Spectrum Utilization Using Game Theory

Thesis Submitted for Degree of MPhil

By

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ABSTRACT

Spectrum utilization is the most recent communications issue which takes great deal of attention from communication researchers where most of the efforts have been dedicated for spectral efficient utilization. Spectrum sharing is one of the solutions considered in the problem of lack of available frequency for new communication services which are unlicensed. In this work we propose an optimal method for spectrum utilization to increase spectral efficiency. It considers the problem of spectrum holes found in Primary User's (PU) band and detected using one of the spectral sensing methods. The solution is formulated with the help of Game theory approach in such a way that the primary user who has unoccupied frequency can share it with a group of secondary users (SU) in a competitive way. One of the SUs will be a secondary primary user (SPU), share available frequency from PU then offer his sharing to serve other SUs in different rate of sharing. Each user in the group of secondary users has a chance to be secondary primary user depending on reputation of each SU. Enhancing reputation is the only way for any SU to assure a share in the spectrum where it considered the factor of increasing or decreasing rate of sharing as well as factor of being SPU or an ordinary SU. A theoretical non-cooperative game model is introduced in a comparison with a proposed non-dynamic technique which depends on number of subscribers who occupy frequency in each time period. Multi-users compete on sharing the frequency from one of the users who offers sharing at a time when he has low number of subscribers that occupy his band. It is found that non-dynamic sharing results in inefficient spectrum utilization which is one of the reasons of spectrum scarcity where this resource is allocated in fixed way. Spectrum sharing using game theory solves this problem by its ability to make users compete to gain highest rate of spectrum allocation according to the real requirement of each user at each time interval. The problem of urgent case is also discussed when the primary user comes back to using his band which is the specific band of sharing with the secondary users group. SPU makes it easy to unload the required band from multi-users because PU does not need to request his band from each SU in the group.

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CHAPTER 1

Introduction

1.1 Motivation

Spectrum is considered the backbone of wireless communications and its allocation issues are becoming a problematic issue that is inadvisable to have a choice of its bandwidth without careful analysis of information theoretic limits. However, although there is increasing in wireless telecommunications and wireless internet services but the problem in lack of spectrum is both a pragmatic and perceptual problem. The problem of spectrum scarcity appears from poor utilization caused by spectrum use policy [1], this makes spectrum frequency is an expensive commodity. Some regions suffer from reaching full capacity in the cellular infrastructure while increasing demands in the market on such service, in other regions (for example, in many rural areas, a single broadcast TV source may be nearly 200 miles away and there is a little or no local TV service) there are significant opportunities to provide internet and telecommunications services using this under-utilized spectrum [2].

Federal Communication Commissions (FCC) has studied frequency utilization and gave results in multiple allocations of all the frequency bands to show how the spectrum is crowd especially at the frequencies below 3GHz according to its useful characteristics. Figure 1.1 shows the spaces found in the frequencies between 0 and 2.5GHz. OfCOM in the United Kingdom found that most of the radio frequency spectrum was inefficiently utilized [3], FCCs Spectrum Policy Task Force reported vast temporal and geographic variations in the usage of allocated spectrum with utilization ranging from 15% to 85%. These measurements seriously question the efficiency of the current regulatory regime [4]. The licensed users which have the right to use allocated band don't use it all the time. These are considered wasted frequencies that can be used by other users which are unlicensed.

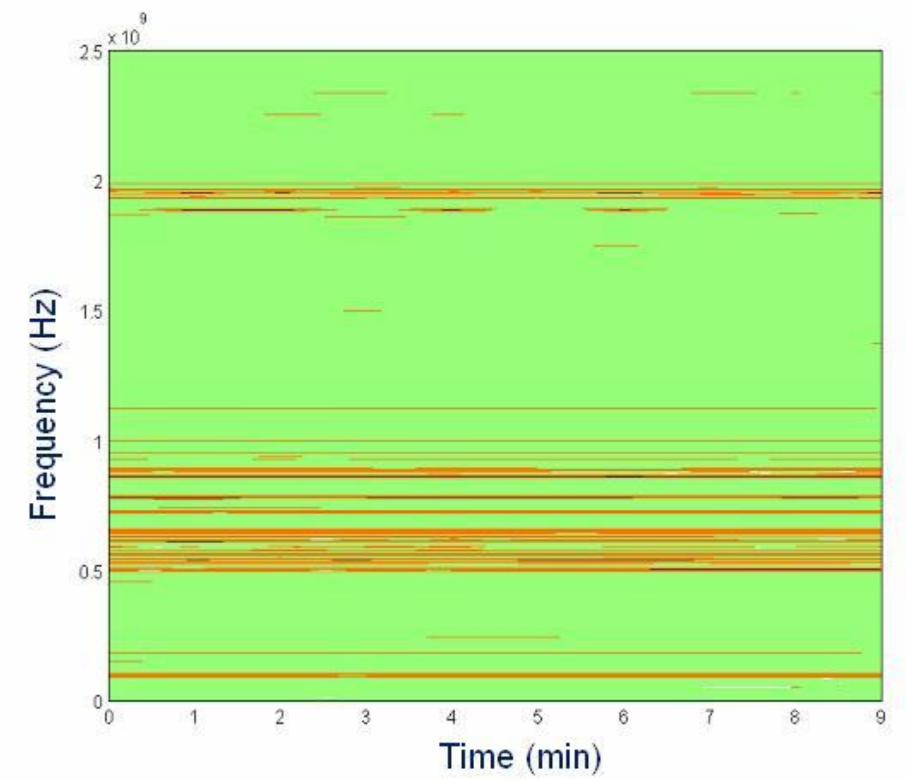

Figure 1.1: 0-2.5GHz spectrogram taken at BWRC over 9 minute intervals; green color indicates empty spectrum. [3]

This problem made many regulators issued new rules and programs to get full advantages from the spectrum and unlicensed bands as follows [2]:

1- Federal Communication - Recommends opportunistic usage of wireless technologies in TV bands.

2- Defense Advanced Research Projects Agency – Allow multiple users to share the spectrum through adaptive mechanisms.

3- US Army – Has been researching the so called “Adaptive Spectrum Exploitation” for real time spectrum management in battlefield.

The basic principles of the three above programs are if the radio devices can explore the wireless spectrum and locate sparsely-used spectral bands, they can exploit these bands in an opportunistic way to improve not only the devices’ performance but also the overall spectrum utilization.

Several researches have focused in this area and suggested different methods for optimal utilization of the frequency. One such method for implementing above recommendations and programs is 'Opportunistic Spectrum Sharing' mechanism. In this mechanism we can classify the wireless users into two types:

- Primary Users (PU): are the licensed users those who are allocated frequency bands by the regulatory body as they pay for using these bands therefore they have the right and the authorization to utilize their frequency so they have the first priority.

- Secondary Users (SU): are unlicensed users those who need to use some bands of the frequency which are allocated to the primary users but they have no authorization for using them.

The FCC legalized a utilization type that gives the right to the secondary users to share the spectrum with the primary users at the time when the frequency isn't used by the primary user on the following conditions: Firstly don't cause an interference with the primary users and secondly the SUs must vacant the band as soon as possible when it has been needed by PU and always sensing the environment to stop the frequency using when the SU finds that PU become active again.

1.2 Aim of the Research

In this thesis the best methods are investigated used for spectral allocations and opportunistic utilization to the allocated spectrum bandwidths. The main objective of the research is identifying a method that can make spectrum sharing among multi-user possible. Cognitive radio technique is the candidate method for this purpose as it has the ability to measure, sense, and learn the environment in order to find where and when can we use the spaces which may be found in the allocated bands and then we need a decision on how and who can use these spaces. Game Theory is one of the methods used for making a rational decision; it has deferent types, in our research we used non-cooperative method as this assumes that there is no cooperation among users. There are different types of scenarios which can be implemented to achieve this goal. One of such methods depends on the using of the spectrum allocated by license. This method called licensed users as Primary Users and we want to use the spaces in their bands by sharing among multi unlicensed (Secondary) users in a competitive way.

1.3 Contribution to Knowledge

In this research we identified a method that can be used to utilize the spectrum allocated to (PU) using the Game Theory. This method is considered the best way for making a rational decision, assuming that there is scanning to the environment to sense the spaces in the bands used by (PU) and it intends to share its frequency with multi secondary users in a competitive manner. The benefit then returns to both primary user that can get revenue from selling its own spectrum, and secondary users by subleasing available channels. The scenario can be put according to the agreement between (PU) and (SUs), so we assume the price is a unit price with number of categories each SU has one of these categories and will compete with other SU according to number of units it obtained. The contribution in this work is to propose a new method of sharing among multi-secondary users to compete on the available frequency by considering one of the SUs in the group as a primary secondary user who serve other users. The choice of the SU to be primary SU depends on each user’s reputation according to its need of sharing which assure maximum rate of utilization and minimize the time. The contribution in this work can be illustrated by the following points:

1. Find a new method of spectrum allocation as poor utilization within one hundred years of spectrum sharing came from fixed frequency allocations which led to fracturing in spectrum utilization [5]. Therefore, this work can be used as a new method of allocation also, which means if there is unlicensed band intended to be allocated to users, then this band could be rented to multi-user at same time. Each user can benefit from the frequency band according to his real demand at a specific time, and then no lost of frequency found because no user will request to use the band only if he needs. It can be used as spectral management method to allocate frequency by this way rather than fixed allocation.

2. In this research we found a mathematical model formulated which can be used to utilize the spectrum using the Game Theory as it is considered the best way for making a rational decision.

3. A new method of sharing among multi-secondary users (SUs) has been proposed to compete on the available frequency found in primary user's band by considering one of the SUs in the group as a secondary primary user who serves other users after taking his demand from the available band. The choice of the SU to be primary SU depends on each user's reputation according to its need of sharing which assure maximum rate of utilization and minimize the time.

4. Solving urgent case problem when PU needs from SUs to quickly vacate the band in such a way makes it easy because PU has to request band vacating from one user always (i.e. the secondary primary user).

5. Increase spectral efficiency by finding best method for spectrum utilization as it is (i.e. spectrum) a scarce resource.

6. Contribute to encourage development of wireless technology if we could provide enough resource for implementation.

7. Develop the market, as it could be considered as an economically successful business then new products and services will be found.

1.4 Thesis Structure

This thesis is organized as follows:

Chapter 2 introduces literature review of the spectrum efficient utilization related to spectrum managements and the ITU models and its recommendations about the best rules for managing the spectrum. Monitoring also discussed as an important key of spectrum management. Then spectrum efficiency has been illustrated for both low and high efficiency with the main important methods used in this field then cognitive technique explained as one of the most recent and the candidate mechanism for spectral efficient utilization so it takes separate section.

Spectrum sensing which considered as one of the important tasks in the cognitive cycle, is discussed in Chapter 3 which shows the main concepts, sensing dimensions, and some of previous researches on this subject are viewed too.

Chapter 4 introduces game theory with its basic concepts and definitions and its relation with communication systems.

Chapter 5 proposes 'Non-Dynamic Spectrum Allocation' methodology and mechanisms with its results.

In chapter 6 method and numerical results of the second method used for efficient spectrum utilization 'Spectrum Sharing using Game Theory' has been proposed. A comparison between the two methods proposed in Chapter 5 and Chapter 6 is also illustrated in this chapter.

Chapter 7 concludes the work of this research and suggests future modifications which can be applied to the model explained in chapter 6

CHAPTER 2

Spectrum Utilization

Soaring number of mobile service subscribers, the huge numbers of viewers and listeners to television and radio, the transition to digital broadcasting, and the new wireless technology as Wi-Fi and WiMAX radio access where all of these require the radio spectrum, demonstrate that there is a great importance of the spectrum. In addition, the importance of the spectrum came from its direct relation with the national security and emergency services and because of increasing the demands for interference-free frequency assignments, then it is necessary to have international coordination and *manage* this wealth efficiently, where the ITU plays a particular role.[6]

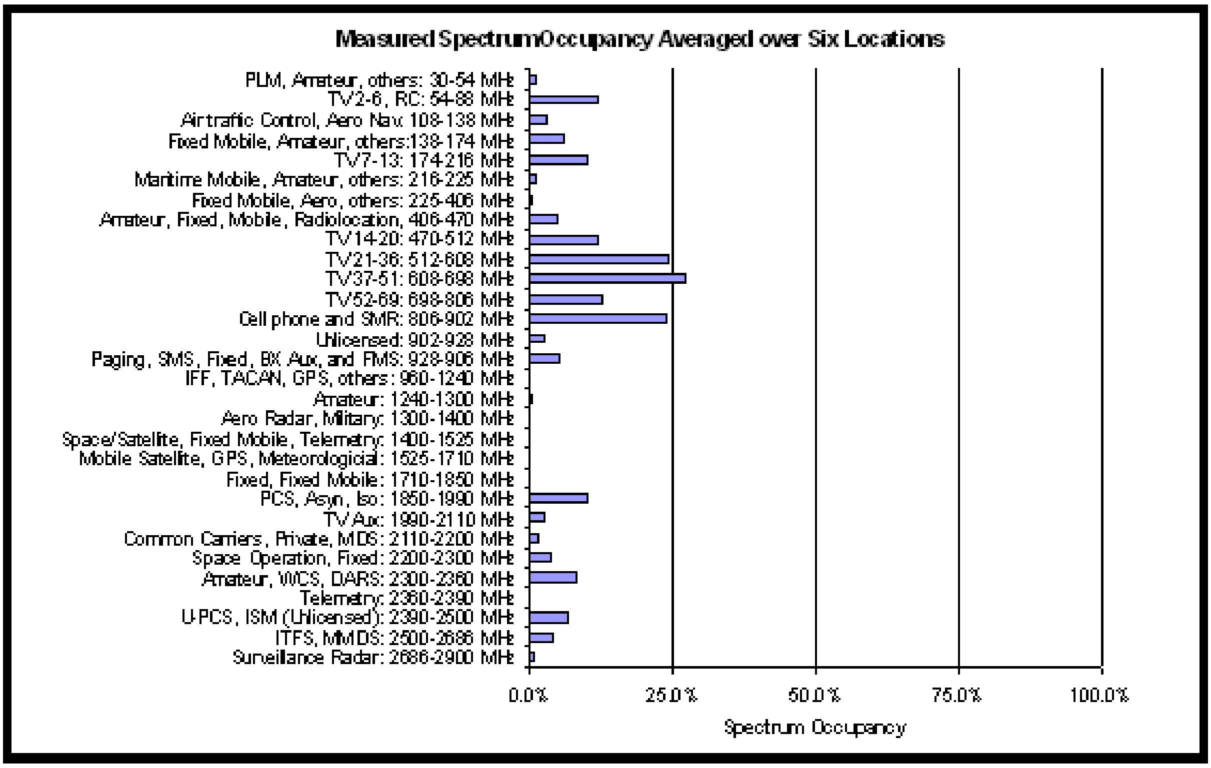

Figure 2.1: Spectrum Occupancy in six locations [7]

Communication researches are focused on spectral research as it considered a national resource. The research results on the spectral efficiency proved that there is bad utilization of the frequency. Figure 2.1 shows the average of the spectrum occupancy as an example of six locations [7]

2.1 Spectrum Management:

Spectrum management has two central issues they are, price and allocation. Choices in allocation issue are depending on competing uses. There are many applications uses spectrum as resource. The spectrum usage is different from application to another one where:

- Several applications don't matter on which frequency, they work on any frequency.
- Some applications can work on different frequencies but on a specific range.
- Some applications can work on different amounts of spectrum.

Allocation decisions for available frequency range have been made in competing way among applications or services and implemented in two stages under traditional management of spectrum. According to international agreement, first stage is taken place by allocating frequency to particular applications. Second stage is depend on the base "first-come, first-served", where particular frequencies are allocated to certain operators within the applications assigned in first stage. The operators have assigned frequencies are charged rate of fees according to revenues expected from operators' services. New technologies provide applications or services with higher frequency opportunities; the problem is when this frequency is already allocated to operators or other applications. Development in the spectrum technology is growing faster than movement in spectrum regulation. The frequency become more scarce and valuable with the new communications technology and widening range of services which require radio spectrum as a resource of implementations. That leads to necessitating in spectrum efficient utilization. Inertia and legacies of licensees and bad spectrum management caused inefficiency in spectrum field.

The public sector in United Kingdom holds about half the spectrum below 15 GHz, the largest user is the UK Ministry of Defense. This also one of the spectral inefficiency reasons because public sectors use spectrum inefficiently. [6]

ITU developed and implemented four radio spectrum management models:

- The traditional “command-and-control” model, it gives spectrum use the harmonization, therefore it can develop "economies of scale" and reduce costs of equipment manufacturing to benefit both manufacturers and customers. So it is considered by some as the most suitable model for "public interest policies".
- A “market-based property rights” model where exclusive usage rights and spectrum trading and pricing is involved. It should provide Incentive to change technology of applications which are spectral-based and usage that yield in different degree of harmonization and production falling costs.
- The “commons” or “unlicensed” model is "open" model that it is available to all users on a shared basis, but in conditions:

1- They should have certain technical limits determined previously "(e.g., total transmission power/output limits)".
2- For interference avoidance, equipment certification is required.

It has the following features

1- Usage rights flexibility.
2- Lowers the limitations on access to radio spectrum usage.
3- Opens effective spectrum allocation in case of absence of centralization.
4- As a result, it develops market by quicker new market entry.
5- Develops technological spectrum-efficient applications (e.g. Wi-Fi) because of its above features.

The only limitation of this model is that it may encourage overuse spectrum while the efficient use of alternative resources are required.

An “easement” model, it depends on intelligent or smart technologies. The model based on the market-based and commons approaches. It was implemented more recently when there was scarcity in spectrum, so it can only be used where there are spaces in spectrum use. The intelligent or smart technologies enable spectrum sharing. They allow to unlicensed users of devices (called them as secondary users) to use spectrum in the same frequencies which used by licensed users the only users who have the rights to use this spectrum.

It is clear from all above that:

1- The ICT sector has been developed in field of spectrum management policy, where it was limited to pure "command and control" then become including the other three models with more contributions.
2- It is impossible to apply a single model in all situations.
3- Higher flexibility is preferred from many operators in using their allocated spectrum.

ITU has discussed the regulators problems and their challenge in achieving a balance among the four models to find the best for their circumstances. Spectrum management takes very important place in the agenda of regulatory in developing countries since wireless is the most popular technology in these countries. [6]

2.1.1 Key Spectrum Management Functions:

- Spectrum Planning
- Spectrum Engineering
- Spectrum Authorization
- Spectrum Monitoring

Planning, authorization and engineering keys are depending on the information received from monitoring key as data base to do their functions properly; therefore, we need to know what is monitoring [8].

2.1.2 Monitoring

Monitoring is calculated detailed information to be supplied to the Spectrum Planning and Authorization so it can be defined as determinations to support the proper functioning of the general process of spectrum management

2.1.2.1 Why Monitoring?

- Information on the technical or operational characteristics of radio systems can be obtained from monitoring.
- Monitoring helps regulatory bodies in implementing rules and regulation by providing them with information used to determine if there is compliance with these rules and with technical and operational standards.
- It supplies spectrum manager with general measurements used in planning of channel and band usage and assure the effectiveness of current planning and the activities of authorization.
- Spectrum managers need to avoid incompatible usage and prevent interference, so spectrum monitoring helps them in this function and in identifying harmful interference sources.
- Spectrum occupancy and the statistical information about its technical and operational nature can be provided by spectrum monitoring.
- Organized crime can be detected and combated with the help of spectrum monitoring. [8]

2.1.2.2 International monitoring system

Member countries of the International Telecommunication Union cooperate among them in the operation of an international monitoring system, because it is uneconomical and inefficient operational to develop and duplicate the monitoring facilities. They need monitoring facilities operation to ensure that the frequencies use is compliant with the internationally planned spectrum framework. According to the monitoring determination, ITU sends an infringement report for non-compliance condition to the country which has infringed via the "Radio communication Bureau".

Spectrum monitoring is provided with accurate, complete and timely information on current assignments and licenses from spectrum authorization and spectrum engineering functions. The benefit of this information is to compare the level of spectrum use or occupancy with assignments in order to use the spectrum resource efficiently [9].

2.1.2.3 Who is responsible of Monitoring?

- Spectrum Regulators.
- Defense departments. (Have responsibility over frequencies allocated to governmental use).
- Transport departments. (Have responsibility over frequencies allocated to governmental use).
- Private sector participants in fields of industry associations, advisory and councils.

Regulators are different in dependency where some of them are independent agencies, and others are attached to the Ministry of Telecommunications. [8]

2.2 Efficient Spectral Utilization

Spectral Efficiency can be defined as a scale of a radio performance to measure the traffic load which can pass through a given bandwidth or the quantity of users or services that can be simultaneously supported by a limited radio frequency bandwidth. If we have a given traffic load we need to increase spectral efficiency to optimize the service.

ITU-R Recommendation SM.1046-1 on “DEFINITION OF SPECTRUM USE AND EFFICIENCY OF A RADIO SYSTEM” mentions that efficient spectrum utilization is achieved by one of the following methods:

- Geographical spacing
- Frequency sharing
- Time-sharing or time division
- Orthogonal frequency use
- The isolation obtained from antenna directivity

Spectrum Utilization factor, U, is the product of the frequency bandwidth, the geometric (geographic) space, and the time denied to other potential users [10]:

$$U = B.\ S.\ T \qquad (2.1)$$

Where, B: Frequency bandwidth, S: geometric space (usually area) and T: time.

The area here is considered as an important factor in spectrum utilization and can be classified into regions for example: Urban, Suburban, and Rural, as shown in figure (2.2). The traffic density is different from one area to another and the spectrum utilization will be different accordingly. [10]

In cellular radio system the spectrum efficiency can be expressed in several ways such as number of channels per cell, Erlangs per square kilometer, number of users per square kilometer. [11]

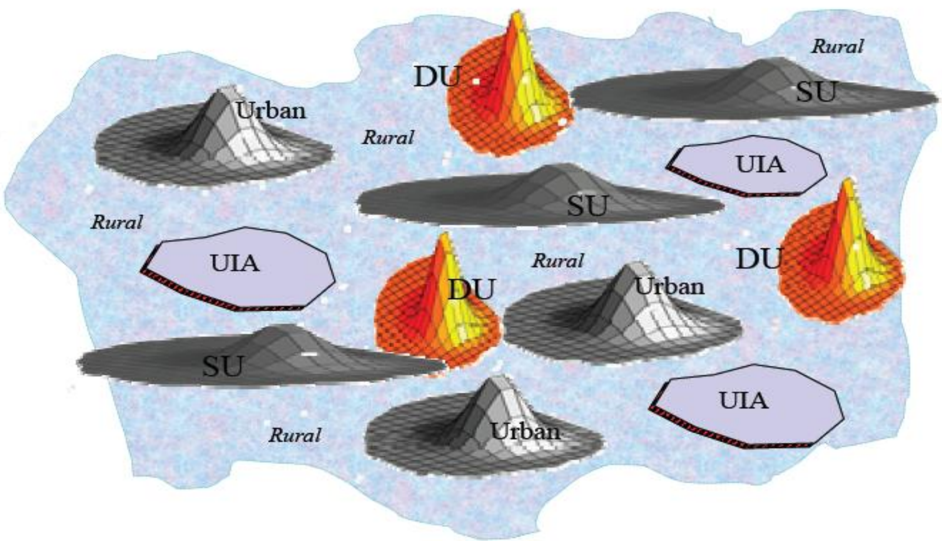

Figure (2.2): Area classification [10]

2.2.1 Low Spectral Efficiency

Low spectral efficiency values are obtained when:

- Given data rate (b/s) is transmitted through a very large bandwidth.
- Very small data rate (b/s) transmitted through a given bandwidth.
- No large bandwidth & no small data rate, but a large number of receive antennas

2.2.2 Methods of Efficient Spectral Utilization

We can utilize spectrum efficiently by:-

2.2.2.1 Organize geographical spacing

As in equation 2.1, the definition of the spectral efficiency factor depends on frequency bandwidth, geometric space and time, one of the methods of increasing spectral efficient utilization is by organizing the areas. ITU-R Recommendation SM.1046-1 mentions a definition of Spectrum efficiency (SUE) of a radio communication system by [10]:

$$SU\,E = M \div U = M \div (B \,.\, S \,.\, T) \qquad (2.2)$$

Where, M: amount of information transferred over a distance.

According to the area classification that is mentioned in section 2.2 above, the traffic distribution will be uneven as well. Therefore it is required to make an organization to the area of utilization in order to calculate the spectral efficiency that is defined in equation 2.2 as it needs to calculate U in each sub-area which it equals to the product of frequency bandwidth, the geometric space (area), and time.

However, there is requirement of founding and developing computational model for SUE which may be tuned for specific city or group of cities and it should meet computations requirements such as flexibility and capability to create rules; ability to deal time to time and geographical differences; finding the best possible utilization depending on traffic pattern; ability to evaluate efficiency in a network with multi types of technology**;** considering the gain which may be achieved by using new techniques such as smart antenna and network synchronization or another technique available at defined point in time.

Computational model may be used and developed for assessing spectral utilization called Computational Model for Spectral Efficiency with abbreviated name COMSUE. The model helps in finding the geographical variations influence on the spectrum utilizations in addition to other factors such as time, type of technology and technique used in the measurements. [10]

2.2.2.2 Using OFDM Technique

Orthogonal Frequency Division Multiplexing (OFDM) concept was born in the mid-1960s as a multi-carrier transmission technique. Recent researches in frequency field found and adopted the OFDM as "an effective technique for high-speed bidirectional wireless data transfer". It can be used in WiMax, DAB, DVB-T because it has particular features such as [12]:

1- OFDM is not affected by channel defects.
2- At a particular rate of transition, OFDM as a comparison with traditional modulation scheme can transmit with lesser bandwidth. Therefore, it is considered as a technique that uses spectrum frequency very efficiently.

2.2.2.3 Using Mobile WiMax rather than GSM/EDGE

A comparison made in [13] concluded that between Mobile WiMax and GSM/EDGE, it is found that around 20% to 40% higher spectrum efficiency can be offered if we use Mobile WiMax instead of the established GSM/EDGE technology according to the traffic model has been assumed in this comparison.

2.2.2.4 Using digital cellular channels

In [14], the author found as a result of his comparison between digital cellular and analog cellular channels that higher spectral efficiency can be obtained if he use digital cellular channels rather than the latter. The parameter of measuring spectrum efficiency used here is called radio capacity. It is proved that splitting analog channels did not increase the spectrum efficiency in cellular radio systems, while it (i.e. spectrum efficiency) increased using digital cellular channels.

2.2.2.5 Sectorization

Sectorization distributes channel resource more thinly among the different sectors. This will reduce, for a given cellular cluster size, co channel interference and increase the Signal to Interference ratio (S/I ratio). If the cluster size remains constant, spectrum efficiency of a sectorized system will be reduced. [11]

In [15] it has been adopted a definition of spectrum efficiency by expressing it in terms of area, bandwidth, and Erlang.

$$\text{Spectrum Efficiency} = \text{Erlang} / (\text{BW x area}) \tag{2.3}$$

Erlang is: the total amount of traffic carried in the cellular system.

Cluster size can be reduced since lower co channel interference found in case of sectorized cellular system, and, accordingly increasing the spectrum efficiency of the overall system as shown in figure 2.3.

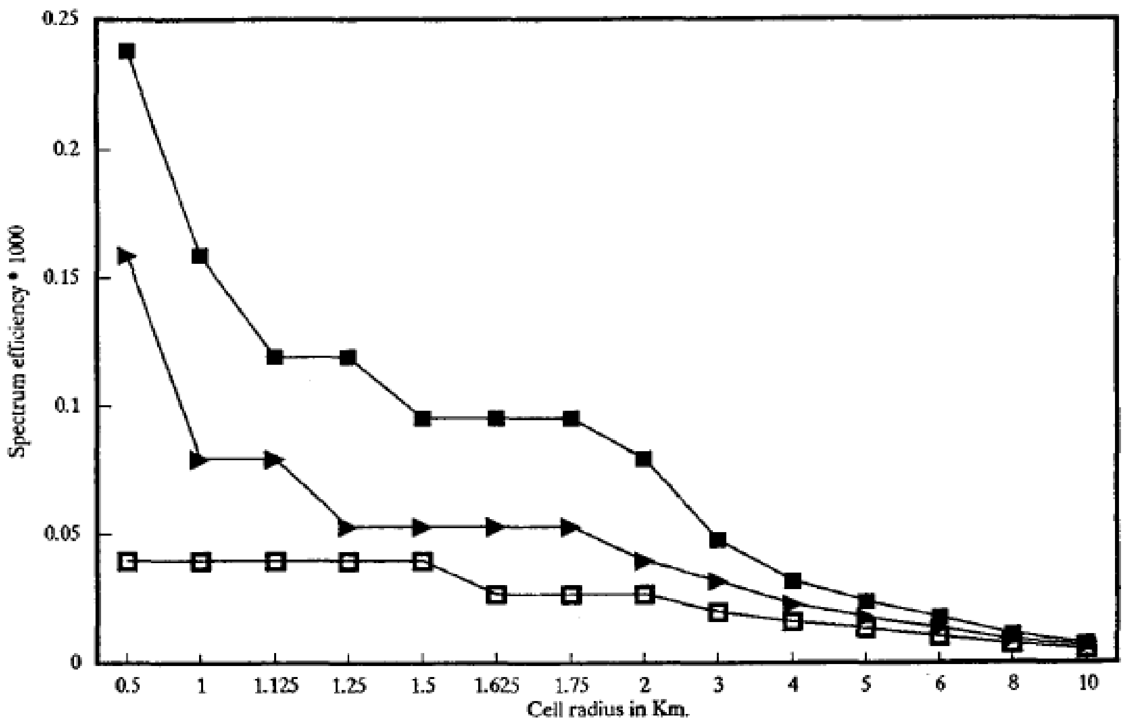

Figure 2.3: Spectrum Efficiency versus cell radius for different cellular configurations [11]

In [11] also it was shown that "higher spectrum efficiency is achieved by reducing the cluster size in a sectorized system without lowering the S/I ratio below 17 dB".

2.2.2.6 Cognitive Technique

Cognitive technique is a recent research topic used to increase spectral efficiency.

2.3 Cognitive Radio & Cognitive Network

Cognitive Radio (CR) technology, defined first in 2000[16], and then it had been advocated by Federal Communications Commission (FCC) to be considered as the best technique for implementing opportunistic spectrum sharing.

A Cognitive Radio can be defined as it is "*a radio that can change its transmitter parameters based on interaction with the environment in which it operates*" [17]. Sometimes secondary user is called a cognitive user as it (i.e. cognitive radio) is the technique that enable secondary user to use or share the spectrum opportunistically.

The differences between the cognitive radio and cognitive network are:

1. The goals of each one, the goals of the cognitive network are how to modify the performances of end-to-end network; but the cognitive radio goals are focused on the radio's users only.
2. The types of communication systems, cognitive network can deal with both wired and wireless networks which means that it is useful with heterogeneous types of network; but cognitive radio can be used only in wireless systems.
3. SDR (Software-Defined Radio) provides cognitive radio with tunable parameters which is useful to know the optimization space of the cognitive process; and SAN (Software Adaptable Network) is used with cognitive network to allow cognitive process to adapt the network.

In [2] the author concludes that *"cognitive radio technology is a way in which one radio or even a network of radios is able to learn a useful degree of adaptively that aids the user, the network, and/or the spectrum owner"*. And he viewed the findings of the previous researchers, such as:

Rondeau and Bostian have proved that a radio can learn proper adoptions successfully to a spectral environment that optimize for objective metrics by studying the use of Genetic Algorithm (GA) used to learn in given a set of objective metrics how a radio could best respond to a spectral environment.[2]

A radio has to recognize the locations and conditions visually, owner's voice and visual characteristics; should have the ability to take verbal commands. That’s all what Mitalo had proposed.

Game theory has been studied by Neel and Reed to apply it to a radio as a member of a cognitive network. They were able to analyze protocols to prove that with game theory cognitive radio behavior could result in stable network behavior. [2]

These researches will develop the market, if we could consider it as an economically successful business, new products and services will be found before general cognition is applied in practice on a radio.

2.3.1 Cognitive Networks

Cognitive networks as it is described in [2] *"has a cognitive process that can perceive current network conditions, and then plan, decide and act on those conditions. The network can learn from these adaptations and use them to make future decisions, all while taking into account end-to-end goals"* .As we mentioned, cognitive system is said to be a cognitive radio or layer except if it works with a network and end-to-end scope.

End-to-end means all the elements may be found in networks that have a contribution in the process of transmission of a data flow. The network probably includes the subnets, routers, switches, virtual connections, encryption schemes, mediums, interfaces, or waveforms, to mention just a few. Software Adaptable Network (SAN) must be fed with elements to modify. These elements are supplied by cognitive network since SAN depends on network which has tenable element, like SDR in cognitive radio, which depends on elements of radio operation such as time, frequency, bandwidth, code, spatiality, or waveform to be modified.

2.3.1.1 Advantages, Limitations, Cost

Advantages:

The cognitive network can be used to improve the end-to-end performance and its objectives as resource management, quality of service (QoS), security, access control, or throughput.

Limitations:

The cognitive networks have limitation in adaptability of the network elements which are hidden or underlying and flexibility of cognitive process.

Costs:

The cost of the network in terms of communications and processing, architecture roll-out and maintenance must be less important in comparison with the advantage of using the cognitive network to improve the performance. Therefore cognitive is not suitable for networks like fixed or static wired networks that have expected behaviour while the ideal candidates for cognitive are heterogeneous wireless networks. [2]

2.3.3 Cognitive Radio

Recent rule of CR spectrum management considered all new spectrum users as secondary (cognitive) users and they can work in a condition that they must detect and avoid the primary users (Primary user means the user that has the priority to use a specific part of spectrum because it uses the band by license).

A new technology becomes easily to implement because of unlicensed band which gives it (i.e. new technology) chance to arise. But it faces a problem since there are other bands that used by other technology and the spectrum bands are usually licensed to certain services, such as mobile, fixed, broadcast, and satellite, to prevent harmful interference among different networks [18]. The new technology must avoid interference with them. Therefore, it couldn't use the unlicensed band with its full capabilities but it is recognized that licensed bands are used partially (i.e. not full utilization). However, cognitive radio devices are used to improve the efficiency of Spectrum-Utilization. The main functions of CR devices are:

- Sensing the environment.
- Detecting the unused channels or portions in the licensed band.

- Access these portions opportunistically.

The main component of CR concept is the ability to sense, measure, learn, and be aware of:

1- Parameters related to the radio channel characteristics;
2- Availability of spectrum and power;
3- Interference and Noise temperature;
4- Radio’s operating environment;
5- User requirements and applications;
6- Available networks (Infrastructures) and nodes;
7- Local policies and other operating restrictions.

Example:

We have licensed band as a primary network or user and unlicensed band, represents a secondary network or user. If the primary network leaves some holes (see figure 2.4) in its band because it does not always use its designated channel, the entire spectrum has spaces can be utilized as a spectral opportunity between t2 & t3 to be accessed by a secondary network.

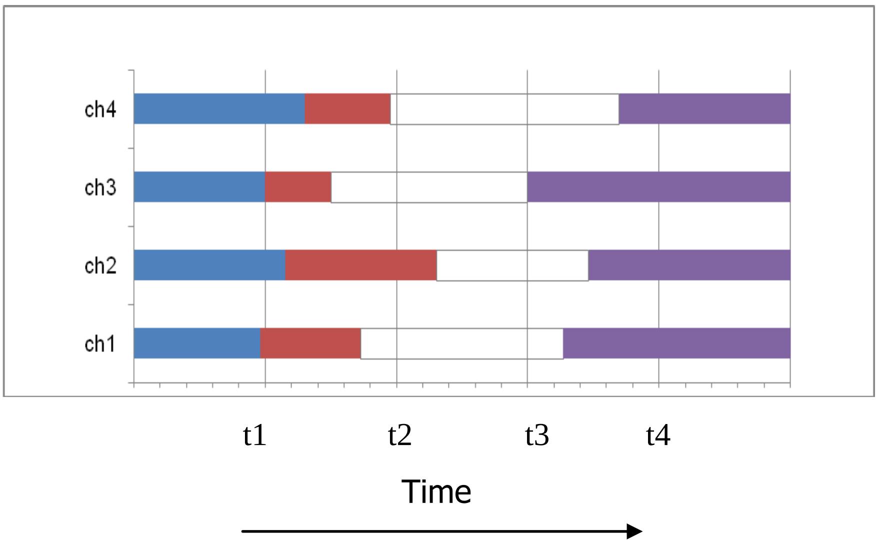

Figure 2.4: The blank spots represent holes and each hole then referred to as spectral opportunity [2]

To achieve the goal of Cognitive Radio it requires development of a new hardware/software and changing the current spectrum allocation policies. SDR

(Software Defined Radio) is used to develop radio interfaces in a flexible and powerful ways for providing spectral agility.

The research in this issue – spectral efficiency – increased in recent years and the researchers need to answer the following questions:

1- To what extent the improvement can be done?

2- How sparsely-used spectrum bands can be discovered and identified by individual devices?

3- How these spectrum bands to be prioritized or characterized?

4- How and when spectrum bands should be utilized?

2.3.4 Cognitive Cycle

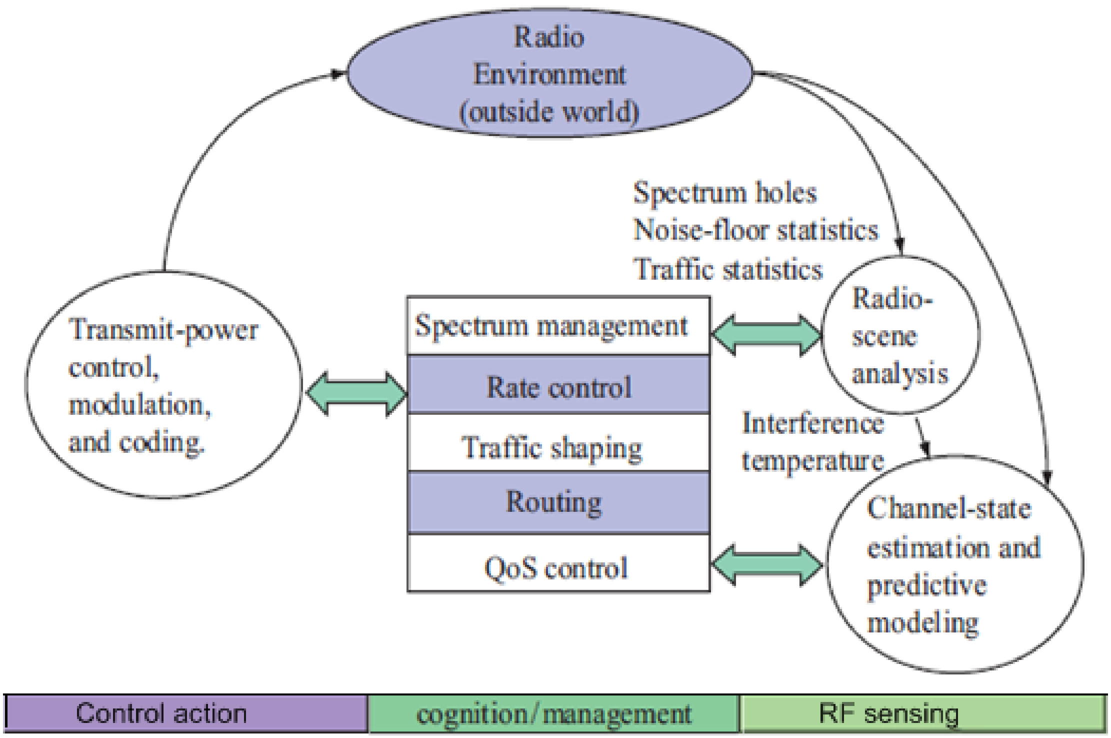

Figure 2.5: Basic Cognitive Cycle [2]

The cognitive cycle includes three major components shown in figure 2.5 and as follows [2]:

1. RF sensing:

This task deals with prediction and spectrum sensing, hence, it places on physical layer issues. The main functions of this task are detecting spaces or holes may be found in spectrum (or unused bands), estimating state information of the channel such as Signal to Noise ratio, total interference estimation (in the radio environment), and channel capacity prediction for use by the transmitter.

2. Cognition/management:

Cognition and management task deals with issues of controlling the opportunistic spectrum access by spectrum management, traffic shaping, routing, and provisioning of Quality of Service (QoS).

3. Control actions:

The main functions of this task of cognitive cycle are controlling of transmission rate, adaptive coding and modulation, and controlling of the transmit-power.

2.4 Summary

There are methods for operations to each task that are mentioned in this chapter. For example one of the methods for task 2 (i.e. cognition/management) is Game Theory approach as the method that has been proposed in [19] in which the author has proposed a method of optimum spectrum allocation in cognitive radio using game theory. There are also large number of papers and researches that has been published about the task 1 (i.e. RF sensing).

In this thesis we will focus on the cognition/management in particular on the use of game theory applications approach within their mechanism.

CHAPTER 3

Spectrum Sensing

3.1 Sensing and Efficient Spectrum Utilization

The spectrum as it is allocated to the users by licenses and then these users have the highest priority to use the licensed frequency bands. Therefore, licensed users called primary users that have the right in utilize the spectrum. The spectrum became scarce and demands increased on the frequency as resource of services implemented by new users. On the other hand the primary users (PU) do not utilize their bands full utilization (i.e. there are spaces or holes in the licensed bands). So that, new users were allowed to use the holes found in allocated frequency but with lower priority as they considered secondary users (SU). However, interference is another issue faced SU because the PU is not responsible on offering frequency to the SU if it harms PU's subscribers. Therefore, it becomes the duty of SU to exploit the holes in PU's bands in a condition prevent PU from interference. This can be done by using the capabilities offered by cognitive radio which one of them is sensing, this is the most important task need for efficient spectral utilization.

Spectrum Sensing can be identified as method of measuring: [2]

1- The spectral content
2- The interference
3- Primary users existence detection
4- Noise
5- Spectral holes

All above measurements serves SU responsibility in exploiting the licensed band; so that, SU called sometimes as cognitive user. The characteristics of spectrum using by cognitive radio technique obtained across multiple dimensions which are time, frequency and space. Type of signals, which occupying the spectrum such as (modulation, waveform, bandwidth, carrier frequency, etc.) can be also determined by cognitive technique. Following are multi-dimensional radio spectrum spaces can be utilized in a way of opportunity [2]:

3.2 Sensing Dimensions

The ways of exploiting and measuring the spectrum space or holes are defined by the definition of spectrum opportunity which is often referred as "*band of frequencies that are not being used by the primary user of that band at a particular time in a particular geographic area*" [20]. The conventional opportunity exploits only three dimensions of the spectrum space: time, frequency, and space. However, other dimensions need to be explored such as the code dimension, angle dimension, and signal dimension of the spectrum space. Naturally, new challenges for detection of this new opportunity will be brought about.

1- Frequency

Spectrum opportunity in this dimension comes from the band situation when not all the bands are used at the same time simultaneously, i.e. availability in the part of frequency as illustrated in figure 3.1 below. Then we can get opportunistic usage from some available bands; in other words, opportunity in the frequency domain.

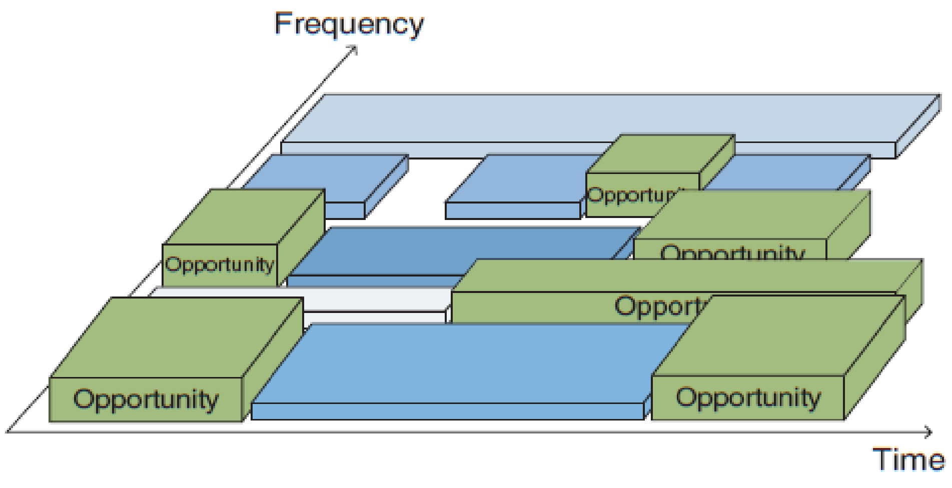

Figure 3.1: Opportunity in both frequency and time dimensions [2]

2- Time

This domain is time corresponding when there is a specific part of the spectrum available in time, i.e. the band isn't used continuously and all the time. That means there are times for this part of spectrum to be available can be utilized in opportunistic usage, also shown clearly in figure 3.1. [2]

3- Geographic space

At a given time the spectrum may be occupied in some parts of the geographical area while it is available in other area parts. Propagation loss (path loss) in space is the issue of this dimension it can take advantage from this loss.
The measurements depend on interference temperature i.e. we can determine the existence of a primary transmission in a local area from situation of interference existence in that area. But there is a problem of hidden terminals arises here that required a careful determination and decision. [2]

Figure 3.2 shows two areas A and B, the opportunity can be found in region A where it is assumed that no existence of a primary transmission in this area.

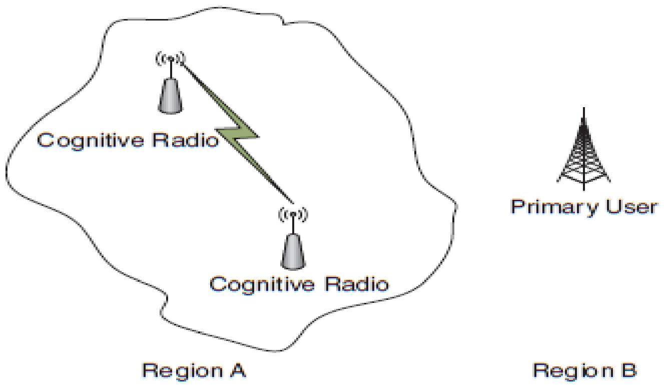

Figure 3.2: Geographic Dimension of Spectrum opportunity [2]

4- Code Dimension

It determines the used codes and multipath parameter. At a given time the spectrum over a wideband is used through spread spectrum. In spite of that, there is availability over this band. Without interfering with primary users, simultaneous transmission could be done in code domain with the orthogonal code with respect to codes used by primary users.

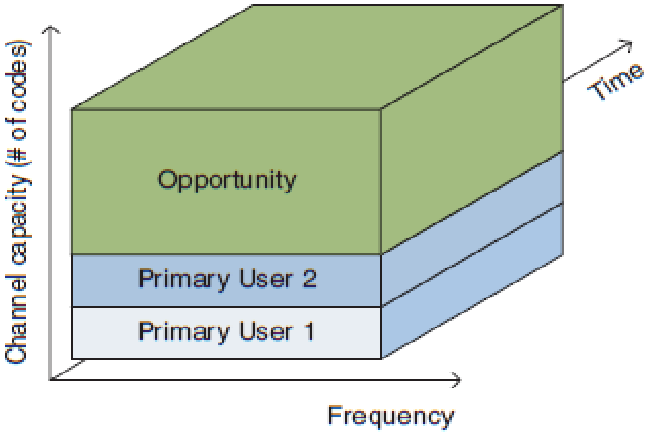

Figure 3.3: Code Dimension Sensing [2]

This offers opportunity in code domain not only detecting the spectrum usage. Then sensing is required in [2]:

- Spreading code
- Time hopping (TH)
- Frequency hopping (FH) sequences those used by primary users.
- The timing information to enable secondary users to synchronize their transmissions with respect to primary users.

The relation between code dimension and frequency with time is shown in figure 3.3

5- Angle Dimension

If it is assumed that the primary users and/or the secondary users transmit in all the directions, then spectrum opportunities in angle dimension can be done by the help of the knowledge of the location/ position or direction of primary users. That mean the secondary user can transmit in a direction differs from the direction of the primary user transition in a condition avoiding interference with primary user [2].

Then it needs to detect the locations of primary users and its beam directions (azimuth and elevation angle) as illustrated in figure 3.4.

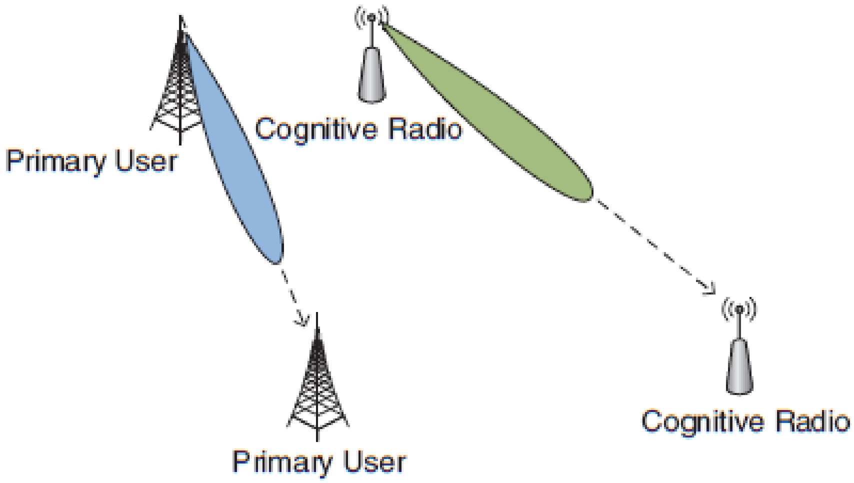

Figure 3.4: Angle Dimension Sensing [2]

6- Signal Dimension

If both the primary and the secondary users transmit a waveform in such a way that no opportunity can be found in all the above dimensions i.e. they transmit at a specific band for a given time in a geographical area in all the directions. Even when that case happens exploitation can be done in the signal dimension by transmitting an orthogonal waveform that does not create interference with primary users. This requires waveform identification in addition to spectrum estimation, and signal polarization to be sensed. [2]

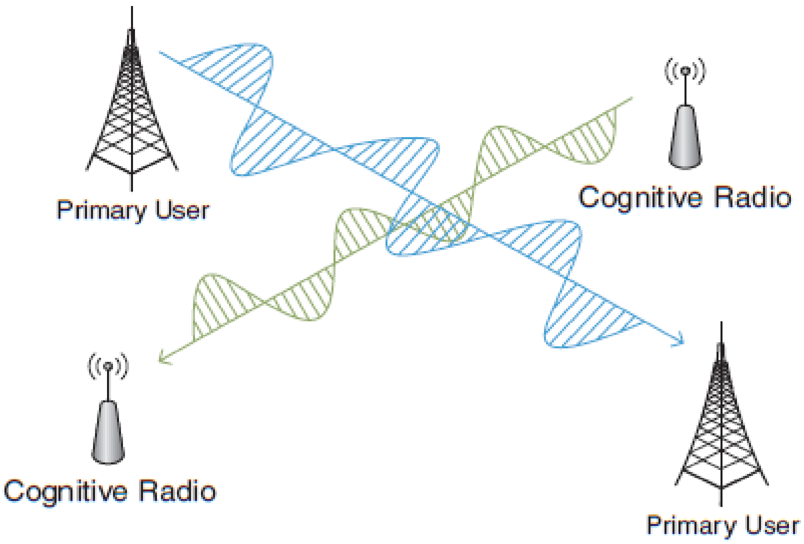

Figure 3.5: Wave Dimension Sensing [2]

3.3 Spectrum Sensing Aspects

There are several methods used in spectrum sensing for cognitive radio and various aspects of spectrum sensing [2] would be briefly explained as follows.

- Matched Filtering
- Energy detector
- Spectral Correlation (Cyclostationarity)
- Wavelet Based Sensing
- Waveform Based Sensing
- Cooperative Sensing
  - Centralized
  - Distributed

3.3.1 Matched Filtering:

It is used to detect primary users with a known transmitted signal .It's main advantage that considered as a feature in comparison with other methods is in achieving certain probability of false alarm or miss detection in short time [2]. Matched filtering has also an important property that it increases output signal to noise ratio when there is a signal corrupted by white Gaussian noise (AWGN) [18].

Then it is required from cognitive radio to demodulate the received signals. Perfect information about features of primary user signal is need such as modulation type, bandwidth, operating frequency, etc.

Drawbacks in this Method:

1- Complex implementation because for all signal types, cognitive radio needs receivers

2- It needs to execute various receiver algorithms for detection; hence it works with large power consumption [2].

3.3.2 Energy Detector:-

The opposite of filtering method is the energy detection method where the secondary user cannot get perfect knowledge about the primary user's features, then the energy detection considered as an optimal detector. It is known as radiometry that measures the received waveform energy to detect unknown signals.

Simply we can implement the method by a block diagram shown in figure 3.6 [18]

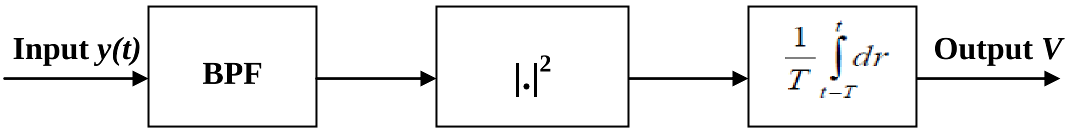

Figure 3.6: Energy detection [18]

The purpose of the bandpass filter (BPF) in the beginning of the process is to select the desired bandwidth and limiting the noise. The energy detector is represented by two components; a squaring device and a finite time integrator. The output signal *V* from the integrator is[18]:

$$V = \frac{1}{T}\int_{1-T}^{t} |y(r)|^2 \qquad (3.1)$$

The signal is detected by comparing the output of energy detector with a threshold, which depends on the noise floor. It is preferred because it is simple in implementation and computation and does not need knowledge on the primary users' signal.

3.3.3 Cyclostationarity-Based Sensing

If there is a signal having statistical properties and can vary cyclically with time, then this process called cyclostationary. Cyclostationary processes treated with two different approaches the probabilistic approach and deterministic approach [21]. In sensing task of cognitive radio cyclostationarity feature detection is used as a method has a capability of detecting primary user transmissions because it can exploit the cyclostationarity features of the received signals. Signal periodicity or the statistics like mean and autocorrelation causes Cyclostationary features [2]. Many advantages offered by cyclostationary features in comparing with the stationary models. In [22] a signal detector is presented that exploits spectral correlation. Its goal is determining the presence or absence of a cyclostationary signal in noise. Therefore the cyclostationarity-based detection algorithms are used to differentiate noise from primary users' signals [2].

3.3.4 Cooperative Sensing

Spectrum sensing process including many problems can be solved by cooperative sensing such as:

- Solving problems due to fading, noise uncertainty and shadowing.
- Decreasing probability of miss-detections.
- Decreasing probability of false alarms.
- Decreasing sensing time.
- Solving hidden primary user problem.

Only one cognitive radio can estimate traffic in a specific geographic area locally, or it can be combined information from various cognitive radio. In fact, the performance would be degraded when the cognitive radio has no knowledge about the primary user's location; "*the challenges of cooperative sensing include developing efficient information sharing algorithms and increased complexity*"[2]. The researcher in [22] modeled a simple Listen-Before-Talk (LBT) scheme and investigated his mechanism via analysis and computer simulation. He discussed the problem of interference to primary users caused by cognitive radio devices using spectrum access mechanisms based on simple LBT scheme. The results proved that unutilized spectrum can be explored using simple local sensing without causing interference to existing users. While the analytical and numerical results show that spectrum capacity gains provided by collaborative sensing is higher than that provided by local sensing.

3.3.4.1 Advantages and Disadvantages of local and cooperative (or collaborative) sensing methods [2]:

- **Cooperative (Collaborative)**

  Higher accuracy; reduced sensing time and it can prevent shadowing effect and hidden node problems. While it has disadvantages in:

  Complexity of sensor, within-system cooperation and among-system cooperation; traffic overhead and requirement of control channel.

- **Local (Non-Cooperative)**

  It is Simple in Computation and implementation. While it has disadvantages in: inability to solve hidden node problem, multipath and shadowing.

The control channel in cooperative sensing architectures can be implemented by different methodologies. One of these methods can be selected according to the system requirements. These include a dedicated band, unlicensed band, and underlay Ultra Wideband (UWB) system.

3.3.4.2 Cooperative Sensing Fashions

Two fashions: centralized or distributed can be used to implement cooperative sensing as follows [2]:

Centralized Sensing

Centralized sensing consists of central unit using cognitive devices and collects the sensing information from it. The collected information used to identify the available frequency, then controls the cognitive radio traffic directly or broadcasts this information to other cognitive radios. Some researchers' results discussed in [2] as follows:

- Access Point (AP) represents the name of a central place where the hard (binary) sensing results are gathered. It is a method to reduce the fading effects of the channel and increase performance of detection.
- Another research worked on the above one for its sensing algorithm. Resulting detection and false alarm rates are given here.

- For detecting TV channels the sensing results are combined in a master node as a central node. To reduce the probability of missed opportunity, hard and soft information combining methods are investigated here.
- The results of other research show in terms of the probability of missed opportunity that soft information-combining surpasses hard information-combining method.

Distributed Sensing

Cognitive nodes in case of distributed sensing can share information among each other but they have their own decisions about the part of the spectrum they can use. It is no requirement for a backbone infrastructure; therefore it considered more advantageous.

3.4 Spectrum Sensing Methods

Following are some previous researches on the sensing methods mentioned above:

3.4.1 Energy Detection Methods

3.4.1.1 Multimode Spectrum Sensing Based on Energy Detection for Dynamic Spectrum Access

Dynamic Spectrum Access (DSA) is a spectrum sharing between licensed primary users (PUs) and unlicensed secondary users (SUs) in a way that unlicensed SUs are allowed to access the spectrum in a condition they do not make interference with the PU. Figure 3.7(a) illustrates the geographical overview of a DSA Network (DSAN) to share the spectrum with a PU. The DSAN, including several SUs, is located where the distance between it and the primary transmitter (PT) is d. A region of decodability around the PT is limited with a radius of rdec. Decodability region is the region in which PU receiver can only decode the signal if it is inside this region in the absence of interference and fading. The secondary users region which they are clustered in is with radius rs termed as DSAN. Since all the SUs are located in the region of decodability, then they can use the spectrum only when the PT does not transmit.

Two techniques *"for weighted combining of the channel sensing results of users: weighted gain combining and log-likelihood combining"* [23]. The power of receiving signal which received by SUs from PU is different on average from some SUs to others because of shadowing, or slow fading. The average power of the signal at a secondary node can be estimated since shadowing changes slowly over time.

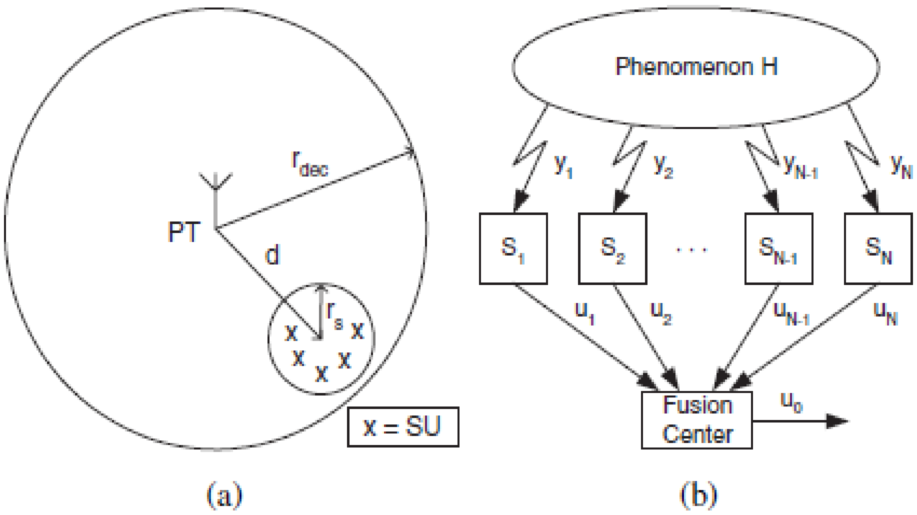

Figure 3.7: System model: (a) Geographical overview of the considered network, (b) Parallel cooperative detection topology with fusion centre [23]

Both techniques exploit the information that is direct measure for the node quality of detection in order to weight the information of the SUs to be able to enhance the detection quality.

The secondary users have to cooperate in sensing the channel state because in case of sever shadowing plus detection of Rayleigh fading single node is not reliable sufficiently for DSA. This technique of weighting which exploits the knowledge of the local mean SNR results in a great improvement compared to other techniques which do not use this information. Log-likelihood combining surpasses all the other techniques in the case of low number of nodes in the network and low SNR. A parallel network as shown in figure 3.7(b) represents the detection topology used for cooperative detection with a fusion center. It consists of more than one detector to observe the same phenomenon. The fusion center which is one of the nodes dedicated in the DSAN, receives the measurement statistics from the local detectors. [23]

3.4.1.2 Other Energy Detection Methods

Many researches have done depending on the energy detector-base sensing with different calculations and results as follows [2]:

1- In [24, 25] used energy detector to analyze and identify the idle and busy periods of WLAN channels.

2- The sensing in [26] has special case that is the cognitive radio has to be synchronized to the primary user network and the time of sensing is limited to slot duration. In this work a comparison is made for identifying the idle slots for exploitation by measuring energy level for each Global System for Mobile (GSM) slot.

3- Unused cellular slots are opportunistically exploited in [27] by approach similar to [26].

4- In [28], in order to identify the number of used TV channels a threshold is used to be compared with power at the output of Fast Fourier Transform (FFT) of incoming.

5- In [29], it is investigated the performance of energy detector-based sensing over various fading channels. Fading channels and closed-form expressions for detection probability under AWGN are derived.

6- The performance of energy-detector is observed to be degraded considerably under Rayleigh fading in [30]. Average probability of detection is also derived for energy detector-based sensing algorithms under Rayleigh fading channels and log-normal shadowing.

7- For unknown noise power scenarios it is suitable to use forward methods based on energy measurements as in [31]. It is suitable practically for cases where noise variance is not known because the proposed method estimates the noise level adaptively.

3.4.2 Cooperative Sensing Methods

Following are two methods for spectrum sensing using cooperative sensing method to scan the environment and detect the spaces in the spectrum that can be utilized opportunistically:

3.4.2.1 Cooperative Spectrum Sensing and Detection for Cognitive Radio

Suboptimal fusion rule is the basic notion of this method that handles correlation issues and it is not dependent on the model or on exact knowledge of the statistics of the signal.

The goal is to detect times when a specific licensed band at a particular place is unused and use the band for transmission avoiding any significant interference to the transmissions of the primary user (license-holder). The author considers the problems that face the secondary user (cognitive user) in order to design practical solutions to the detection problem which are:

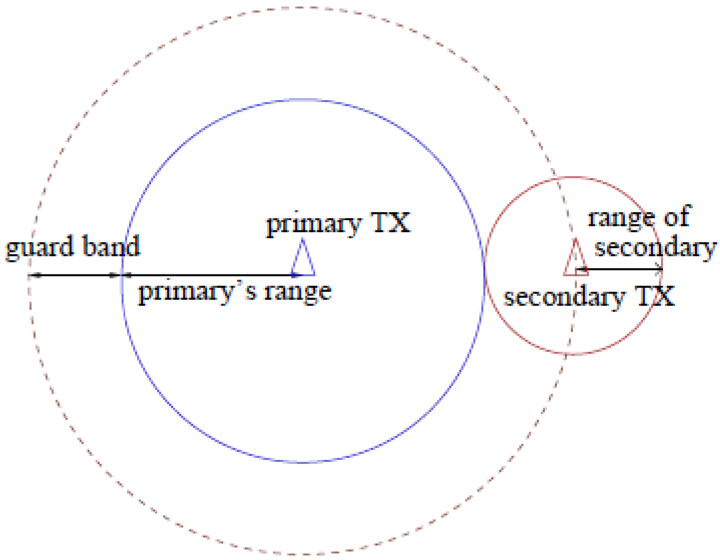

Figure 3.8: Guard band. The interior of the primary's range and the guard band together form the protected region. [32]

1- The SNR of the primary user's signal received by the secondary users may be very small. Then secondary users must be sure that they avoid interference even at the edge of the primary's coverage area as shown in Figure 3.8. The location of secondary users assumed to be within the primary's range or around it in the *guard band* this make a risk of potentially interference with the primary's transmissions.

2- The transmission scheme used by the primary users is not known by the secondary users and may be not synchronized to the primary's signal then secondary users use non-coherent feature detectors or energy detectors. That means poorer performances under low SNR.

3- Shadowing which causes in the hidden-terminal problem. Some secondary users may be located in such a way that is shadowed away from the primary's transmitter while there may be found secondary users that close to primary receivers that are not shadowed from the primary transmitter. Hence, it may be interference between the primary receiver's reception and the secondary when it transmits.[32]

3.4.2.2 Cooperative Spectrum Sensing Using Random Matrix Theory

This method introduced a new cooperative scheme for frequency band sensing for both AWGN and fading channels, uses asymptotic random matrix theory tools. The new scheme is related to the behavior of the largest and smallest random matrices' eigenvalue. The knowledge of the noise statistics is not required nor its variance.

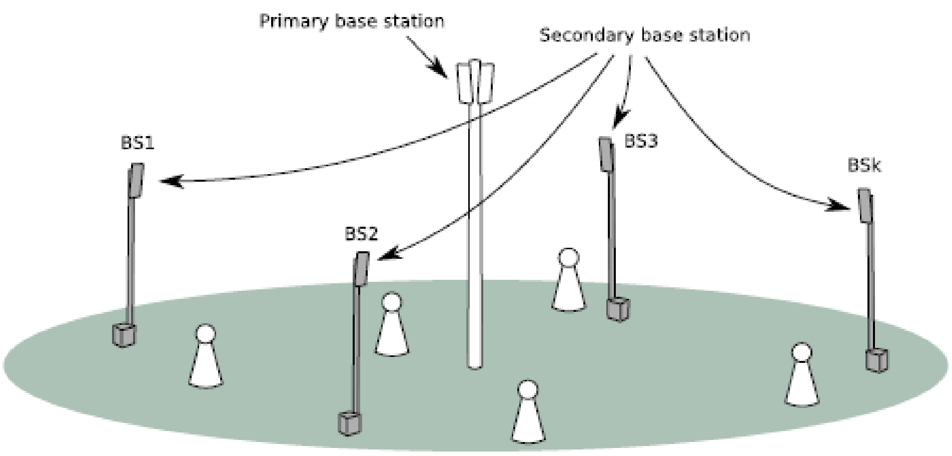

Figure 3.9: Considered scenarios for spectrum sensing. [33]

Figure 3.9 illustrates the scenario used in this method where the primary users (white figures) communicate to their dedicated (primary) base station. Cooperatively, secondary base stations *{BS*1, *BS*2, *BS*3, ... , *BSK}* are sensing the channel in order to detect and identify a space found in the medium to be exploited.

The author concludes the comparison between the performance of new cooperative spectrum sensing using random matrix theory technique and the cooperative energy detector scheme for both a known and unknown noise variance. The new one is quite robust and does not need any information of the signal or noise statistics. [33]

3.4.3 Distributed Sensing Methods

3.4.3.1 Distributed Spectrum Sensing for Cognitive Radio Systems

This method has the ability to modify the spectral estimation reliability and decrease the probability of interference between cognitive radios (secondary users) and the primary users (i.e. existing systems). The joint work of cognitive radio is the base of determining the spectrum occupancy instead of individually determination of each cognitive radio.

The block diagram of this method is shown in figure 3.10 as a parallel fusion network. Cyclic feature-based method for distributed signal detection and classification is proposed in this work. This technique is an approach for the unknown signal detection problem instead as opposed to using radiometer, which is "*highly susceptible to unknown and changing noise levels and interference*" [34]. There are important advantages of cyclic feature-based technique such as capabilities of signal classification and minimizing sensitivity to unknown and changing background noise, exploiting timing or phase properties of signal that is digitally modulated. IEEE 802.22 work group have a great deal of attention of such techniques.

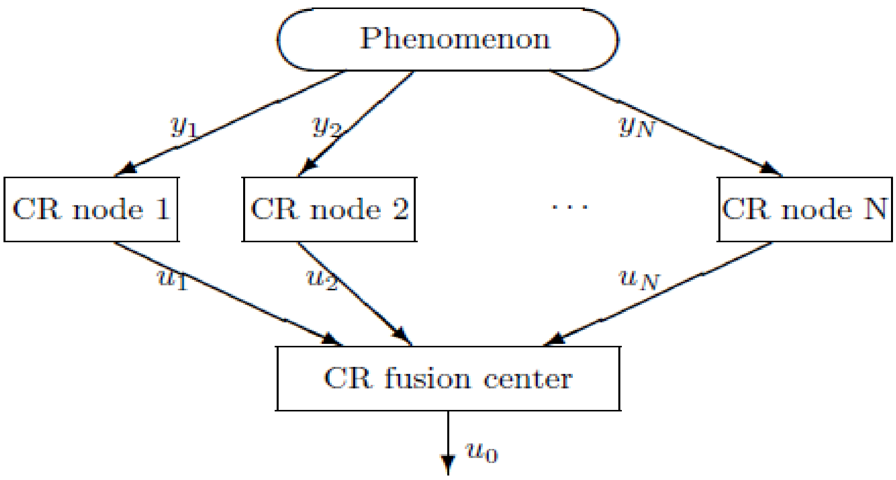

Figure 3.10: Block diagram of a parallel fusion network. [34]

Figure 3.11 shows that the probability of detection increases from approximately 30% to 60%, for a probability of false alarm equal to 10% if 10 sensors are used instead of using a single sensor to perform signal detection. The results also show that the use of cyclic feature-based methods for signal detection and classification provides reliable detection/classification even at low signal-to-noise ratio scenarios. [34]

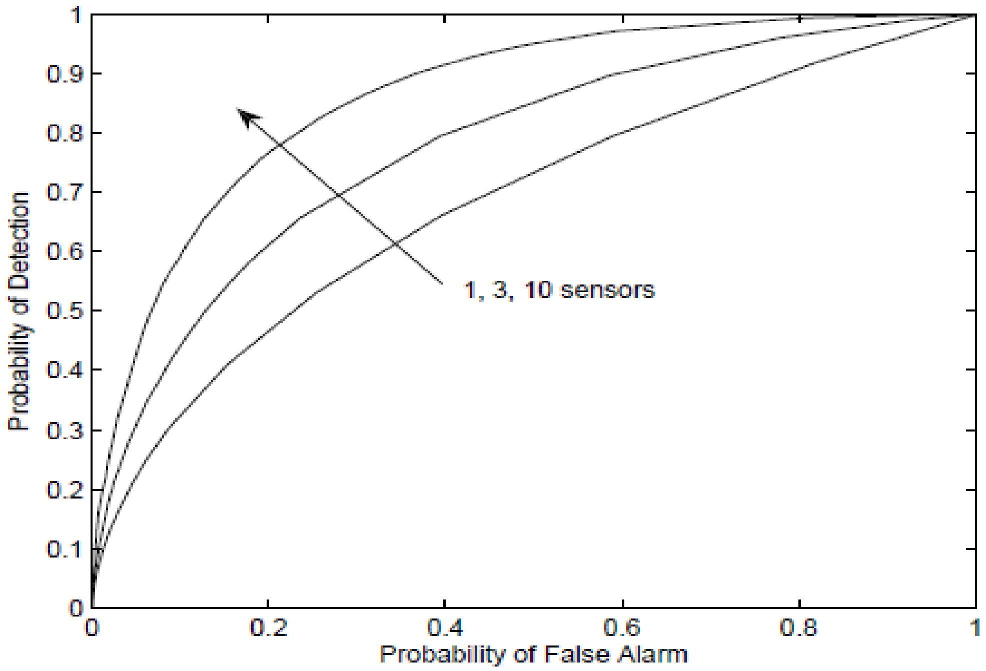

Figure 3.11: Distributed detection of a known signal in AWGN using single-cycle detectors [34]

3.4.3.2 Other Distributed Sensing Methods

Following are other researches about distributed sensing [2]:

- GUESS (Gossiping Updates for Efficient Spectrum Sensing) is proposed which is an incremental gossiping approach to perform efficient coordination between cognitive radios in the distributed collaborative sensing. The proposed algorithm has low-complexity with reduced protocol overhead and has robust to network changes and fast convergence as it does not require a setup phase to generate the clusters. Incremental aggregation and randomized gossiping algorithms are used in the same research for efficient coordination within a cognitive radio network.

- Another distributed collaboration algorithm is proposed that perform the collaboration between two secondary users in different locations. One of the users is located closer to primary transmitter, so it has a better chance of detecting the primary user transmission, cooperates with the second user which is far away. Also proposed algorithm for pairing secondary users without a centralized mechanism.
- Multi-Secondary users can share their sensing information among themselves by distributed sensing method. As a way of minimizing the network overhead due to collaboration, only final decisions are shared. Each secondary user receives decisions from other users then makes a decision according to others' decision. If any of the received decisions plus its own is $H1$, it would decide $H1$, a fusion rule known as OR-rule. This research results show the improvements of performance that achieved through collaborative sensing.

3.5 Urgent Case

Secondary user has to *quickly* vacate the licensed frequency band in urgent case if the primary user wants to use this portion of the band**.**

In [35] has been discussed a method of distribution change in frequency domain to empty licensed frequency band from secondary radio networks occupation. At the beginning the cognitive user has to sense and detect the change of spectrum activity i.e. the change in primary user action at urgent case. Therefore, the theory of quickest detection can be applied to detect the distribution change in observations as quickly as possible. The problem of unknown parameters of primary radio signal is solved by a successive refinement based quickest detection. The author here mentioned that this work is applicable to the single SU only and he was studying the problem of multi-user for the future work.

3.6 Summary

This chapter has been devoted to identify the sensing task and works of previous researchers as an introduction to our work that assumes to use one of the sensing methods. We need to scan the environment by sensing technique to detect dynamically the holes may be found in the allocated band of the PU to be efficiently utilized from the group of the SUs. Chapter 6 in this thesis will clarify the relation between sensing technique and the method of 'Spectrum Utilization Using Game Theory' that has been proposed in this work.

CHAPTER 4

Game Theory in Wireless Network

4.1 Introduction

In general Game theory is a study of how can we choose a rational choice if it (i.e. our choice) affects others and others choices affect us by providing a mathematical analysis of interacting decision-making processes and tools for predicting what might happen if there is conflict in interests among agents. It has the ability to give the way of how players make rational decisions even when they are interdependent and model decision maker with actions affect other decision makers independently [36].

Primarily, Game theory has been applied in economics as a method to model competition among sellers or companies: for example, if a company plans to enter new market, it should consider its competitors' actions in this field which they could make similar (or different) decision. Game theory has also been used to other fields, like politics and biology so recently; it has been applied to communications and networking to their problems in routing and resource allocation [37]. This ability attracts ad hoc network researchers to use game theory as a method of analyzing ad hoc performances [36].

4.2 Classifications of Game Theory

There are many types of games and they can be classified as shown in table 4.1 [38]:

Cooperative	Non-cooperative
Static	Dynamic (repeated)
Strategic-form	Extensive-form
Perfect information	Imperfect information
complete information	incomplete information

Table 4.1: Game's classifications1 [38]

There are further classifications as in the table 4.2 [38]

Zero – sum	Non Zero – sum
Simultaneous	Sequential
Symmetric	Asymmetric
Dominant	Undominant

Table 4.2: Game's classifications2

Each type has a specific use depending on the application which used. However any game is composed of three basic components: a set of players (i = {1, 2, 3, …,N}), a set of possible actions (Ai) for each player and a set of utility function mapping action profiles into the real numbers (Ui).

4.3 Game's Concepts

It is a game because each player strives to get maximum payoff in a competition with other player therefore it is necessary to have a mechanism to prevent any single player from individually improving her payoff by deviating, that is called 'Nash Equilibrium'. It sometimes be unique and other times is multiple (e.g. in coordination games). From all of above we must be able to define the game and its setting, also have to answer these questions [36]:

1- Who are the players of the game?
2- What are the actions for these players?
3- What objectives each player has?
4- Equilibrium existence for the game. If it exists, is it unique?
5- Do players update their strategies by a dynamic process if it exists?
6- If the answer of question 5 is 'yes', what is that dynamic process?

4.3.1 Extensive Form

Extensive form or sometimes called tree form describes how the game is played over time with some important roles. Direct analysis may be done in extensive form, or by converting into an equivalent strategic form [39] as shown in figure 4.1. Each node here is a player which is specified by a number on the node. Actions of players are represented by the lines between nodes. The numbers at the end of the tree represent players' payoffs [21].

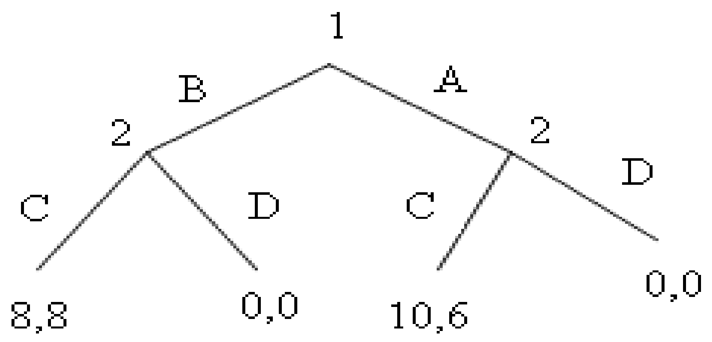

Figure 4.1: Extensive (tree) form [21]

If *Player 1* moves first and chooses *A*, *Player 2* sees *Player 1*'s choice and then chooses *C* or *D*. If *Player 2* chooses *C*, then *Player 1* has *payoff* 10 and *Player 2* has *payoff* 6.

4.3.2 Strategic Form

The strategic form is also called normal form. In a strategic form we can see players, each player's actions which also called strategies that can be taken from players and *payoff* for each player all are represented in a table or matrix as in figure 2.4.

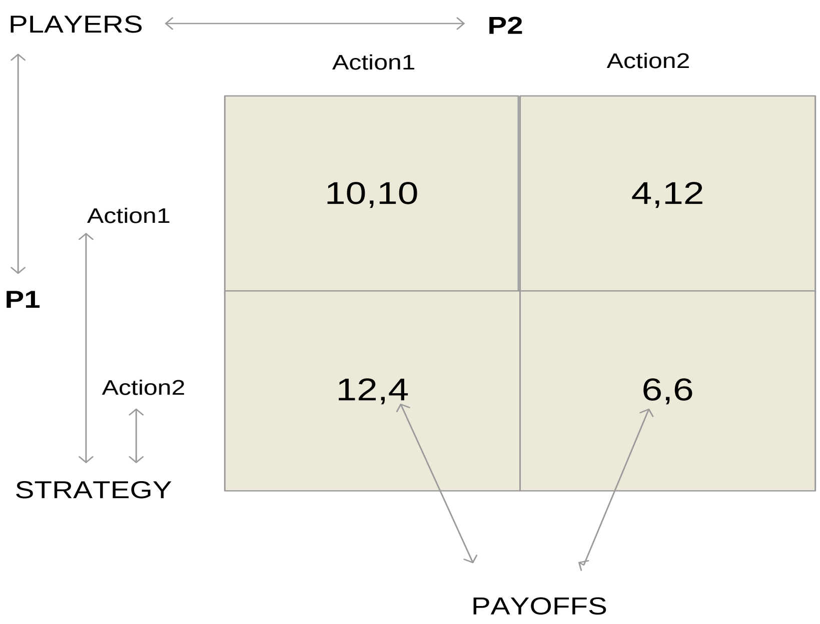

Figure 4.2: Strategic (Normal) Forms

Figure 4.2 shows an example of two players' game; one chooses the row (P1) and the other chooses the column (P2). Each player acts into two strategies (Action 1, Action 2).The first number in each cell in the matrix represents the payoff for player in the row (i.e. P1); the column player (P2) has payoff which represented by second number in each cell. For this example when P1 acts strategy of Action 1 and P2 acts Action 2, then the payoff for P1 equals "4" while for P2 is "12".

If the actions are known to all players, in general the game is presented in tree form. When each player has no information about actions of the others, the game is usually presented in strategic form [21].

4.3.3 Nash Equilibrium

Nash equilibrium is a set of actions (strategies), where no player gains by unilaterally change her action. Any change in strategies of any player under equilibrium, would cause that player to gain less than if she still acts her current strategy. In such condition we can say players are in equilibrium. "For games in which players randomize (mixed strategies), the *expected* or average payoff must be at least as large as that obtainable by any other strategy" [38].

Consider the following example [40] of market the notion is how competitive prices increase the profit of sellers. In other words, we have two sellers (A and B) they sell "widgets" at different prices (one, two, or three) as in table 4.3.

		Seller B		
		p=1	p=2	P=3
Seller A	p=1	0,0	50, -10	40,-20
	p=2	-10,50	20,20	90,10
	p=3	-20, 40	10,90	50,50

Table 4.3: selling strategy form [40]

The competition here is on how many widgets each seller would sell if he reduces the price of selling because he would increase his customers. That means the *payoff* is profit; the *players* are Seller A and Seller B; the *strategies* are p=1, p=2 and p=3. The values of profits in the table are assumption depending on strategies of the two competitors.

The purpose of this example is to find Nash equilibrium. We can see the strategy pairs and check if they can be considered as Nash equilibrium or not. At the beginning we check strategy pair (p=3, p=3) which has utility of (50, 50). If Seller B cut his price, then the utility is either (10, 90) or (-20, 40), (i.e. his payoff in both pairs increased). If Seller A cut his price, then the utility is either (90, 10) or (40, -20) also his payoff in both pairs increased. Therefore, (50, 50) is not Nash equilibrium. We can then check strategy pair (p=3, p=2) which has utility of (10, 90) when Seller A sells at price 3 and Seller B sells at price 2. Seller A gets benefit if he cuts his price to 1, where the utility is either (50, -10) also it is not Nash equilibrium.

Finally, consider the upper left strategy pair (0, 0). Each seller can't get any benefit from increasing his price (i.e. changing his strategy with remaining the other's strategy constant), that means (0, 0) is Nash equilibrium of this game.

4.4 Examples of Games

4.4.1 Prisoner’s Dilemma

It is an example of simultaneous games with two players formed in strategic form as shown in figure 4.3 [39].

I \ II	CII	DII
CI	2, 2	0, 3
DI	3, 0	1, 1

Figure 4.3: Prisoner Dilemma [39]

It is a story of two suspects arrested for serious offense without evidence of conviction. Crime investigators have no way except acknowledgement of one of the prisoners against the other. Each prisoner has one of the choices illustrated in table 4.4 which affected by the other prisoner's action [39]:

CHOICE	PAYOFF
Testifies against the other & the other silent	Immunity from prosecution (3)
Remains silent & the other testifies	Prison sentence for long time (0)
Testifies against the other & the other testifies too	Less punishment (1)
Remains silent & the other remain silent too (cooperation)	Lenient sentence (2)

Table 4.4: prisoner's choices

Figure 4.3 shows the strategic form of the players actions, the players here are the prisoners called for simplification I and II, whereas the strategies are (CI = player I cooperate, DI= player I defect, CII=player II cooperate, and DII=player II defect). I chooses one of the rows (CI or DI), while II chooses columns either CII or DII. Their choices are simultaneously taken so that it is simultaneous game and couldn't be formed in extensive form. It is clear each cell represents the payoff pair for each player according to her (his) choice which is written as combination (e.g. (CI, DII) means player I chose CI, player II chose DII, then the payoff for I = 0 and for II = 3 and so on).

Another property can be found in this example that is the symmetric between the players. If the players are exchange between them and the game remains the same, then this game called symmetric game as this example and shown more clear in figure 4.4. The dotted line in this figure clarifies the symmetry between upper diagonal and the lower one.

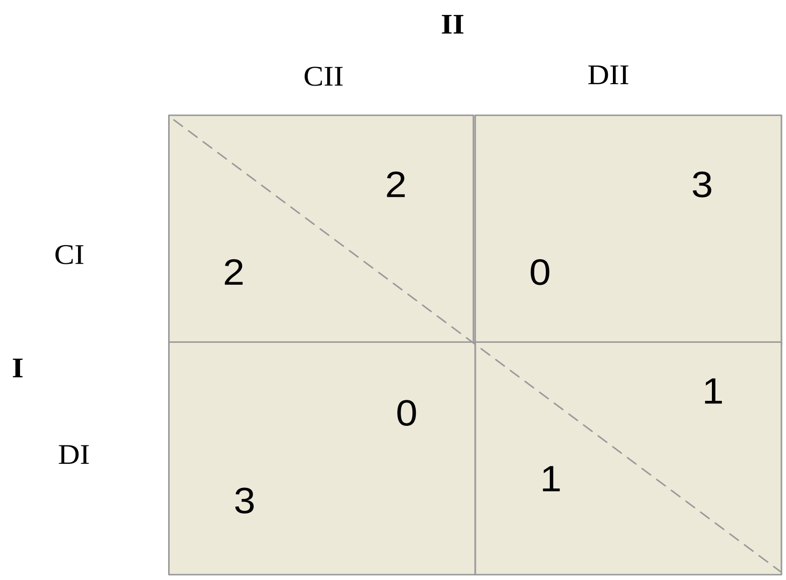

Figure 4.4: Symmetric Game [39]

This property just found in the games where players take action simultaneously because each player has no information about the other's action. So that since there is no order between the two players, then the symmetric become possible. Prisoner Dilemma could be considered as a general game implemented in every case where the individual "defections" may cause in harmful results to others, such as in arms races, or cut-price marketing [39].

4.4.2 Wireless Local Loop (WLL) Sharing

4.4.2.1 Scenario

Two operators of wireless local loop (WLL1, WLL2) have allocated frequency band for voice and data transferring. However, each operator has limited allocated band which is not enough for transmitting and receiving the data in satisfied rate throughout the run time. Therefore instead of increasing the bandwidth of each operator which result in an inefficient utilization of the frequency, we decided to allocate a frequency band can be shared between the operators.

4.4.2.2 Strategic Form Representation

Players: WL1, WL2

- Strategies: {Share, Not share}
- Payoffs: Companies' profits

		WL2	
		Not share	Share
WL1	Not share	10,10	4,12
	Share	12,4	6,6

Figure 4.5: Strategic Form Representation

Assumption

- Each operator earns $10m from its customers
- Sharing costs the operator $4m
- Sharing makes an operator win $6m from competitor.

4.4.2.3 Best Response for WL1

We notice that if WL2 doesn't share, then WL1's payoff is 10 or 12 (i.e. the best payoff for WL1 at this condition is 12 that is obtained when it shares), and if WL2 shares, then WL1's payoff is 4 or 6 (i.e. the best payoff for WL1 at this condition is 6 that is obtained when it shares).

- If WL2 shares ⟶ WL1 shares
- If WL2 does not share ⟶ WL1 shares

That means the best response for WL1 is {share} without care for the action would be taken by WL2. Therefore, the share strategy is dominant strategy and the game is called dominant game.

4.5 Game Theory and Wireless Communications

Decentralized operation, self configuration, and power/energy awareness are common properties widely required in emerging wireless networks especially in the recent years when ad hoc networks took prominent position in the wireless communication which is (i.e. ad hoc network) a self-configuration decentralized authority [36]. Decentralized allocation of the communication resource is another problem added to the communication networks since communication resources are expensive then there is competitive among users on the allocations for each service in communications. It is difficult to make central control for resource allocation because of increasing in the communication scale and the requirements to best quality of service especially in the "newly emerging interactions between administrative domain and end user" leads to modeling new control systems which are decentralized. Recent researches are focused on finding new models of self-interested agents with decentralized decisions. These models need to treat with selfish decisions of the agents and suboptimal resource allocations that arise from the interaction of multiple selfish agents due to the absence of central control [41].

Game theory as it is defined in [36] "The study of the interaction of autonomous agents". So it is clear for modern communications and wireless communications in particular, it is fruitless to spend efforts and time on studying the facilities offered by game theory to reach to the best algorithm and then models which considered the most suitable approach to tackle the problems of own decision that should be taken from each agent in communication networks. It is also required to make balance in the network actions by reaching to the rational decision and reducing selfishness behaviors of the decentralized agents. All that problems can be solved by analyzing the networks using game theory.

Traditionally, game theory analyzes all problems or systems that consist of competitive agents to find the solution to their conflict. Therefore, if we try to find what objectives that agents strive to achieve and what optimization they seek, we could set generally three goals. First agents or nodes – as we talking about communication system – seek only to their user's requirements (selfish behavior), second case, nodes look for ways to destroy the others' performance (malicious behavior). These two cases can be solved straight forward by game theory. Third case if nodes are interested in finding "greater good" of whole network, although this goal is shared among all nodes but still there are differences in the vision and idea about the network situation that yields in different actions taken by each nodes according to their own perspective on the current network (i.e. conflict on the best choice) [36].

4.6 Cognitive and Game Theory

One of the important recent research topics is the efficient management and utilization of spectrum resource by dynamic spectrum access. The motivation beyond this research is the scarcity of available frequency and increasing demands for radio resource led to a way of thinking using the notion of spectrum sharing by unlicensed secondary users (SU). That means finding a method for dynamic access to unutilized frequency channels which are parts of allocated band to the primary license owner to be opportunistically used by SU. This operation is one of the tasks of cognition/management in the cognitive cycle, which mentioned in chapter 2 of this thesis. Dynamic spectrum access means at first detection of spaces in spectrum frequency bands and then using an efficient and fair way to share this available frequency with unlicensed users (SU) [2]. Here the competition will be on different goals, one is the competition among PUs on how can each user get a benefit and how much earn from the spaces found in his band. Another goal is the competition among secondary users on utilizing available frequency from one PU selfishly.

Game theory here give a suitable solution since the problem is briefly a conflict among agents. It is one of the decentralized problems without cooperation among users so it is solved by non-cooperative game. Two important questions remain need to be answered here [2]:

1- Is this game and scenario can find an equilibrium transmission?
2- If the answer of question 1 is yes, how can the user compute it, using the local information only, in a distributed fashion?

4.7 Summary

Game Theory is the main approach we have used in our work to prove the advantage of using dynamic spectrum allocation rather than non-dynamic methods and its effect on the efficient spectrum utilization. In chapter 6 of this thesis we could answer the two questions that have been mentioned above in the last section of this chapter. The work that is proposed in this thesis could find Nash equilibrium and the way of implementation.

CHAPTER 5

Non-Dynamic Spectrum Allocations

Research continues in the area of spectrum utilization towards finding the best ways to exploit the available frequency as a resource of wireless communications. This work proposed two methods of utilization by spectrum sharing among multi users to compete on obtaining a maximum rate of sharing in the unoccupied frequency. First method has been proposed in this chapter.

5.1 Methodology

In wireless system as in the other communication systems we can recognize if there is full usage of the allocated bandwidth by different ways, one of the simplest ways is by monitoring number of subscribers which use that band because we have prior information about maximum number of subscribers with each user. As it is known that there are peak hours at which most of subscribers occupy the allocated frequency and periods of inefficient frequency utilization. We can utilize the unoccupied frequency which allocated to a user according to the time and the number of subscribers in each time slot assuming that there are two periods of peak hours. Also we assume a threshold under which the user can rent its frequency to other users.

The scenario considers three users (first user, second user, third user), the first user has the largest number of subscribers and frequency band so it becomes the provider which serves the other two users when it has free frequency. The first user signs a contract with second user and another one with third user to rent the available frequency to each user according to its traffic and number of maximum subscribers. The band would be shared then:

$$shband = Maxuser - S_t - relax \qquad (5.1)$$
$$relax = Maxuser - \breve{O} \qquad (5.2)$$

Maxuser is maximum number of first user's subscribers; $\breve{O}$ is the threshold which is assumed equals 90% of the *Maxuser*; S_t is the current number of first user's subscribers at time slot *t*. The rate of the threshold here is assumed to be as large as possible to gain maximum spectrum utilization that can be obtained by this method.

When S_t Equals any number less than $\breve{O}$ then *Shband* will be more than zero, which means there will be sharing until the number of subscribers which used the band reaches $\breve{O}$.

Shband represents the available band to be shared with second user and third user; it will be then distributed between them according to their number of subscribers.

$$s_{h2} = \frac{s_{t2}}{s_{t2}+s_{t3}} \times shband \qquad (5.3)$$

$$s_{h3} = \frac{s_{t3}}{s_{t2}+s_{t3}} \times shband \qquad (5.4)$$

S_{h2} and S_{h3} are the sharing bands to second and third users respectively; S_{t2} is the current number of second user's subscribers; S_{t3} is the current number of third user's subscribers at time slot *t*.

Another condition is when number of 2^{nd} user's subscribers or 3^{rd} user's subscribers is very small, that means no need for sharing because at this case they have enough spectrums for their services and subscribers. This can be presented as minimum threshold for 2^{nd} or 3^{rd} users.

Figure 5.1 shows the flowchart that clarifies the procedure of this method.

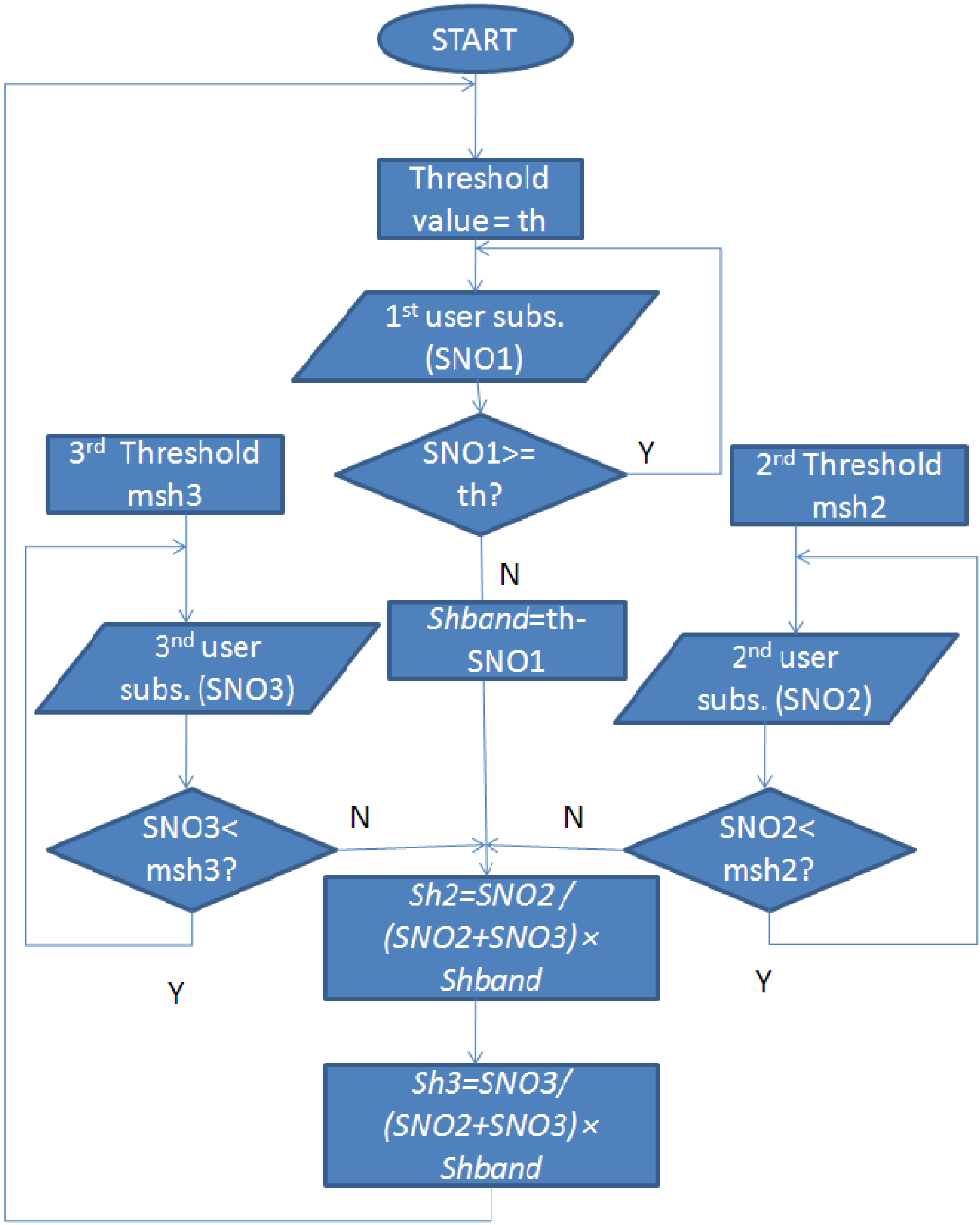

Figure 5.1: Non-Dynamic Spectrum Allocation method

5.2 Results and Numerical Simulation

The results as shown in the figure 5.2, three users which are interested in spectrum sharing have the behaviors shown that the first user is the provider of the frequency from its allocated band when he doesn't use it. The maximum number of subscribers who occupy his band is assumed to be (1000 subscribers), the maximum number of subscribers who utilize the second user's band is assumed to be (450 subscribers), and the maximum number of subscribers who utilize the third user's band is assumed (350 subscribers). Threshold appears where the number of subscribers is (900) represents 90% of the maximum number of subscribers for the first user. First peak hour is around time interval (100), and the second one is around (400).

Sharing periods are clear in the lower graph of figure 5.2 which clarifies the difference between user's behavior before and after sharing. It is noted that there is sharing most of times except three periods, they are: (75-125), (250-325), (400-425).

The first and third periods are ones when the number of subscribers exceeded the threshold line which considers as a guard line for the first user (the frequency resource provider) to assure frequency availability to his main subscribers so that within these periods it can be considered as no frequency available.

In the second period the observer can notice that high rate of spectrum is available from the first user but there is no sharing because the second user doesn't need it at this period as he also has enough frequency for his services and subscribers so he doesn't need to pay to the first user.

Another note can be observed from figure 5.2 that is the rate of sharing is fixed depending on the number of subscriber of each user. When the available frequency rate is 41.4%, the rate of second user sharing is 25.7% and the third user rate is approximately 15.7%. The simulation has based on MatlabR2008 software.

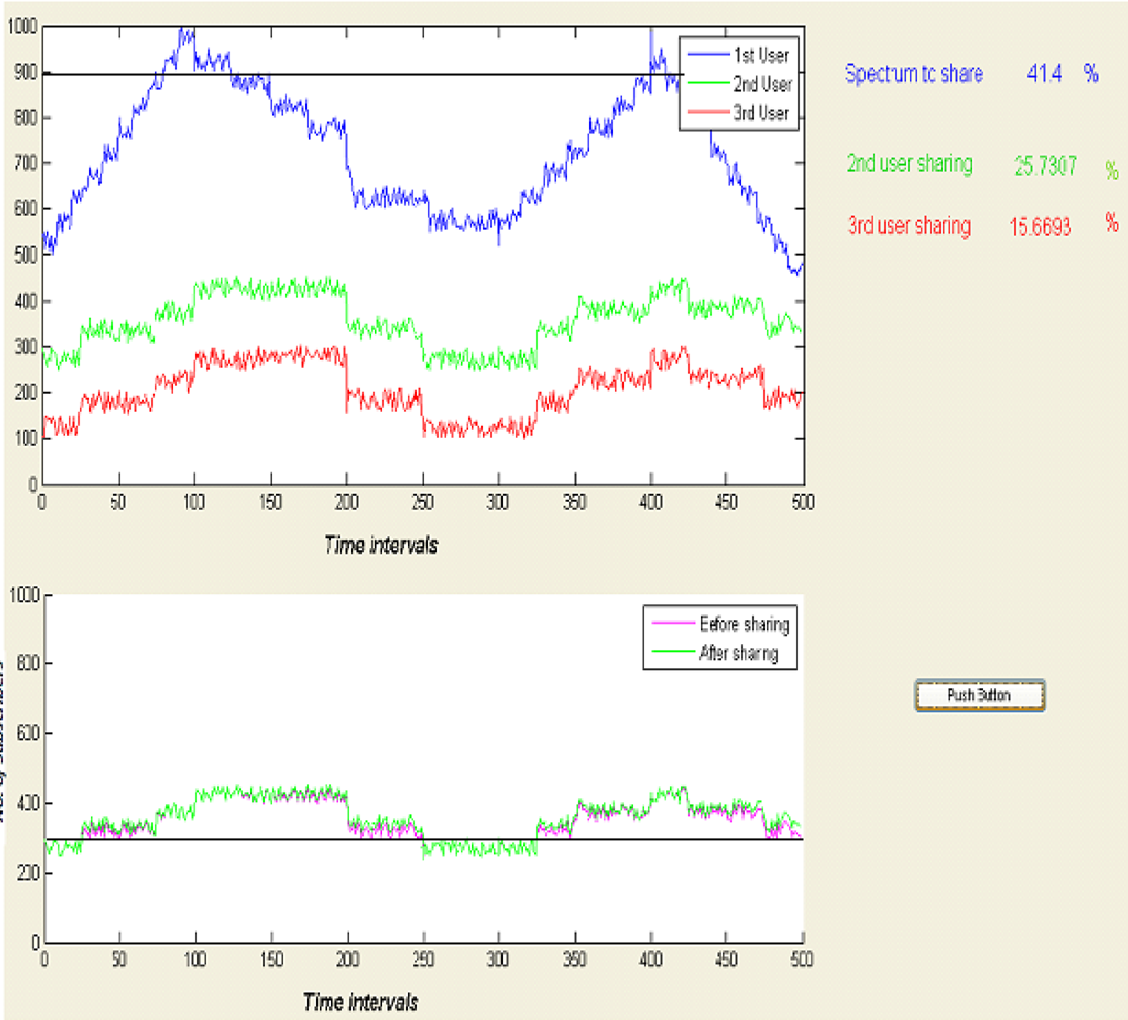

Figure 5.2: Spectrum sharing with multiple subs. (non-dynamic allocation)

CHAPTER 6

Spectrum sharing using Game theory

6.1 Methodology

Game theory can be used as a method of modeling and optimization of wireless communications on a goal of competing performance among users to utilize the resource (i.e. spectral frequency) in an efficient way.

In this work game theory has been used to model an efficient utilization of the allocated spectrum which used by the licensed primary user (PU) mentioned that the problem is in spaces and holes exist in the licensed band which it is a function of time and space, what means there are portions of frequency band unused sometimes or spaces all the time. We assume that the environment sensing has been done and the spaces in the licensed band was detected so available frequency means the vacant channels which have been intelligently detected by cognitive radio technique as shown in figure 6.1.

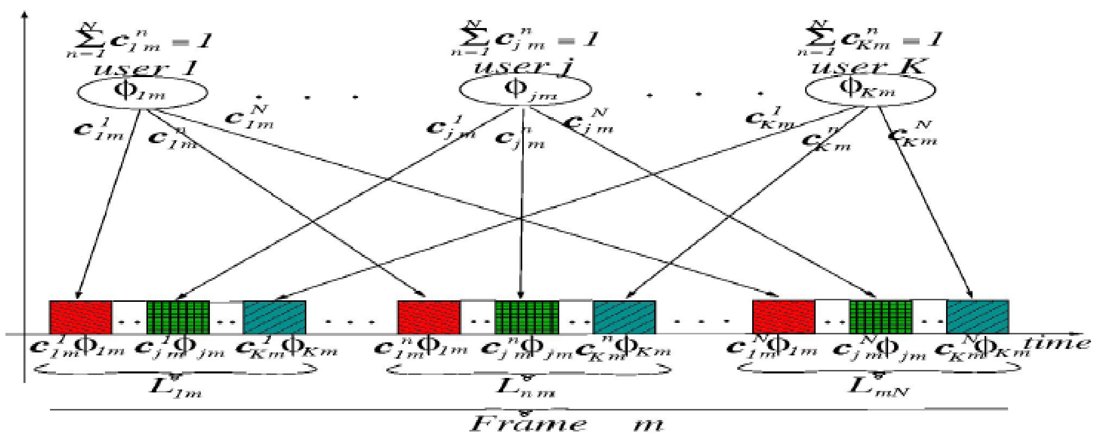

Figure 6.1: Spectrum Allocation in time domain [19]

Figure 6.1 shows three time slots in the frame *m* of secondary user *j*. L_{nm}^{j} represents available length for user *j* to share or allocate a portion according to his requirement, where *n* is the number of slot. The amount of slot which available for *j* in each slot (*n*) is [19]:

$$L^{j}_{nm}(cjm) = L_{nm} - \sum_{i=1, i\neq j}^{N} C^{n}_{im}\, \emptyset_{im} \qquad (6.1)$$

The secondary user *j* in slot *n* of frame *m* can share and get his portion of time by:

$$\emptyset^{n}_{jm} = \frac{L^{j}_{nm}(C_{jm})}{C^{n}_{jm}} \qquad (6.2)$$

By this way any SU can get sharing with primary user in a condition of interference avoidance with PU.

6.1.1 Game's parameters in this work

- Set of players (I={1,2,3,….,N}):-

Nodes or Users

- Set of possible actions (*Ai*) for each player:-

{Share, Not Share}

- Set of utility functions assign a number to each possible outcome *(Ui*). More

  Desirable outcome means higher utility:-

High rate of sharing and low coast

6.1.2 Scenario of the work

6.1.2.1 Sharing between PU and SUs

Primary user chooses a group of secondary users (SU) from many SUs which are interested in competing to share the spectrum frequency with the PU according to a pricing function to be computed by the primary user's administrator. Units with five categories have been determined depending on dimensions similar to those which considered in assessment of the frequency license as [2]:

a) Bandwidth required (in MHz).

b) Demand within the service region.

c) Duration of the contract.

d) Opportunity for growth of services within the service region.

e) Cost of installing and providing service.

Each SU takes his degree according to units he has collected from these five categories and will compete with other SU according to his degree. The priority will be granted to the SUs which has maximum degrees and the number of SUs in the group depending on the number that PU wants to share with them. The PU role would be ended until this stage and he should not force the SU group to a specific way of competing on sharing the available frequency among them but PU knows that one of the SUs in his group will be the Secondary PU as it will be explained in section 6.1.2.3 of this chapter, therefore the suitable type of games in such scenario is non-cooperative game.

6.1.2.2 Non-Cooperative game theory

A non-cooperative game is one of the game types that its players have the ability to make independent decisions and the ability to cooperate among each other in a condition that the cooperation should be self-enforcing. If any contract among players is enforced through a third party, that game would be a cooperative game. It is adopted as a method in this work as assumed that there is no cooperation among users and the third party which is PU doesn't enforce their contract.

6.1.2.3 Sharing among SUs

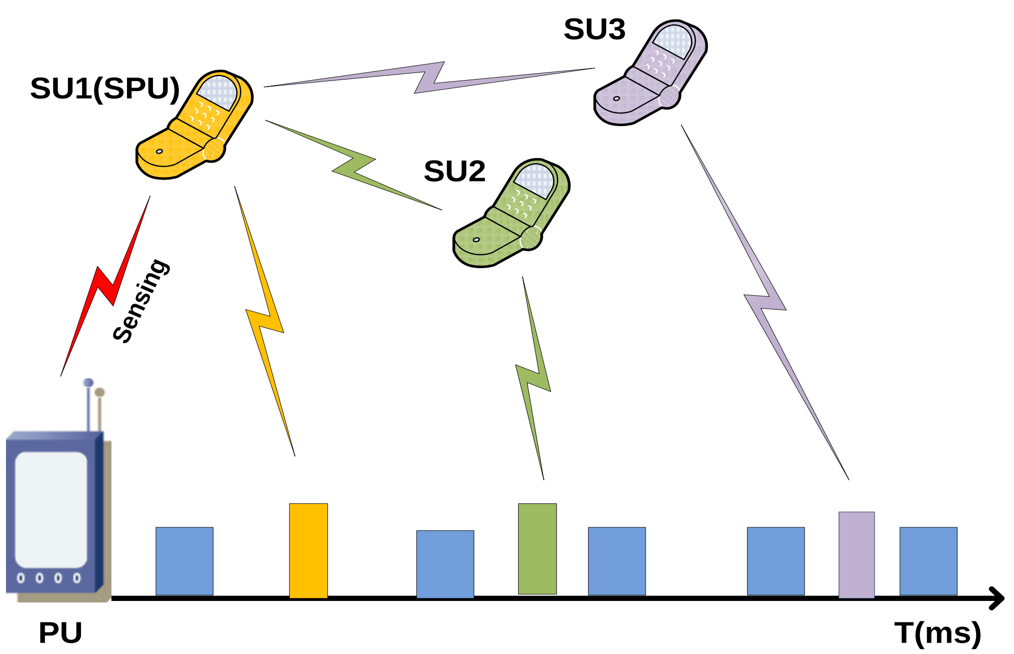

Figure 6.2: Spectrum sharing among users

Each SU in the group has full information about strategies and payoffs of other SU in the same group. SU agrees to compete on sharing the available frequency and take the maximum rate of sharing in a condition he pays more than other SU in the group. SU who acts this role is called Secondary PU (SPU) as shown in figure 6.2; he shares frequency with PU and in the same time with other SUs to save time and manage the available frequency as SPU will serve other SUs by letting them share the rest frequency after he took the sharing rate he needs to assure each SU get the rate he wants when he needs. The network lifetime is assumed infinitely long and divided into individual time periods, represented by *t* for each *t*= 0, 1, 2…… ∞. Some of the SUs send a request at each time period *t* to share the spectrum with the PU, while the other SUs will prefer to share their requirement of the spectrum with the other SU, then the SU can decide if it is better to be secondary PU by sharing the spectrum with the PU, or remain as a SU to share spectrum with other SU and give a chance to another SU to serve others in the group (i.e. become SPU). The user's behavior depends on a factor defined as reputation (*R*).

Reputation (*R*) is affected by a user performance during any time periods (*t*) and in prior time periods (*t-1*). R^i_t represents reputation of player *i* in some time period *t*. So mathematically, user reputation is defined as follows:

$$R_t^i = R_{t-1}^i \times (1-\propto) + w \times \propto \qquad (6.3)$$

Where: $0 \le \alpha \le 1$, $t \ge 2$;

w=1 or 0

Users' reputation is a value between "0" and "1" (including i.e. $R^i_t \in [0, 1]$), and the reputation of all users equals "0" at time slot **t**=0. When the user is interested to share the spectrum, *w* will take the value of "1"; otherwise, it will equal to "0". While α represents the user history depending on his previous time reputation according to the user action. Increasing in α value leads to rapidly increasing in reputation which gives an indication that the user has important need of sharing spectrum with PU to be SPU by taking high priority even if the reputation at that time is low value. Therefore, the value of α is used as a factor to improve the user's reputation quickly when there is an urgent demand in being SPU and share the PU with a high rate of sharing than others and vice versa i.e. if the SPU needs rapidly reduce his rate of sharing and being an ordinary SU he should use high value of α.

6.1.3 Nash Equilibrium

Nash equilibrium is a strategy profile (s^*) at which no user may gain by unilaterally deviating such that [37],

$$U_i(s_i^*, s_{-i}^*) \geq U_i(s_i, s_{-i}^*), \forall_{s_i} \in S_i \quad (6.4)$$

$Where\ s_i^*$: Action of player i within the equilibrium
s_{-i}^* : Action of any player except i within the equilibrium
s_i : Another action for player i

The infinitely repeated version of game is represented in this work which is the case when the game G is repeated continuously in successive time periods as G^∞, so it needs to evaluate the Nash equilibrium of infinite game G^∞.

The classical concept of Nash equilibrium points a way out of the endless cycle of speculation and counter-speculation as to what strategies the players should use. All the players in this game are users in the same network so we need a symmetric Nash equilibrium. The scenario assumes no coordination among user since it is difficult to coordinate among players who are not aware of any differences among themselves if they belong to the same network and they are from a single homogeneous population (i.e. all the users have equivalent capabilities and responsibilities) , therefore it is easier to achieve a symmetric Nash equilibrium.

6.1.4 Strategic Form

Figure (6.3) represents two users strategic form of the game (assumed only two users for simplicity). The payoff of sharing is (– C) and of not sharing is (0), where – C is less than 0.

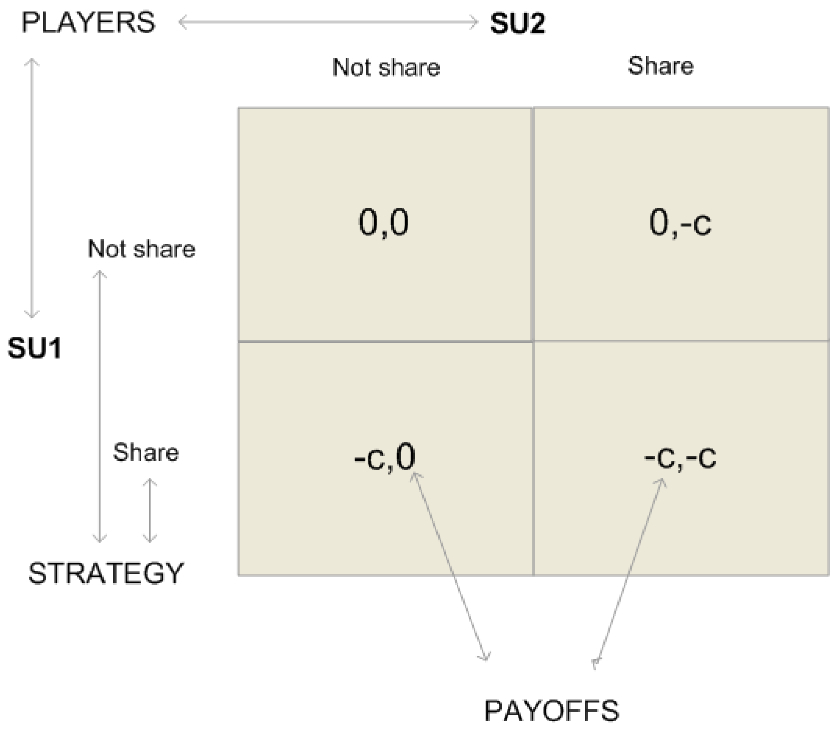

Figure 6.3: Strategic Form Representation

If all users are interested in sharing, this is undesirable Nash equilibrium case because it will be necessary to SUs to compete again and pay more to PU as money consider as a competition factor, then the loss will accrue to all SUs in money and time. If all users aren't interested in sharing, this is Nash equilibrium case because it saves time and money but, there are disadvantage from the practical view for the following reasons:-

1- There is no benefit from the network when none of the users is interested in sharing the spectrum.
2- It is inappropriate to have network in which no user would make connection with the PU especially in practice nodes, when nodes always send some messages irrespective of outcome they obtain in return.

6.1.5 SPU Probability

P is a parameter assigns the probability to the user who wants to share with PU and being SPU. The player who does not want to share he will be assigned (*1-P*). $Payoff_{\ share}$ denotes the expected payoff of the user in any time period *t* when it chooses the action {share}, that is:

$$p \times (-c + R_t^{share} \times U) \tag{6.5}$$

Where U is: the utility.

This can show clearly the direct relation between user's reputation and his probability to become a SPU.

The expected payoff of the user who selects {not share} at any time period t is denoted as $Payoff_{not\ share}$ and equals:

$$(1 - p) \times (R_t^{not\ share} \times U) \tag{6.6}$$

User's reputation when he wants to share is R_t^{share}, while $R_t^{not\ share}$ denotes the user's reputation if he does not want to share both of them at time period t. Then we can say according to equation 6.3 that:

$$R_t^{share} = R_{t-1} \times (1-\propto)+\propto \tag{6.7}$$

And

$$R_t^{not\ share} = R_{t-1} \times (1-\propto) \tag{6.8}$$

With positive probability, expected payoff of each user in equilibrium is its expected payoff to any of its actions (i.e. each user cannot gain from any action if he deviates from equilibrium). That is an important feature in mixed-strategy Nash equilibrium which means:

$$Payoff_{share} = Payoff_{not\ share} \tag{6.9}$$

From (6.5) and (6.6) we get:

$$p \times (-c + R_t^{share} \times U) = (1 - p) \times (R_t^{not\ share} \times U) \tag{6.10}$$

Using (6.7), (6.8), and (6.10) yields to:

$$P \times (-c + (R_{t-1}(1-\propto)+\propto) \times U) = (1 - p) \times (R_{t-1}(1-\propto) \times U) \tag{6.11}$$

Then finally *P* equals:

$$P = \frac{R_{t-1} \times U \times (1-\propto)}{-c+2R_{t-1} \times U \times (1-\propto)+U \times \propto} \quad (6.12)$$

It is clear that *P* isn't constant and depends on reputation of the user he gets from previous time period (*t-1*). As the assumption is no collusion among users, the mixed strategy Nash equilibrium for this game is the mixed strategy pair (*p, 1-p*) for actions {want to share, does not want to share} respectively, and it is certainly better than the strategy of no user wants to share for the same reasons mentioned in section 6.1.4 above.

6.1.6 Features of the mixed strategy (*p, 1-p*) Nash Equilibrium

1- Simplicity of calculations

The calculation of the probability to achieve the equilibrium among SUs based on aware which user will have a decision of sharing the available frequency with PU to be a SPU, the decision depends on the user's reputation at the end of the prior time period whether they should ask to share the offered spectrum or not. This is not fixed and repeated at each time period accordingly, the probability would be continuously changing from one time period to another depending on the prior reputation, and since users at each time period knows exactly what did they choose in the previous time period (i.e. share, not share); therefore, it is easy to calculate equation 6.3 which depends on previous reputation in time period *t-1*, then it is easy to achieve the equilibrium point among users.

2- Tackle the competitive sharing problem

Without the submitted equilibrium each user behaves selfishly that is trying to share the spectrum rather than serves other. Obviously, each user in the network knows that the best strategy to him is to serve other users as little time as he could if he knew that others provide as little service as possible. If we assume $C \ll U$ then C can be ignored from (6.12) then:

$$P = \frac{R_{t-1} \times (1-\propto)}{2R_{t-1} \times (1-\propto)+\propto} \quad (6.13)$$

That means the probability for each user to be a secondary PU is less than (0.5) i.e. less than 50% of all the time of sharing the available frequency with PU. Accordingly, no user can serve other users in the group most the time and as we proved that the best equilibrium is at least one of the users must share and be SPU, then when the maximum period of sharing, which is less than 50%, is over it is better to all user to choose another one to be the next SPU and serves others.

3- Fairness in cost sharing

As in equation 6.13 appears that the probability is less than 50% which leads to overall system inefficiency because of selfish behavior of the SPU which likely does not accept all other users requests at the time when he is SPU if he needs all the available frequency at that time. So 50% of the requests may be turned down. By this Nash equilibrium it is assumed that the user who has a rejected request he tries at another SPU to be capable of serving the request and it is also (i.e. the probability of serving his request successfully) depending on his current reputation. On the other hand, there is fairness in the cost of system inefficiency that it is not caused by a single user, but it is shared among all the users in the group this fairness provided by the proposed Nash equilibrium.

4- Fast addressing the spectrum to the right user

The theoretic model predicts that the best action of each user is to serve others and become SPU even when he isn't interested to share the spectrum with PU at that time, in which the decision of who will be SPU is depending on reputation. This will make balance between total services received from user with total services offered by that user.

6.2 Results and Numerical Simulation

The results are obtained from theoretical models and implemented using MatlabR2008 software.

6.2.1 Reputation (*R*) effectiveness

User's reputation value is the major parameter in the calculations of this work as it was discussed in Section 6.1.2.3. In this section we shall see the effect of reputation on user's choice to share the PU (i.e. be secondary PU) or not. Figure 6.4 shows the node's (user's) reputation in each time period depending on their Nash strategy and using equation 6.3.

It is assumed that there are three users in the secondary users group which compete to share the available frequency provided by PU

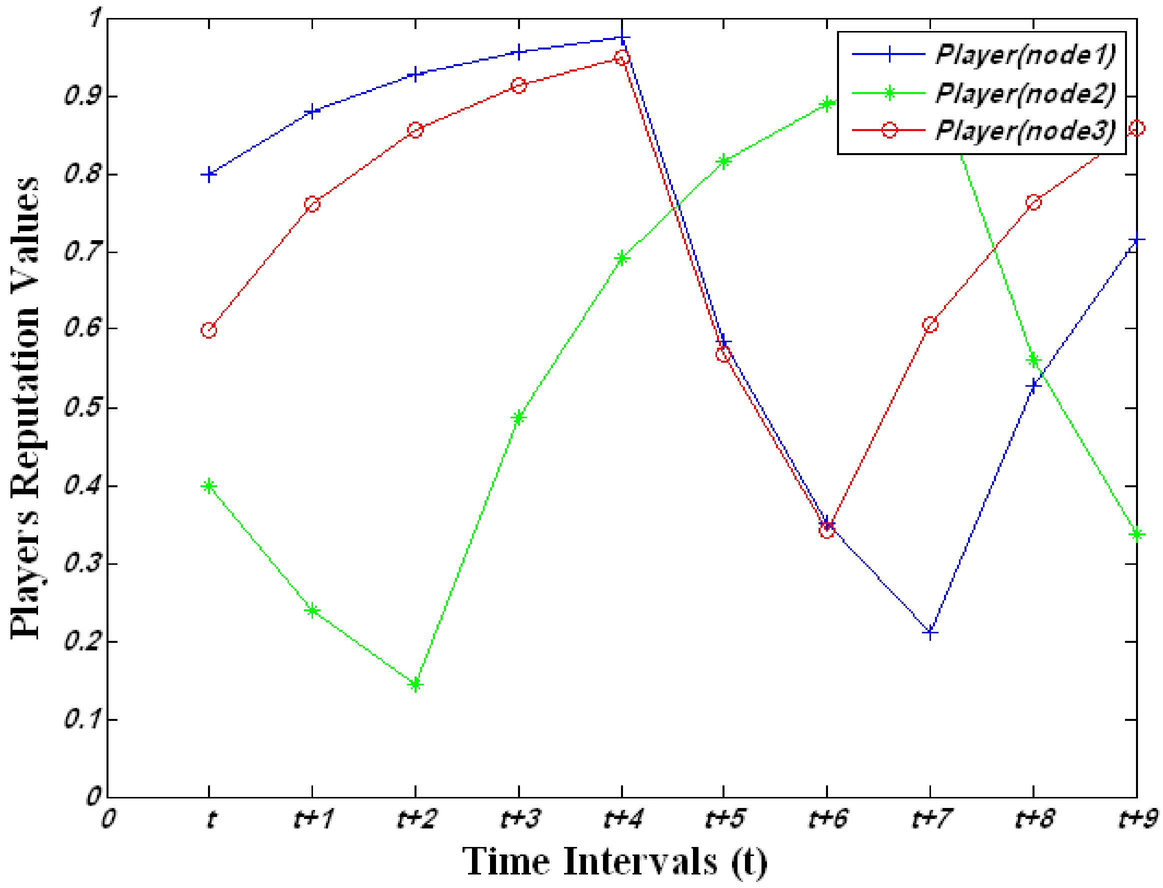

Figure 6.4: Change in player's reputation controlled by their Nash equilibrium strategies.

The reputation of all users at time interval "0" is "0", then at the beginning of the game with time interval *t*, user1 and user3 were interested in sharing, but they began communication with different value of reputation, user1 began with value "0.8" which is higher than others reputation so he was the candidate to be a SPU, he was competing to get the higher rate and managing the available frequency which means serving user2 and user3 until the time interval *t+3,* while user3 at these intervals was a SU served by SPU (i.e. user1 here). User2 wasn't interested in sharing until time interval *t+2* when he began increasing his reputation as an indication to his willing to share and be the next candidate for being SPU after user1.

The period between time intervals *t+2* and *t+3* has seen an increase in the reputation values of all the three users with different sharpness; therefore, while in the period *t+3* to *t+4* there was increasing in user2's reputation and decreasing in reputations of the others. So the probability of sharing to be SPU depends on the user's reputation at the end of last time period, and the reputation in the current time period determines whether the user will be serviced.

Same these results, but with longer time period can be implemented and its result shown in figure 6.5.

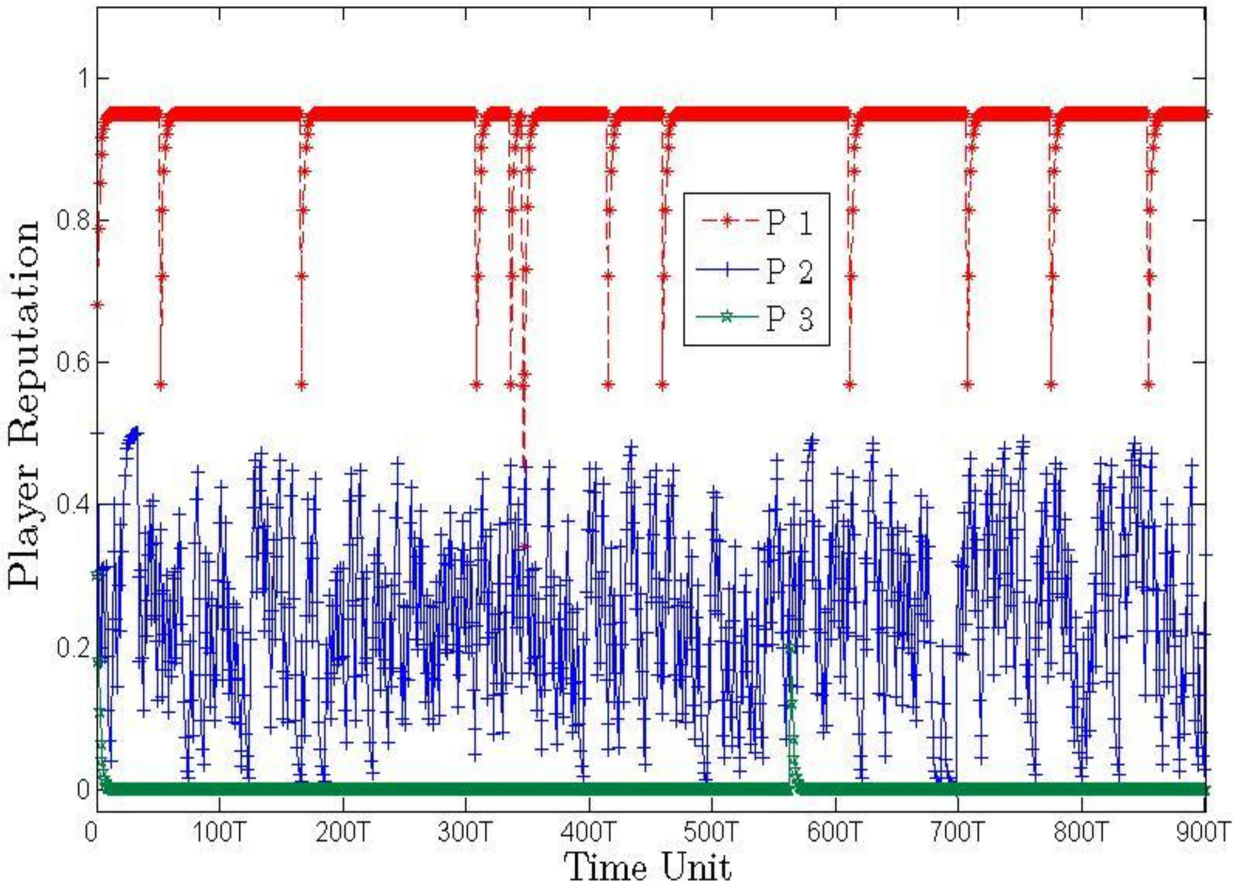

Figure 6.5: changing player reputations over a longer time period.

The time period is taken around nine hundred time intervals. Three users are assumed also to compete with each other; player one manage the available frequency and service other users (i.e. P2 and P3) as he considered SPU with highest reputation and player three have the lowest.

Random matrix generator was used to show different reputation when user 1 needs to share the spectrum for 80% of the time, user 2 is interested to share for 50% of the time while user 3 needs it only for 8% of the time.

6.2.2 Alpha (α) effectiveness

Figure 6.6 shows the case for one user if he doesn't want to share with different values of α to clarify its effect on the reputation probability of the user.

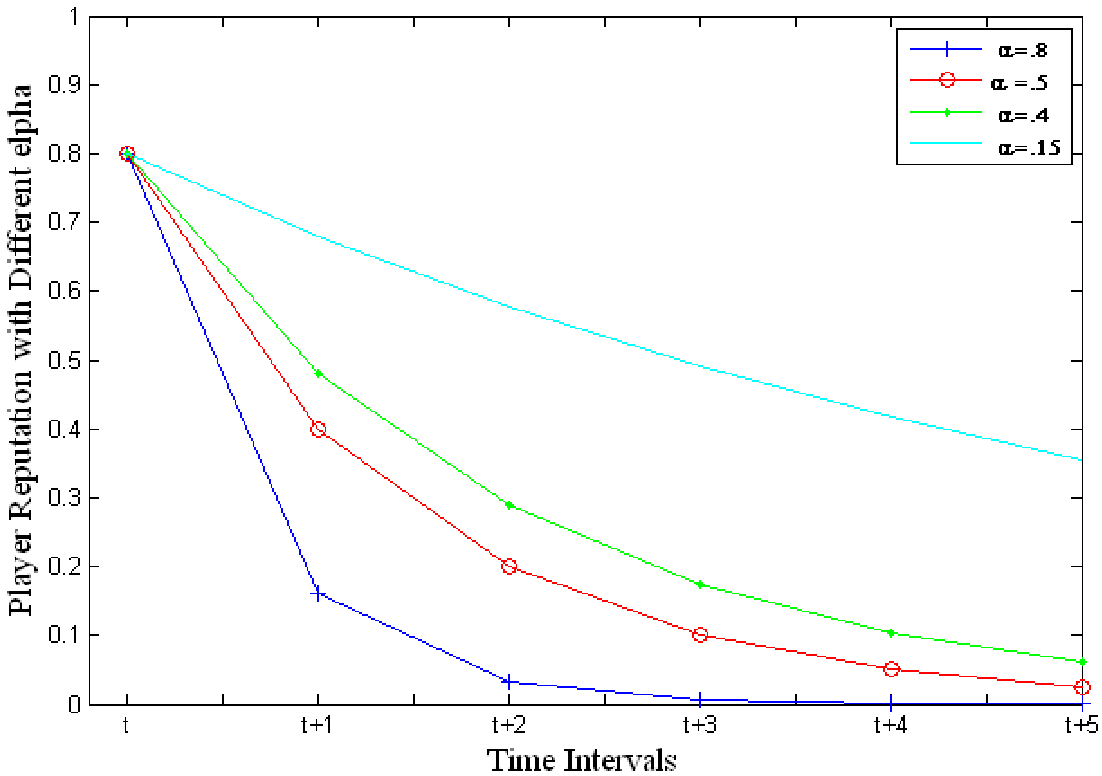

Figure 6.6: Players reputation with respect to α, and the node is not interested in sharing the offered spectrum

Low value of α raise the curve of reputation probability upwards, and since the case is asked not sharing, then the upper curve means gradually lose sharing. Opposite situation is true in the lower curve where the reputation decreases rapidly means the user leaves his role as servicing other users (i.e. being SPU) faster. However, different values of α came from different decisions taken by the user in each time period as α is considered a factor effects on the value of reputation in each time interval, but Slow decreasing in the reputation probability and accordingly, slow lost of sharing gives network more stability.

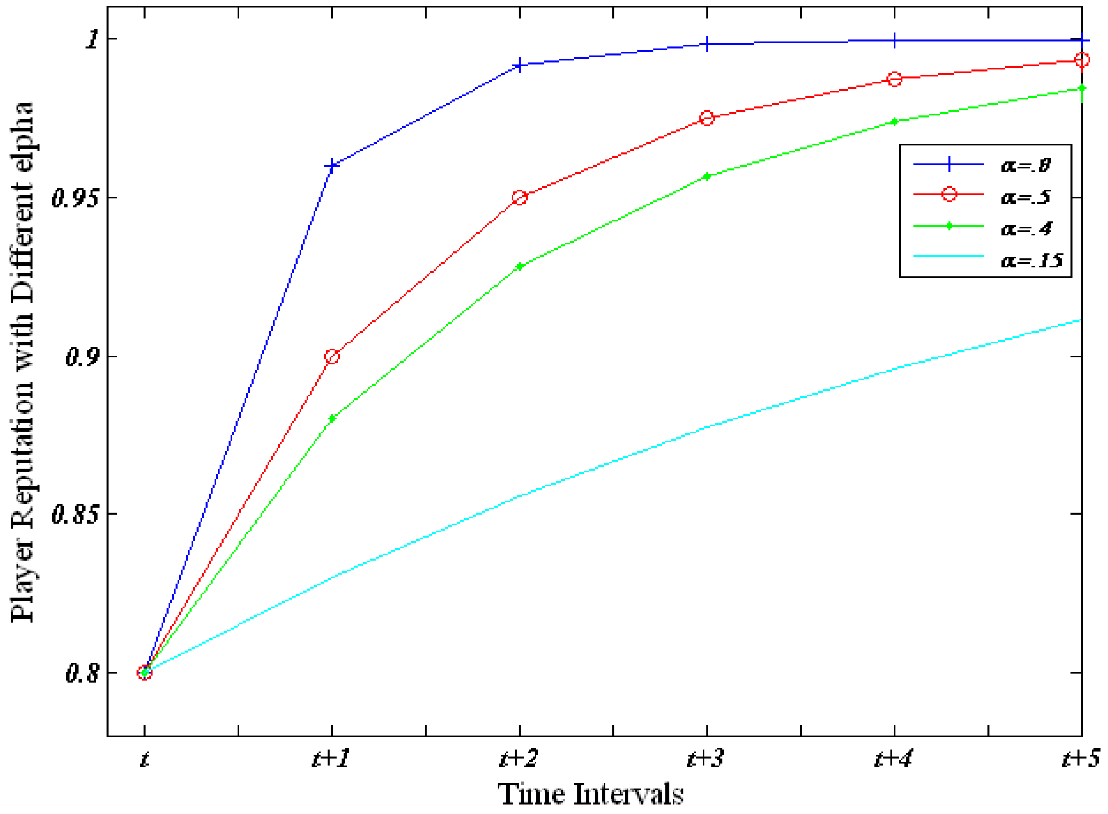

Figure 6.7: Players reputation with respect to α, and the node is interested in sharing the offered spectrum

Figure 6.7 shows how the change in the value of α affects the reputation of user, it is also depending on the desire of the user to share or not. High value of α shifts the reputation curve upwards, and means fast increasing in reputation which gives the user ability to quickly access the PU spectrum an being SPU. This explains the function of α that sets the level of importance to be given to user's performances and the comparison between current and past service record. If α is low, means past action of the user was more important up to the current time period that yields in user's need to remain provides service as a way makes him able to maintain high reputation and sharing spectrum offered from the PU. If α is high, it will enable user to increase its reputation easily in the period of being SPU and provide service to other users even when the history of his services provided to others was rather than the required level.

From results explained in figure 6.6 and figure 6.7 we can conclude that decreasing the value of α to be as low as possible can improve the system efficiency.

6.2.3 Urgent Case

These cases are as it has explained in section (3.5) of this thesis when there is an urgent need from the PU to use his band which was rented to the SU group as an available frequency, there is a condition that in such cases the SU group must vacant the band to let the primary user who has the first priority in utilizing the band as he is the owner.

The proposed game theory method in this work treated with this problem by submit simple solution that makes the SU immediately leave the band he occupied by stopping sharing. Figure 6.8 shows the results of this solution.

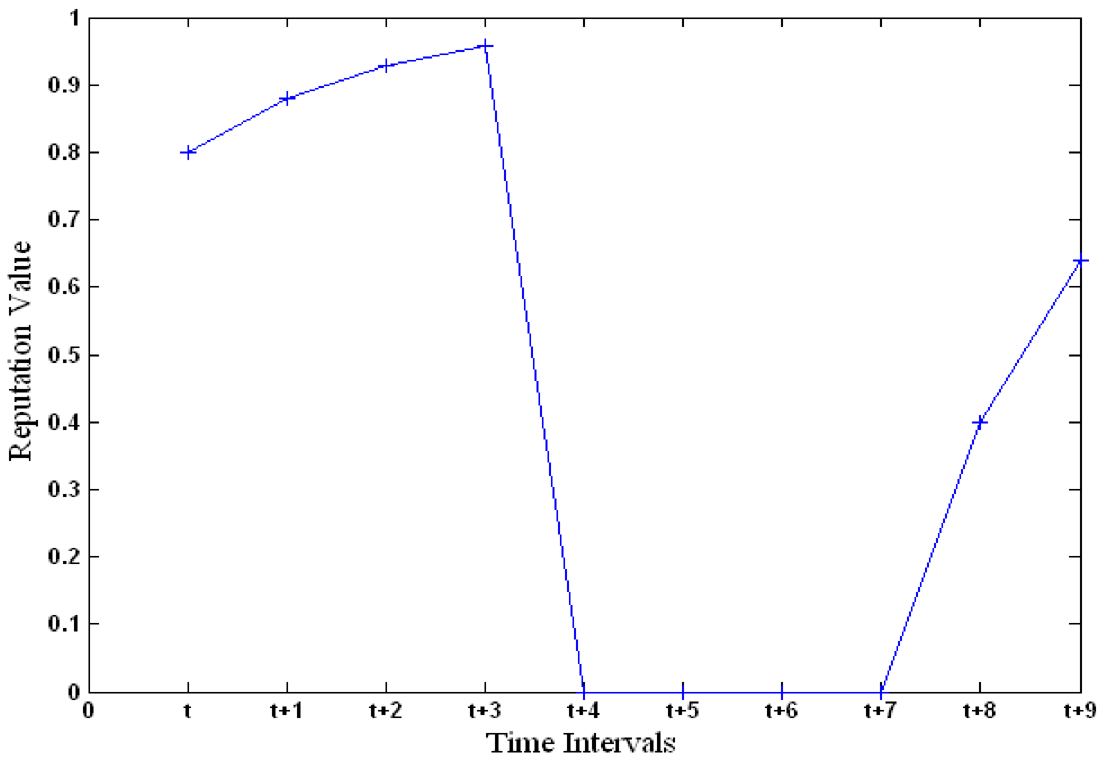

Figure 6.8: Primary User needs his band for urgent case

We can see in time intervals between *t+4* and *t+6*, the user lose sharing according to the primary user demand. It can easily return to sharing after the primary user finishing his using and requesting SU to come back. As it is shown clearly, the reputation returns increasing at *t+7* although the urgent period was between *t+4* and *t+6* because it depends on SU demand and if he is still interested in sharing. That means SU was not interested in sharing at *t+6*.

Figure 6.8 shows the results if we have one secondary user is interested in sharing. In case of a group of SU, It is not so difficult to implement because our proposed method in this work, assumes that the available frequency is managed by a secondary PU in each time period. So there is always one secondary user who leads the SU group and becomes responsible of frequency sharing with PU as well as with other SUs in the group.

Figure 6.9 shows the same results in figure 6.8 but for multi-SU. It is easier to PU and faster response when he treated with one user rather than with group.

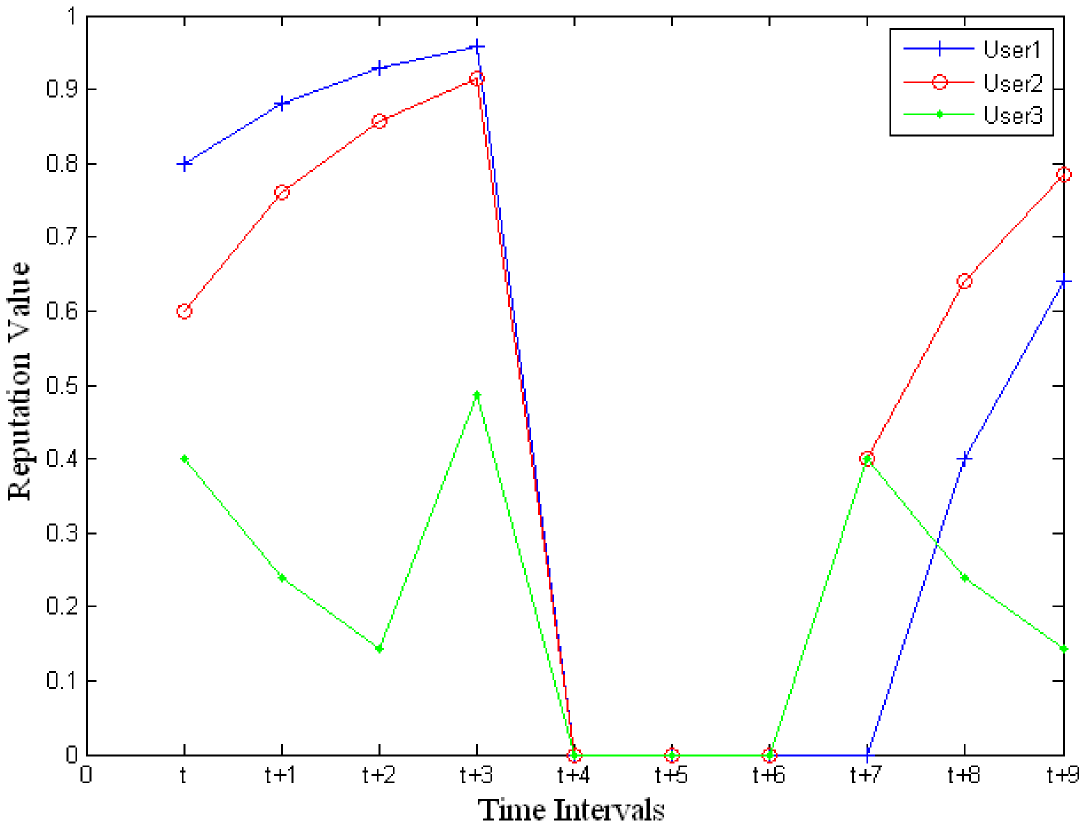

Figure 6.9: Primary User needs his band for urgent case with multi-SU

6.3 Comparison between Dynamic and Non-Dynamic Methods

In this section as we explained in chapter 5 of this thesis the notes found in the results of Non-Dynamic allocation method, we print here some preliminary results on the comparison between the game theory method and non-dynamic allocation method that have been used in this work as shown in figure 6.10 below:

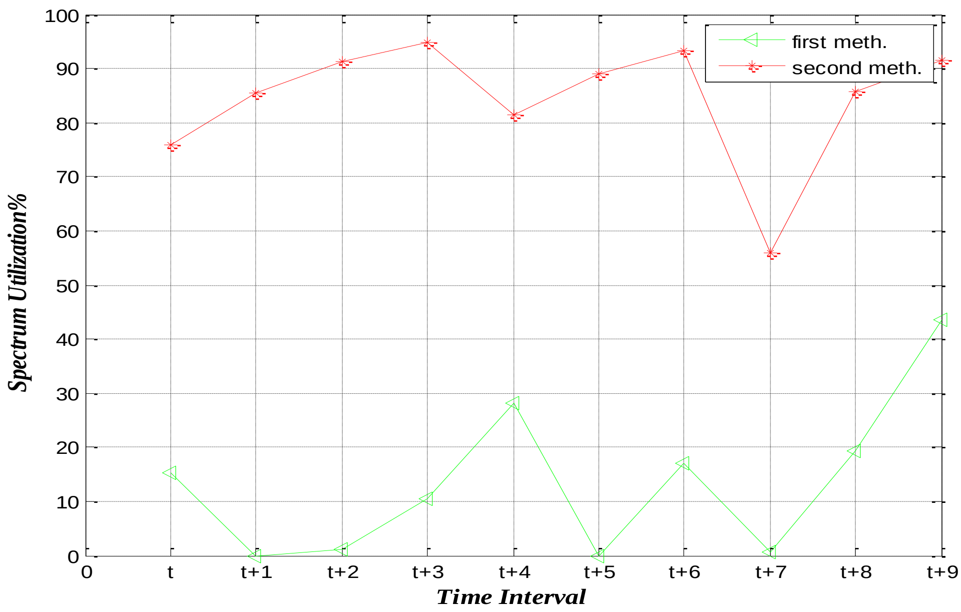

Figure 6.10: Comparison between the two methods

Lower graph in figure 6.10 represents the possible utilization rate of the available frequency which is between 0% and 45% using the first method (i.e. Spectrum sharing depending on number of subscribers). Whereas the upper graph represents the spectrum utilization rate using game theory (i.e. 2nd method), it is between 55% and 95%.

The results show that no waste will be in the spectrum using the second method because the rate of utilization wouldn't be less than 55%. While in the first method we can see that there are some periods recorded 0% of utilization.

CHAPTER 7

Conclusion and Future Work

7.1 Conclusion

Spectrum sharing between a primary user and secondary users is the emerging solution of spectrum allocation in the communications systems. Further issues arise even when we use cognitive radio devices to sense available frequency such as interference among users, decentralized nodes and the problem of urgent case when primary user needs his sharing band suddenly. However, in our work we have proposed two mechanism of spectrum sharing and made a comparison between them. Sharing according to number of subscriber of each user and sharing between primary and multi-secondary users. In game theory approach, a simple non-cooperative game mechanism based on a node's reputation to tackle the problems of competitive spectrum sharing which is another problem arises after detecting the unused frequency. The model presented predicts the best strategy even for selfish users serving others.

Optimum Nash equilibrium strategies were predicted using game theory for selfish nodes such that maximizing their profits. Individual nodes behavior and performance of the overall system can be also presented by using game theory. Several significant advantages are found in the proposed game theoretic solution of the problem of spectrum sharing problem such as fairness, simplicity in implementation, and ease of calculating optimum strategies. We assumed that all users with all service types have the same cost and utility attached with serving and obtaining services. The results and numerical simulations show that the game theory model is better than the other model which depends on number of subscriber in sense of optimal utilization and sharing.

Urgent case is also addressed as a problem may be facing the secondary users if the primary emerges again in the area of sharing.

7.2 Limitations and Features

Referring to the results in chapter 5 and 6 we can observe limitations and features of the two methods proposed in this work as follows:

7.2.1 Limitations on the first method (Spectrum Sharing depending on number of subscribers):

1- The competition depends on the number of subscribers that means the user who has more subscribers get higher ratio of available frequency.

2- The rate of sharing is fixed and may cause in more waste of spectrum.

3- The period between threshold and the peak hour can't be utilized.

7.2.2 Features of the second method (Spectrum sharing using Game Theory)

1- The competition depends on the reputation which gives it flexibility.

2- Probability (P<50%) prevents other secondary users from selfish behaviour.

3- There is no rate of sharing & it isn't fixed, that made us sure that no user will get sharing unless he wants it at that time which gives us trust in optimal utilization because game theory means rational decision.

4- No threshold means100% of the available frequency can be utilized.

5- This method can be used as a new method of spectrum allocation.

6- It can be used by regulatory bodies as spectral management method especially in the countries that still have free frequency bands.

7- Easier and faster unload frequency band in urgent case.

7.3 Future Work

- Optimum allocation for SU will be used in cognitive radio access for future work that based on a non-cooperative game theoretic load balancing algorithm or 'Spectrum Load Balancing' as it is used and referred to in [19]. Here each user determines his optimum fraction of his requirement with the consideration of other user demands and allocations. By this linking with our work we can enable the SPU to serve other SUs in his group with optimum spectrum utilization.

- Heterogeneity of service types and users is the way will be chosen to develop more models that take into consideration the desired type. When the heterogeneity is the over-riding factor in protocol design, the applicability of game theory in cognitive radio systems would be investigated.

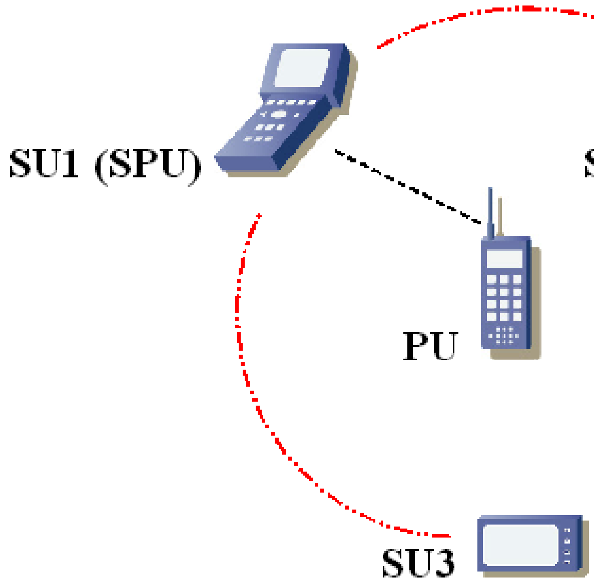

Figure 7.1: Heterogeneity of service types and users

Figure 7.1 shows the system including three types of users can be implemented to the same scenario of spectrum sharing using game theory that has been proposed in this thesis. The problem will be in obtaining previous knowledge about the performance of each user and in calculating the probability of being secondary primary user (SPU) which depends on many factors because of differences in type, performance and capacity of each user. If the calculations result in selfish behavior, then it will be limitation in using specific type rather than another type.

- Multi-Primary users also one of the suggested work to find alternative solution for secondary users in urgent case to share the spectrum they need with another primary user in the period of urgency.

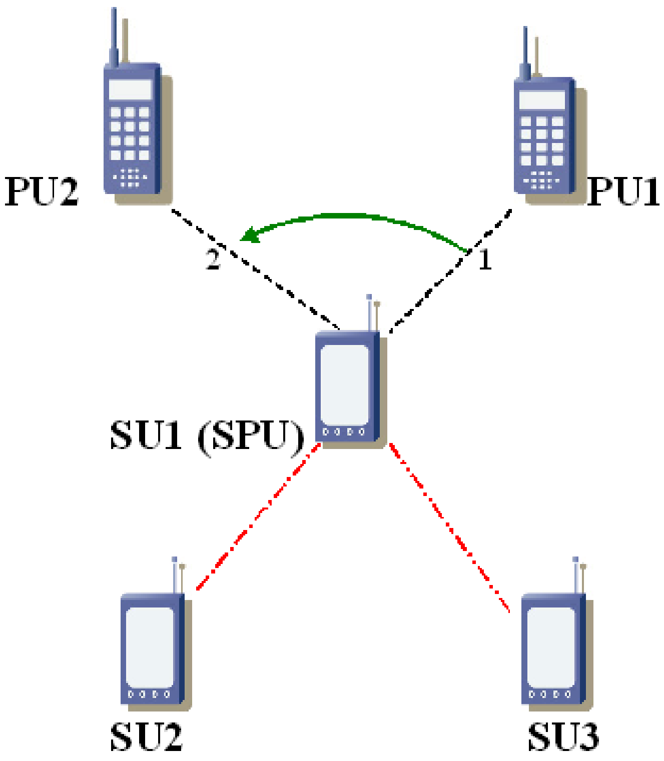

Figure 7.2: Spectrum Sharing using Game Theory with more than one PU

In urgent case when the primary user needs its frequency that has been rented to the secondary users which they (i.e. SUs) loose the resource of their service suddenly what means stopping their services. It needs as an urgent case for the SUs to go on and find an alternative solution by looking for another resource of spectrum from another primary user as illustrated in figure 7.2. PU1 is the main primary user which shares his spectrum with SU1, SU2, and SU3 while PU2 is the alternative user which can support SU1, SU2, and SU3 with the required resource of spectrum. Calculations must take into consideration the time delay for exchange and the compatibility of equipments used with each PU. The price is another issue that may be different from PU to another one.

- In future work the practical linking of the different sensing with the game theory-based and spectrum allocations especially using of cyclostationary sensing can be investigated further.

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1. Omar Raoof, Zaineb Al-Banna, H.S. Al-Raweshidy, "*Competitive Spectrum Sharing in Wireless Networks: A Dynamic Non-cooperative Game Approach*," WMNC'2009, the Second Joint IFIP Wireless and Mobile Networking Conference September 9-11, 2009 - Gdañsk, Poland.

2. Zina Jerjees, Zaineb Al-Banna, H.S. Al-Raweshidy, "Optimized Handover Schemes Over WiMax," WMNC'2009, the Second Joint IFIP Wireless and Mobile Networking Conference September 9-11, 2009 - Gdañsk, Poland.

3. Omar Raoof, Zaineb Al-Banna, H.S. Al-Raweshidy, "*A Dynamic Non-cooperative Game Approach for Competitive Spectrum Sharing in Wireless Networks,"* Accepted in 15th EUNICE International Workshop - The Internet of the Future, September 7, 2009. Bercelona, Spain.