request message, it computes the minimum and maximum signal to noise ratio (SNR) of its different channels, $\mathrm{SNR}_{\mathrm{Max}}^{\mathrm{C_i}^{\mathrm{PU_j}}}$ and $\mathrm{SNR}_{\mathrm{Min}}^{\mathrm{C_i}^{\mathrm{PU_j}}}$, respectively, by using Shannon's capacity law as following:

$$\mathrm{SNR}_{\mathrm{Max}}^{\mathrm{C_i}^{\mathrm{PU_j}}} = 2^{\frac{\mathrm{B_{C_i}}}{\text{channel size}}} - 1 \tag{4.4}$$

$$\mathrm{SNR}_{\mathrm{Min}}^{\mathrm{PU_j}} = 2^{\frac{\mathrm{B_{desired}}}{\mathrm{F_{PU_j}}}} - 1 \tag{4.5}$$

$$\mathrm{SNR}_{\mathrm{Min}}^{\mathrm{C_i}^{\mathrm{PU_j}}} = \frac{\mathrm{SNR}_{\mathrm{Min}}^{\mathrm{PU_j}}}{\mathrm{K}} \tag{4.6}$$

Equation (4.5) computes the minimum signal to noise ratio over the total PU spectrum, $\mathrm{SNR}_{\mathrm{Min}}^{\mathrm{PU_j}}$, which is divided by the number of its channels to find the signal to noise ratio for each channel assuming all channels have the same properties. The resulting values from equations (4.4 and 4.6) will be useful in finding the power levels that can be used by the SUs to achieve their QoS without disturbing other users in the network.

The PU wants to know how many channels, Z, to be assigned for a SU which have sent a request. The following equation is used to find that,

$$\mathrm{Z} = \left(\frac{\mathrm{B_{desired}}}{\mathrm{B_{maximum}}} * \mathrm{K}\right) \tag{4.7}$$

Therefore, j^{th} PU can calculate the value of the power to be assigned to a SU to send over i^{th} channel, $\mathrm{P}_{\mathrm{assigned}}^{\mathrm{C_i}^{\mathrm{PU_j}}}$, as following:

$$\mathrm{P}_{\mathrm{assigned}}^{\mathrm{C_i}^{\mathrm{PU_j}}} = \mathrm{P}_{\mathrm{max}}^{\mathrm{C_i}^{\mathrm{PU_j}}} - \mathrm{P}_{\mathrm{used}}^{\mathrm{C_i}^{\mathrm{PU_j}}} - \mathrm{P}_{\mathrm{max}}^{\mathrm{C_i}^{\mathrm{PU_j}}} * \left(\frac{\mathrm{B_{desired}}}{\mathrm{B_{maximum}}}\right) \tag{4.8}$$

$$0 \le \mathrm{P}_{\mathrm{assigned}}^{\mathrm{C_i}^{\mathrm{PU_j}}} \le \mathrm{P}_{\mathrm{max}}^{\mathrm{C_i}^{\mathrm{PU_j}}} \tag{4.9}$$

where $\mathrm{P}_{\mathrm{max}}^{\mathrm{C_i}^{\mathrm{PU_j}}}$ represents the predefined maximum power value which can be used for transmission over the i^{th} channel of the j^{th} PU, and $\mathrm{P}_{\mathrm{used}}^{\mathrm{C_i}^{\mathrm{PU_j}}}$ represents the transmission power value that is used by j^{th} PU over i^{th} channel.

When the SU uses the PU's channel(s), it causes interference on each PU channel, $\mathrm{I}_{\mathrm{C_i}}^{\mathrm{PU_j}}$, which is limited by the following constraint:

$$\mathrm{I}_{\mathrm{C_i}}^{\mathrm{PU_j}} \le \gamma_{\mathrm{C_i}}^{\mathrm{PU_j}} \tag{4.10}$$

where $\gamma_{C_i}^{PU_j}$ represents the predefined interference threshold on the i^{th} channel of the j^{th} PU. Another constraint is applied where the summation of all interferences caused by different SUs, which rent the j^{th} PUs' channels, should not exceed the total interference threshold, and can be represented as following:

$$\sum_{m=1}^{M} \sum_{i=1}^{K} I_{C_i}^{SU_m PU_j} \leq \sum_{i=1}^{K} \gamma_{C_i}^{PU_j} \tag{4.11}$$

where $\sum_{i=1}^{K} \gamma_{C_i}^{PU_j}$ represents the total interference over all channels that the j^{th} PU owns.

After the PU checks all these constraints, it can compute the final price of each requested channel and send it to the SU which is requesting the channels. It can be computed as following:

$$\mathrm{Price}_{C_i}^{PU_j} = \left\{ \left(\frac{B_{desired}}{X * B_{maximum}} \right) \left(IP_{C_i}^{PU_j} \right) \right\} + IP_{C_i}^{PU_j} \tag{4.12}$$

where X represents the number of requests that the PU receives, i.e. the number of SUs which request that channel. The j^{th} PU computes the new price of the channel depending on the bandwidth desired by the SU for its transmission over that channel and it is effected by the number of SUs (X) that request the same channel.

Each PU can compute its profit Ω from renting its unused channels as follows:

$$\Omega = \left\{ \left(\sum_{i=1}^{K} \mathrm{Price}_{C_i}^{PU_j} \right) - C_{BS} - C_{DegQoS} - C_{interference} \right\} \tag{4.13}$$

where C_{BS} represents the cost paid by the PU to its base station, C_{DegQoS} represents the cost due to the degradation of the QoS of the PU, $C_{interference}$ represents the cost because of the interference caused by SU(s) to the other users (SU(s), or PU(s)) in the spectrum.

The cost due to the degradation of the QoS of the PU could be computed as follows:

$$C_{DegQoS} = \mu \left(\frac{B_{SU_m}^{desired}}{B_{PU_j}} \right) \tag{4.14}$$

where μ represents the weight coefficient of cost due to the degradation of the QoS of PU, $B_{SU_i}^{desired}$ represent the desired bandwidth of the m^{th} SU, and B_{PU_j} represents the spectrum bandwidth of j^{th} PU.

The following equation is used to compute the cost due to the interference caused by the SUs that rent channel(s),

$$C_{interference} = \beta\left(\sum_{i=1}^{K} P_{assigned}^{C_i{}^{PU_j}}\right) \tag{4.15}$$

where β represents the weight coefficient of cost due to the interference caused by SU(s) that rent the channel(s) of j^{th} PU.

The proposed pricing mechanisms could be summarized as the following steps:

Step1: PUs get frequency bands from their service providers.

Step 2: PUs divide these frequency bands to different channels which are equal in properties (price and power).

Step 3: SUs send requests to PUs to rent their channels after they do the spectrum sensing.

Step 4: PUs get these requests, and start processing them by calculating the transmission power levels to be assigned and the prices of the different channels.

Step 5: PUs calculate their profit from renting their channels to SUs, and if it is worthy to them, they send messages back to SUs providing them the power levels to be used and the price to pay.

Step 6: If SUs accept that, they pay and start using the PUs' channels with the predefined constraints.

4.2.2 System Performance Evaluation

In this part, we show the performance of the proposed model to trade the power. The scenario reveals a real time situation. The simulated network consists of two primary users (PU_1 and PU_2) and two secondary users (SU_1 and SU_2) as shown in Figure 4.1.

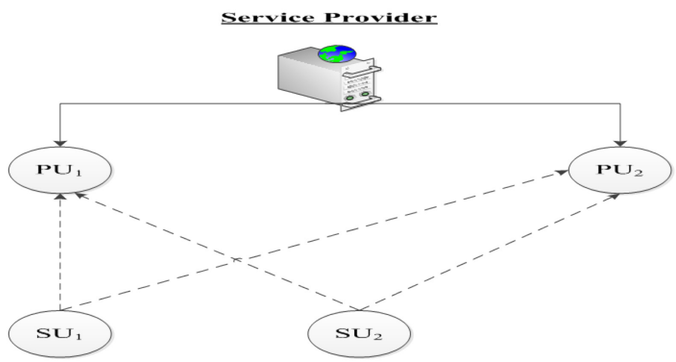


Figure. 4.1: The Simulated Scenario

Table 4.1 shows the simulation parameters as in [22]. As mentioned before each PU is responsible to specify the power level to be assigned to the requesting SUs depending on their desired bandwidth, and the channels' prices too.

Table 4.1 Simulation Parameters

Spreading noise L	128
Background noise	0
Required bandwidth of PU_1 and PU_2	0.46, 0.46 Mbps
Path loss exponent	4
Size of spectrum of PU_1 and PU_2	1.5, 1.5 MHz
Price of each channel	$4
Power used by PU_1 and PU_2	0.5, 0.5 watts

Coefficient of cost due to the quality degradation of PU_1 and PU_2 ($\mu1$ and $\mu2$)	3.5, 2.75
Coefficient of cost due to the interference created by SUs of PU_1 and PU_2 ($\beta1 = \beta2$)	2, 2
Desired bandwidth of SU_1	0.34 Mbps
Desired bandwidth of SU_2	0.46 Mbps

4.2.2.1 Numerical Analysis

In the simulated scenario shown in Figure 4.1, each PU has four different choices which are: serve SU_1 only, SU_2 only, both SUs, or no SU. Table 4.2 shows the calculated values of the power to be assigned to the requesting SUs, the prices of the different channels.

Table 4.2 Profits of PUs

Case	Offer no band	Serve SU_1	Serve SU_2	Serve both SU_1& SU_2
$P_{assigned}^{C_i\,PU_1}$	0	1.05	0.89	0.43
$P_{assigned}^{C_i\,P2}$	0	1.05	0.89	0.43
$Price_{C_i}^{PU_1}$	4	5.05	4.89	4.43
$Price_{C_i}^{PU_2}$	4	5.05	4.89	4.43

In order to determine the performance of the proposed model, especially to let the PUs do power control and its effect on the profit, we compare it with two different models. First a model without power control is considered where $P_{assigned}^{C_i\,PU_j}$ is randomly chosen in the range of [0.03, 2] watts. Second, a model with power control proposed in [22] is considered.

Table 4.3 (a) and (b) shows the profit to be gained by each PU, as shown in equation (4.13), in our model as well as the models without power control and the one in [22]. If we consider the last two rows that show the possible profit of both PUs (PU_1 & PU_2), it is clear that more profit could be achieved by serving both SUs taking in consideration that the total desired bandwidth is less than the maximum bandwidth owned by each PU. It shows that our model helps the different PUs to achieve more profit and the SUs will not interfere with the other users in the network while in the model without power control the profits of PUs are less and there are no constraints control the network.

The transmission power levels have direct effect on the profit of PUs and the price of the different channels of PUs. Each PU decides which SU to serve depending on its profit to be gained. It is clear in Table 4.3 (a) and (b) that our proposed model helps the PUs to gain more profit by serving both SUs simultaneously in comparison with the other model proposed in [22]. In our model, PUs can make up to 40% of additional profit in comparison with the proposed model in [22].

Table 4.3 Profits Comparison

(a)

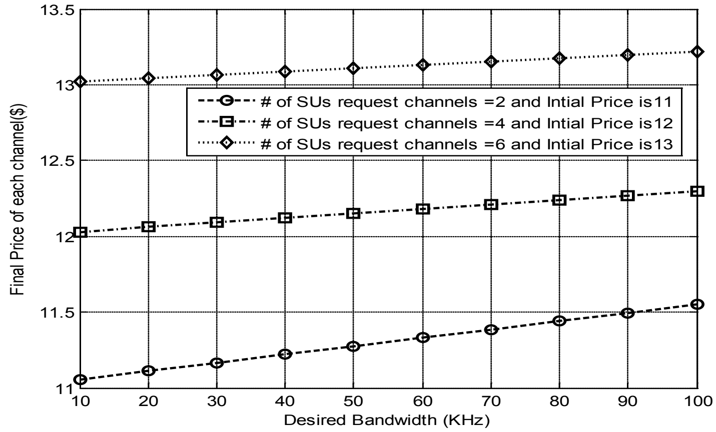
Case	Our model without Game Theory						Model without Power Control					
	PU_1			PU_2			PU_1			PU_2		
Served SU	SU_1	SU_2	Both	SU_1	SU_2	Both	SU_1	SU_2	Both	SU_1	SU_2	Both
Ω	5.87	8.44	11.17	6.04	9.53	12.51	4.23	5.17	8.12	4.65	7.13	9.11

(b)

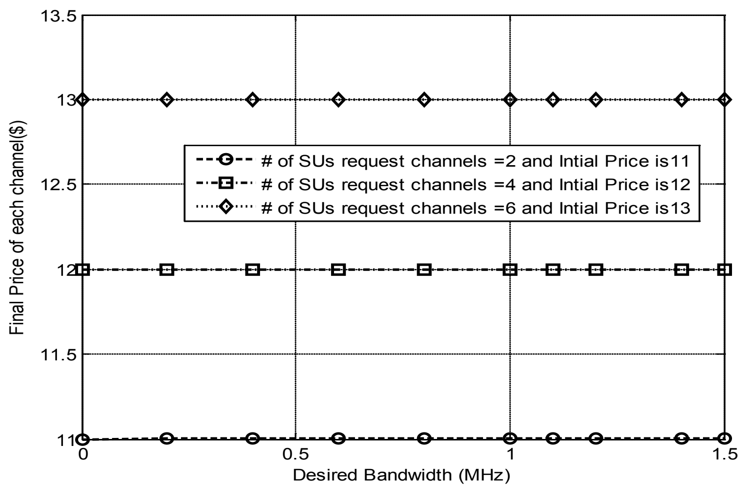
Case	Our model without Game Theory						Model in [22]					
	PU_1			PU_2			PU_1			PU_2		
Served SU	SU_1	SU_2	Both	SU_1	SU_2	Both	SU_1	SU_2	Both	SU_1	SU_2	Both
Ω	5.87	8.44	11.17	6.04	9.53	12.51	5.23	5.71	4.66	6.39	6.87	7.44

4.2.2.2 Simulation Results

In this section, we demonstrate the performance of our proposed scheme by showing some simulation results using MATLAB. Figure 4.2 (a) and (b) illustrate the relationship between the final price of the channels owned by a PU and the bandwidth desired by a SU which are described in equations (4.8 and 4.12). It is clear in (a) that the final price of each channel to be offered for the requested SUs is increasing if the required QoS (desired bandwidth) of a SU increases, and if the initial price increases too. Moreover, when the desired bandwidth approaches the maximum bandwidth of the channel, the change in the final price will be limited because of the interference that might result from the transmission over the channel in its maximum data rate i.e. the SU is constrained for requesting bandwidth. While (b) shows that the difference in the final price of the channel cannot be seen because the high increment of the bandwidth.



(a)



(b)

Figure. 4.2 : Price to be offered for SUs.

Figure 4.3 illustrates the relation between the desired bandwidth of SUs and the transmission power to be assigned by PUs to their customers (SUs). We compare this relation in our proposed model with two different models, one is without power control and the second one is the proposed model in [22].It shows that the transmission power decreases while the desired bandwidth increases because while the desired bandwidth approaches the maximum bandwidth of a PU more interference results which will be controlled by the defined constraints. SUs always look forward to use higher power levels over the PUs' channels in order to accomplish their QoS. In Figure 4.3 it is obvious that the PUs can assign higher power levels to SUs in comparison with the other two models, and these power levels help the SUs in achieving their QoS which leads to more spectrum utilization.

The relation between the desired bandwidth ($B_{desired}$), the power to be assigned to SUs (${P_{assigned}^{C_i}}^{PU_j}$), and the profit to be gained by PUs (Ω), which are described in equations (4.8, 4.12 and 4.13) is illustrated in Figure 4.4. It is shown that the PU can gain more profit if the assigned power level decreases and the desired bandwidth increases.

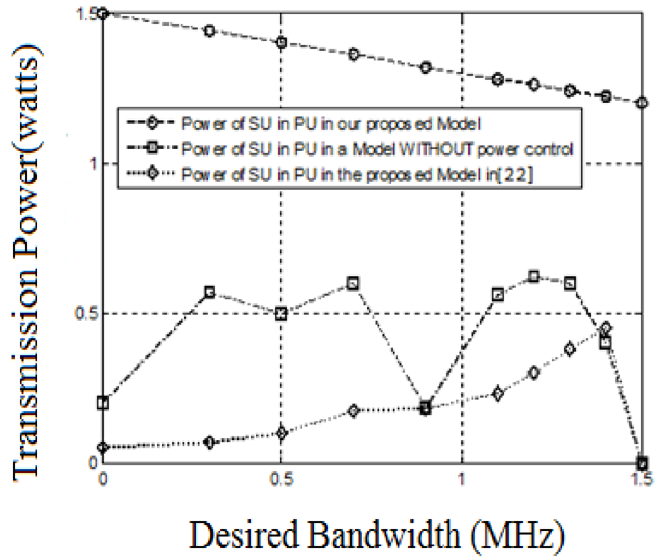


Figure. 4.3: The Relation between the Desired Bandwidth and the Assigned Transmission Power

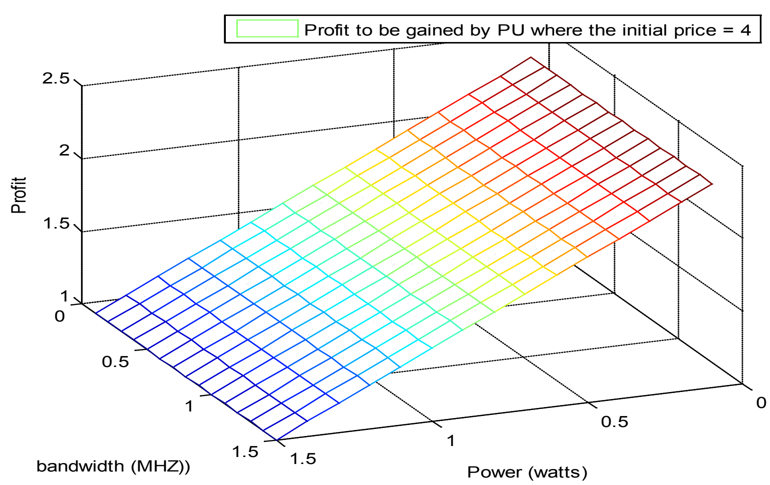


Figure. 4.4: The Relation between the PUs Bandwidth, the Assigned Transmission Power, and the PU’s Profit.

4.3 Power Trading Approach with Game Theory

4.3.1 Introduction

Recently, game theory has been considered as a useful tool to discuss the power control issue in wireless networks. Each game could be defined by three major components which are a set of players, a set of actions of each player, and the utility (payoff) for each player. Each player chooses an action to gain its payoff. There are two major approaches of game theory which can be used to model the different spectrum access schemes which are the cooperative and the non-cooperative game approaches. In the former approach, the players form groups and they play to attain their group payoffs, while in the latter one, the players play individually to achieve their own utilities without considering other players' utilities.

This section proposes a non-cooperative game theoretic model that demonstrates a pricing function which is used to guide SUs to use less power level for their data transmission and accordingly reduce the interference caused in the system. Meanwhile, this function helps the PUs in making more profit from leasing the spectrum.

4.3.2 The Model

The described system in Figure 1.2 can be modeled as a Stackelberg game (see Chapter 2), where the primary users (PUs) are the leaders and the secondary users (SUs) are the followers. In a Stackelberg game, the leader broadcasts a strategy first and all the followers make their own decisions depending on the acquaintance of the leader's action. In a Stackelberg game, we define the two players; the leader (L) and the follower (F). We also define the strategy set and the information set for each player. Q_L and I_L represent the strategy set and the information set, respectively, for the leader. In the same way, we define Q_F and I_F to represent the strategy set and the information set, respectively, of the follower. In the proposed model, the PUs are assumed to be the leaders while the SUs are the followers. The utility functions of the follower (SU) and the leader (PU) are defined as follows, respectively,

$U_F: Q_F \times Q_L \rightarrow Z$ and $U_L: Q_L \times Q_F \rightarrow Z$.

For any strategy q_{L_0} that belongs to Q_L chosen by the leader L, the follower F will choose a reaction strategy q_F^* which belongs to Q_F to maximize its own payoff U_F.

$$q_F^* = \arg\max U_F(q_F; q_L) | (q_L = q_{L_0}) \tag{4.16}$$

Now the leader knows the reaction strategy of the follower, q_F^* , L will announce a strategy q_L^* which belongs to Q_L to maximize its own payoff U_L.

$$q_L^* = \arg\max U_L(q_L; q_F) | (q_F = q_F^*). \tag{4.17}$$

After that Stackelberg game concepts are applied on the proposed cognitive radio system. Firstly, we define the strategy set of the leader (PU) as follows:

$$Q_L = \{\text{Price}_{C_i}^{PU_j}, j = 1 \dots N, i = 1 \dots K\}. \tag{4.18}$$

where $\text{Price}_{C_i}^{PU_j}$ represents the price of *i*th channel owned by j^{th} PU which is offered to the SU(s) which is/are requesting channels in the system.

In the same way, we define the strategy set of the follower which is the SU as follows:

$$Q_F = \{\text{Power}_{C_i}^{SU_m}, m = 1 \dots M, i = 1..K\} \tag{4.19}$$

where $\{\text{Power}_{C_i}^{SU_m}\}$ represents the power level to be used by the m^{th} SU for its transmission over the i^{th} channel.

The primary user's strategy is to choose a price from its strategy set $\{\text{Price}_{C_i}^{PU_j}\}$ while the secondary user wants to select the best power value which optimizes its own payoff. The utility function for the PU and SU has to be defined clearly in order to let each of them select the best strategy for achieving its utility. The utility function of the PU includes three parts: satisfaction of its own transmission, revenue from assigning power level to the SU, and the performance degradation due to the shared power with SU. So, we define the utility function of the PU as follows:

$$U_L = s\left(\text{Power}_{C_i}^{Max} - \text{Power}_{C_i}^{SU_m}\right) + \left(\text{Price}_{C_i}^{PU_j} * \text{Power}_{C_i}^{SU_m}\right) - \left(\text{Power}_{C_i}^{SU_m} * \log B_{C_i}\right) \quad (4.20)$$

where s weights the value of data transmission, $\text{Power}_{C_i}^{Max}$ represents the maximum power that can be used by any user over an i^{th} channel, and B_{C_i} the bandwidth of the i^{th} channel in bps.

The price for i^{th} channel could be used using the following formula:

$$\text{Price}_{C_i}^{PU_j} = \left\{\left(\frac{B_{desired}}{X * B_{maximum}}\right)\left(IP_{C_i}^{PU_j}\right)\right\} + IP_{C_i}^{PU_j} \quad (4.21)$$

where $B_{desired}$ represents the requested bandwidth by the secondary user, $B_{maximum}$ represents the maximum bandwidth of all channels owned by the j^{th} primary user, both in bps, $IP_{C_i}^{PU_j}$ represents the initial price of i^{th} channel of j^{th} PU, and X represents the number of SUs requesting a specific PU's channel.

On the other hand, the utility function of the SU consists of three terms too: revenue from using the PU channels, cost from leasing the PU's channel, and the interference caused in the network. So we define the utility function of the SU as follows:

$$U_F = s\left(\text{Power}_{C_i}^{SU_m}\right) - \left(\text{Price}_{C_i}^{PU_j} * \ln \text{Power}_{C_i}^{SU_m}\right) - r\left(\log B_{C_i}\right) \quad (4.22)$$

where r represents the cost of SU's channel usage.

In order to define the equilibrium point of this game between the PU and the SU, which is the next step in the gaming process, we differentiate the utility function of the SU in equation (4.22) with respect to its strategy variable which is the $\text{Power}_{C_i}^{SU_m}$,we get

$$\frac{\partial U_F}{\partial \text{Power}_{C_i}^{SU_m}} = s - \left(\frac{\text{Price}_{C_i}^{PU_j}}{\text{Power}_{C_i}^{SU_m}} \right) \tag{4.23}$$

Let $\frac{\partial U_F}{\partial \text{Power}_{C_i}^{SU_m}} = 0$, we have:

$$q_F^* = \text{Power}_{C_i}^{SU_m} = \frac{\text{Price}_{C_i}^{PU_j}}{s} \tag{4.24}$$

which means that for a given strategy $\text{Price}_{C_i}^{PU_j}$ chosen by the PU, the best response strategy of the SU is to select the power value as given in equation (4.24).

According to the Stackelberg game concepts, the best strategy chosen by the SU is known for the PU, and it takes it in its utility function, where equation (4.20) can be expressed as follows:

$$U_L = s\left(\text{Power}_{C_i}^{Max} - \frac{\text{Price}_{C_i}^{PU_j}}{s} \right) + \left(\text{Price}_{C_i}^{PU_j} * \frac{\text{Price}_{C_i}^{PU_j}}{s} \right) - \left(\frac{\text{Price}_{C_i}^{PU_j}}{s} * \log B_{C_i} \right) \tag{4.25}$$

We rewrite equation (4.25) as follows:

$$U_L = s * \text{Power}_{C_i}^{Max} + \frac{\left(\text{Price}_{C_i}^{PU_j}\right)^2}{s} - \text{Price}_{C_i}^{PU_j} - \left(\frac{\text{Price}_{C_i}^{PU_j}}{s} * \log B_{C_i} \right) \tag{4.26}$$

Now, we differentiate the utility function of the PU as expressed in equation (4.26) and let the result equal to zero, we get the following:

$$2 * \text{Price}_{C_i}^{PU_j} - \log B_{C_i} - s^2 = 0 \tag{4.27}$$

At the beginning of the game, the PU would notify the SU with the size of the shared spectrum of each channel, the number of the channels that could be assigned for its transmission and the channel price. Then the SU will set its power level to be used in the transmission.

There are many constraints that should be taken in consideration of the two players before setting their best strategies.

$$0 < \mathit{Power}_{C_i}^{SU_m} < \text{Power}_{C_i}^{Max} \tag{4.28}$$

The power to be used by a SU must be more than zero and less than the maximum allowed power value.

Another constraint is that the SU interference value over an i^{th} channel should be in the accepted range as follows:

$$0 \leq I_{C_i} \leq \gamma_{C_i} \tag{4.29}$$

where γ_{C_i} represents the predefined interference threshold on i^{th} channel of the PU.

4.3.3 Performance Evaluation

In this section, we demonstrate the performance of our proposed scheme by showing some simulation results. We assume the following system parameters:

Table 4.4 Simulation Parameters

Parameter	Value
Number of PUs	3
Number of channels per PU	4
Number of SUs	5
Channel bandwidth $\mathbf{B_{C_i}}$	10Kbps
Desired bandwidth	[10,100] Kbps
Frequency Band	{10,20}KHz
Data-transmission coefficient s	5
Cost coefficient r	2
Maximum interference over a channel $\boldsymbol{\gamma_{C_i}}$	1.5
Maximum power	5watts
Price range	$[0,20]

We use MATLAB to simulate our model by using the simulation parameters in Table 4.4. In order to demonstrate the performance of our model, we show the values of the best strategies to be chosen by both players PU and SU where this point leads to Nash equilibrium.

The utility function of each game player is demonstrated in Figure 4.5. Where the lower shape represents the utility of the SU and the upper one is for the PU. It illustrates that the utility function of PU increases while the chosen strategy which is the channel price is increasing. Meanwhile, while the strategy of the SU which is the power value to be used for its data transmission is increasing, its utility increases too. According to the two-dimensional plane indexed by two decision variables price and power, the PU calculates the Nash equilibrium point (q_L^*; q_F^*) according to equations (4.24) and (4.27) respectively. Then it waits until the SU announces its policy q_F as q_F^*. In our simulation, we have calculated (q_L^* ; q_F^*) = (14.5; 2.9) ,which is referred by the arrow, where the first value represents the best price of the PU and the second value represents the best power value of the SU such that there is an equilibrium between both of them. It is clear that the utility function of the PU does not achieve maximum utility when q_F^* = 2.9. However, if and only if the PU selects q_L^* = 14.5, then the SU would cooperate with the PU and the whole system attains the highest efficiency.

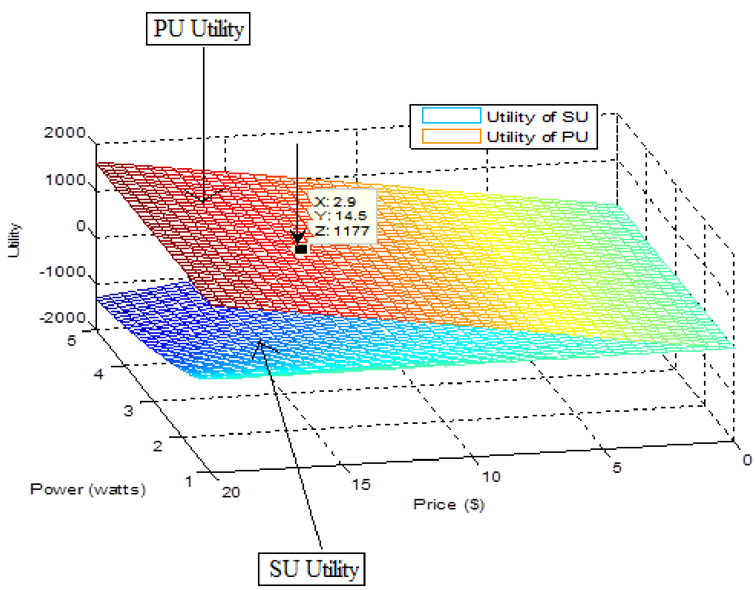


Figure 4.5: Utility Functions of PU and SU.

In Figure 4.6, the utility functions of one PU and one SU are shown while the power range is [0,1.5]watts. The point marked by the arrow is the Nash equilibrium point ($10, 0.675 watts) which illustrates that the best price of the PU channel considering the SU's utility is \$10 and the best power value to be assigned for the SU considering the PU's utility is 0.675 watts.

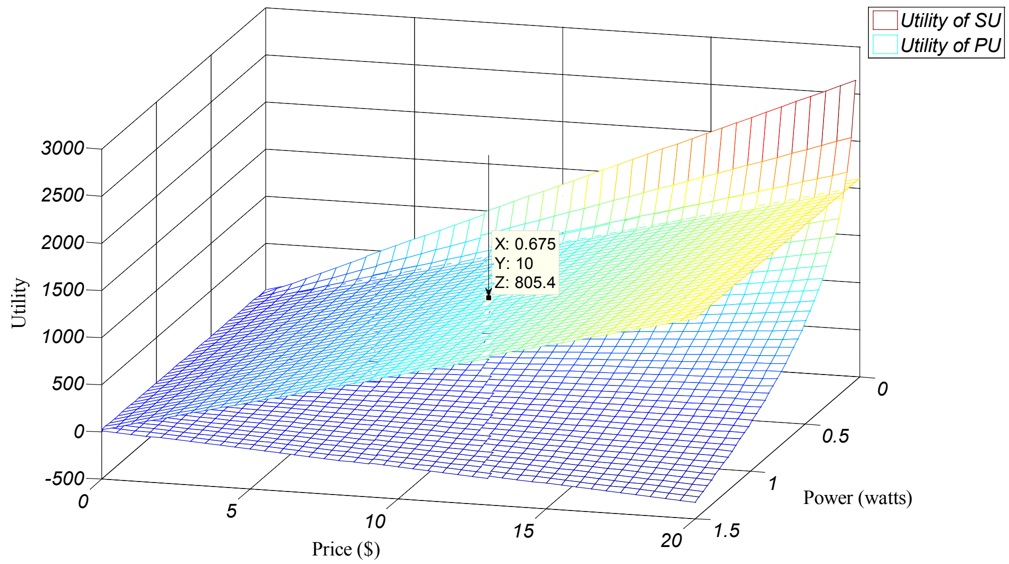


Figure 4.6: Nash Equilibiruim Point between PU and SU.

4.4 Comparison between the Power Trading Approaches (Without Game Theory and With Game Theory)

In this section we compare the non-game theoretic model proposed in Section 4.2 and the game theoretic model proposed in Section 4.3. To do so, we simulated the scenario shown in Figure 4.1.

The profit of a PU is computed by using equation (4.13) in the two different models as shown in Table 4.5. It is revealed that the profit of a PU in the power trading model without game theory is higher than that in the model with game theory. This is because the former model focuses in increasing the profit of the PUs without considering the QoS of SUs, while the later one focuses in achieving a balance between both PUs and SUs. The purpose of using the game theory is to balance the utility achieved by the game players (PUs and SUs). The row before the last in Table 4.5 shows the power values that are assigned to SUs for their data transmissions. The power values, in the game theory approach, are equal to the value of the SU's best strategy as defined in equation (4.24) which is 0.675 watts. Last row shows that the profit of a PU, in the non-game theory model, is higher than that one in the game theory; however the game theory approach allows the different users to satisfy their objectives by balancing them. For instance, in the non-game theory approach PU1 can get $11.17 as a profit by assigning 0.43 watts for each SU (SU1 and SU2), while in the game theory approach the profit is $7.06 but the two SUs can use higher power values. In general, applying the game theory reduces the profit of the PU and increases the transmission power of the SU providing more satisfaction to the SU. The big advantage of using game theory is the balance that could be attained between both the players (PUs and SUs).

The non-game theory approach aims to let the PUs achieve high profit by leasing their unused band, while the game theoretic approach aims to make a balance between the PUs and SUs i.e. let the PUs achieve accepted profits and the SUs use proper power values. These power values and profits make the best utility for each player (PU and SU) with respect to other player (SU and PU).

Table 4.5 Comparison between our Two Approaches

Case	**Our model without Game Theory**						**Our model with Game Theory**					
	PU_1			PU_2			PU_1			PU_2		
Served SU	SU_1	SU_2	Both	SU_1	SU_2	Both	SU_1	SU_2	Both	SU_1	SU_2	Both
${P_{assigned}^{C_i}}^{PU_j}$	1.05	0.89	0.43(for each)	1.05	0.89	0.43(for each)	0.675	0.675	0.675(for each)	0.675	0.675	0.675(for each)
Ω	5.87	8.44	11.17	6.04	9.53	12.51	2.62	3.17	7.06	2.62	3.17	6.94

4.5 Summary

The different developed models were presented in detail in this chapter. Moreover, their performance was evaluated and shown. The evaluation of the developed model of the power trading process without game theory clarifies the efficiency of the developed model in terms of achieving the objectives of the different users in the system. Meanwhile, it increases the utilization of the spectrum.

The model of the power trading with game theory was evaluated and the results of the evaluation shows that the model helps the primary users to gain a high revenue by leasing their spectrum to secondary users which get proper power values to use for their data transmission. The model achieves a balance between both users by converging to a Nash equilibrium point. By comparing both models we can conclude that applying game theory in our model helps to balance the different conflicting objectives of both types of users (PUs and SUs).

Chapter 5: Conclusion and Future Work

5.1 Conclusion

The power management issue in Cognitive Radio Networks is investigated in this thesis. More specifically, this research focuses on the power management and control in the two main functionalities of cognitive radio network, which are spectrum sensing and trading. We developed an efficient method to exchange the results of spectrum sensing process between the sensing nodes. This model helps in reducing the power consumed through the results exchange phase. Next, the power management and spectrum trading issues are merged together leading to a new approach of power trading. Two new models are developed for power trading where in the first model the power is traded during a negotiation process between the spectrum owners and the requesting users. The spectrum owners (PUs) gain more profit by trading proper levels of power to the requesting nodes (SUs) that desire to utilize the spectrum for their data transmissions. Finally, we used the Game Theory to develop a model that balances the users' objectives and reaches a Nash equilibrium point.

The performance of the developed models is evaluated using simulation. The simulation results of the model developed for exchanging the spectrum sensing results show less power consumed in comparison with the broadcast model. The simulation results of the non game theory power trading model illustrates that the spectrum is available for SUs data transmission while the PUs get more revenue by renting the spectrum. However, the drawback of this model is that the objectives of PUs to gain more profit are met more than the SUs objectives of spectrum utilization. The channels' prices and the interference level on the PUs side should be balanced with respect to the proper power levels to be used by SUs and the desired data rate on the SUs side. The Game Theory is applied to achieve this balance between the different goals of users and is shown in the simulation result of the game theory model.

5.2 Future Work

For the future work, many ideas could be applied to enhance the efficiency of the three developed models in this research. In the spectrum sensing model, the way of forming the clusters, choosing the clusters heads, and exchanging the sensing results could be improved and made more dynamic to further decrease the power consumed.

In the two models of power trading the complexity in terms of profit and transmission power level is a nice and attractive topic in CRN and it could be considered as a part of future work. In power trading with game theory model the Nash equilibrium does not achieve the highest profit for each primary user so the channel price to be offered to the requesting SUs, which gives the highest profit, could be obtained by applying optimization techniques.

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