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SPECTRUM SHARING IN COGNITIVE RADIO NETWORKS WITH QUALITY OF SERVICE AWARENESS

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This thesis is submitted in partial fulfilment of the requirements for the degree of Master of Science in Electrical Engineering

Under the Supervision of Dr. Mohammed Abdel-Hafez

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Declaration of Original Work

I, Nadir Hussin Sulieman Adam, the undersigned, a graduate student at the United Arab Emirates University (UAEU), and the author of this thesis entitled "*Spectrum Sharing in Cognitive Radio Networks with Quality of Service Awareness*", hereby, solemnly declare that this thesis is an original research work that has been done and prepared by me under the supervision of Dr. Mohammed Abdel-Hafez, in the College of Engineering at UAEU. This work has not been previously formed as the basis for the award of any academic degree, diploma or a similar title at this or any other university. The materials borrowed from other sources and included in my thesis have been properly cited and acknowledged.

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Abstract

The goal of this thesis is to study performance of cognitive radio networks in terms of total spectrum utilization and throughput of secondary networks under perfect and imperfect sensing for Additive White Gaussian Noise (AWGN) and fading channels. The effect of imperfect sensing was studied by applying non-collaborative and collaborative sensing techniques using energy detecting and square law combining techniques, respectively. Spectrum allocation for heterogeneous networks in cognitive radio networks was discussed and a new sharing algorithm that guarantee Quality of Service (QoS) for different secondary users' applications was proposed. The throughput degradation of secondary users due to the activities of the primary users was explored by varying the arrival rate of the primary users in a given spectrum band. Computer simulation showed that increasing the primary user's activity will increase the total spectrum utilization but decreases the secondary users' throughput simultaneously. The effect of the received Signal to Noise Ratio (SNR) of the primary user on the cognitive radio network performance is studied in which, a high SNR of primary users led to a higher throughput of secondary network in AWGN channels compared to Nakagami fading channels. The effect of applying cooperative sensing is also presented in this thesis. As we increased the number of cooperating sensors, the network throughput increased which proves the advantage of applying cooperative sensing. A spectrum allocation algorithm for heterogeneous network model is developed to study the QoS assurance of secondary users in cognitive radio networks. The system performance of the heterogeneous network was investigated in terms of the total spectrum utilization. It is found that, higher number of secondary users, better channel's condition and low required QoS of applications would increase the spectrum utilization significantly.

In this thesis, the proposed allocation algorithm was applied to the heterogeneous cognitive radio model and its performance was compared to the First Come First Served (FCFS) algorithm in both AWGN and fading channels. The proposed algorithm provided a higher average SNR and spectrum utilization than FCFS algorithm and guaranteed the QoS requirement for applications of secondary users. The effect of imperfect sensing on the system performance was investigated, and it was shown that, as the probability of detection increases the total applications' data rate increases significantly. The proposed algorithm guaranteed the QoS requirement for each application of secondary users. The effect of imperfect sensing on the system performance was investigated, and it was shown that, as the probability of detection increases the total data rate increases significantly.

Keywords: Cognitive Radio Networks, non-cooperative sensing, cooperative sensing, spectrum sharing, heterogeneous network, Hungarian algorithm, spectrum utilization.

Title and Abstract (in Arabic)

مشاركة الطيف في الشبكات الراديوية الإدراكية مع الوعي لجودة الخدمة

الهدف من هذه الأطروحة هو دراسة أداء الشبكات الراديوية الإدراكية من حيث إجمالي استغلال الطيف و انتاجية الشبكات الثانوية الإدراكية باستخدام الاستشعار المثالي و غير المثالي في القنوات ذات الضجيج الابيض المضاف و القنوات ذات توزيعيّ رايلي و نكاجامي. تمت دراسة تأثير الاستشعار غير المثالي بنوعيه التعاوني و غير التعاوني باستخدام تقنيتي كاشف الطاقة و موحّد القانون-التربيعي. تمت مناقشة تخصيص الطيف للشبكات غير المتجانسة في الشبكات الراديوية الادراكية و تم اقتراح خوارزمية توزيع جديدة تضمن جودة الخدمة للتطبيقات المختلفة للمستخدمين الثانويين. تم استكشاف التدهور في الانتاجية للمستخدمين الثانويين بسبب نشاط المستخدمين الاساسيين من خلال تغيير معدل وصول المستخدمين الاساسيين في نطاق طيفي معين و أظهرت المحاكاة الحاسوبية أن زيادة نشاط المستخدمين الرئيسيين تؤدي الى استغلال أعلى للطيف و لكن تؤدي لنقص انتاجية المستخدمين الثانويين في نفس الوقت. في هذه الأطروحة أيضا، تمت دراسة تأثير معدل -الاشارة الى الضوضاء- المستقبَل من المستخدمين الرئيسيين على أداء الشبكات الراديوية الادراكية و تم الوصول الى أن معدل أعلى لنسبة -الاشارة الى الضوضاء- يؤدي الى انتاجية أعلى في الشبكات الثانوية في القنوات ذات الضجيج الابيض المضاف مقارنة مع القنوات ذات توزيع رايلي. عند زيادة عدد أجهزة الاستشعار تم الحصول على انتاجية أعلى للشبكة مما يثبت مدى الاستفادة من الاستشعار التعاوني. تم تطوير خوارزمية تخصيص الطيف لنموذج الشبكة غير متجانسة التطبيقات لدراسة جودة الخدمة للمستخدمين الثانويين في الشبكات الراديوية الادراكية. تم تطبيق خوارزمية التوزيع و تمت مقارنة أدائها في القنوات ذات الضجيج الأبيض المضاف و القنوات ذات توزيع رايلي. تم الحصول على معدل أعلى لنسبة الاشارة الى الضجيج و استغلال للطيف باستخدام الخوارزمية المقترحة وذلك مع

ضمان جودة الخدمة لكل تطبيق للمستخدمين الثانويين. تم أيضا في هذه الأطروحة دراسة تأثير الاستشعار غير المثالي في أداء النظام و تبين أن الزيادة في احتمالية اكتشاف المستخدمين الأوليين ترفع معدل البيانات للتطبيقات بشكل ملحوظ.

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Dedication

To my family

For their endless love, support and encouragement

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List of Abbreviations

AWGN:	Additive White Gaussian Noise
BER:	Bit Error Rate
CR:	Cognitive Radio
CRBS:	Cognitive Radio Base Station
D2D:	Device-to-Device
DPSK:	Differential Phase Shift Keying
FCC:	Federal Communications Commission
FCFS:	First Come First Served
LOS:	Line of Sight
MAC:	Media Access Control
MIMO:	Multiple Input Multiple output
OFDM:	Orthogonal Frequency Division Multiplexing
Pdf:	Probability Density Function
PU:	Primary User
QoE:	Quality of Experience
QoS:	Quality of Service
SINR:	Signal to Interference plus Noise Ratio
SLC:	Square Law Combining
SNR:	Signal to Noise Ratio
SU:	Secondary User

List of Symbols

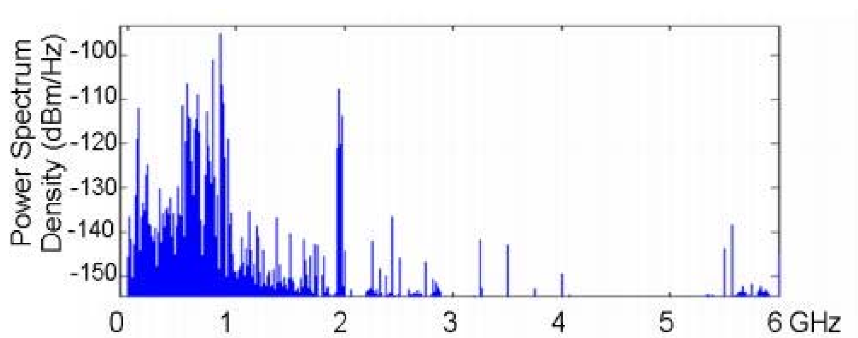
N	Number of secondary users
K	Number of available channels
e	Euler's number
P_{md}	Probability of misdetection
P_f	Probability of false alarm
γ	Instantaneous channel's SNR
$\bar{\gamma}$	Average channel's SNR
λ	Threshold
σ^2	Variance of the channel
$\Gamma(.)$	Incomplete gamma function
S	Half number of samples
Q_S	Generalized Marcum Q function
m	Nakagami fading parameter
$P_{d,Nakagami}$	The probability of miss detection in Nakagami fading channel
$P_{d,Rayleigh}$	The probability of miss detection in Rayleigh fading channel
k	Number of sensors
Δw	Minimum value in a row
Δn	Minimum value in a column
${C_i}^j$	Cost for assigning channel i to secondary user *j*
SNR_i	Energy to noise power spectral density ratio for channel i
SNR_j	Energy to noise power spectral density ratio for secondary user *j*
g_i^s	Channel gain for secondary user i
g_j^p	Channel gain for primary user *j*
N_i	Total noise affecting secondary user i
P_i	Transmission power for secondary user i
$P(H_1)$	Hypothesis of the primary user's signal presence
$P(H_0)$	Hypothesis of the primary user's signal absence

Chapter 1: Introduction

The role of wireless communications is becoming a corner stone in providing both coverage and capacity for fixed and mobile broadband access where radio spectrum is a precious resource in wireless communication networks.

The demand for this resource is growing rapidly due to the innovations that increased the number of connected devices, widened and eased the access of average users to versatile wireless services that requires high data rates. Wireless communication tries to rise to the occasion by using small size cells and larger spectrum. On the other hand, the Federal Communications Commission (FCC), which is the interstate communication regulator in the United States, has shown low spectrum utilization on the allocated spectrum – FCC showed that in most cases 70% of the allocated spectrum is unused [1]. Figure 1.1 shows measurements taken in downtown Berkeley, which reveal a typical spectrum underutilization [2].

The problem, which started as a lack of scarce resource is now transferred to a problem of spectrum management. This change of direction inspired many researchers to develop new policies to access the licensed spectrum and techniques that lead to a better utilization of the spectrum.



Freq (GHz)	0~1	1~2	2~3	3~4	4~5	5~6
Utilization(%)	54.4	35.1	7.6	0.25	0.128	4.6

Figure 1.1: Measurement of spectrum utilization (0-6 GHz) in downtown Berkeley

1.1 Cognitive Radio Networks

Cognitive Radio (CR) is a promising wireless technology that aims to better utilize and manage the spectrum. Cognitive radio networks consists of two types of users: the primary users (PUs) and the secondary users (SUs). The primary user is the user who is licensed to use the spectrum at any time while the secondary user is the user who does not have a license to use the spectrum but will exploit the spectrum holes based on agreed upon policy.

Due to the dynamic behavior of radio environment, cognitive radio must have the capability of adapting and changing the appropriate communication parameters. A visual demonstration of the cognitive radio concept is shown in Figures 1.2 and 1.3.

Researchers have focused on three main paradigms of cognitive radio networks: underlay, overlay and interweave. The underlay paradigm allows secondary users to access the spectrum if their interference to primary users is less than a certain threshold. In overlay systems, the secondary users use advanced signal processing and coding to assure and enhance the communication of primary users while being able to utilize the spectrum at the same time.

In interweave networks; the secondary users opportunistically exploit spectral holes to communicate without affecting the primary users' communication [3, 4].

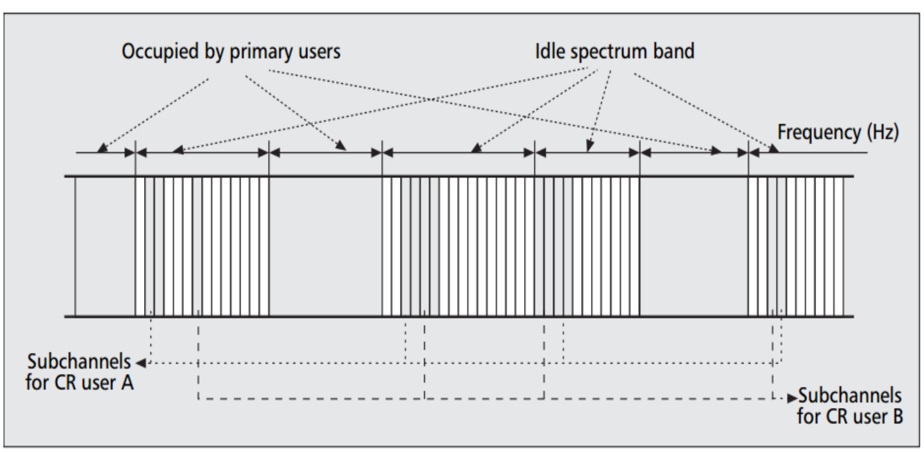


Figure 1.2: Channel structure of the multi-spectrum decision [3]

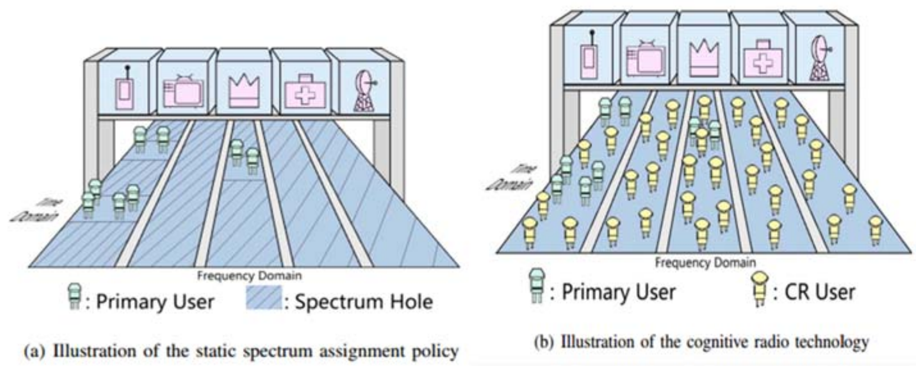


Figure 1.3: (a) Static spectrum assignment policy (b) Cognitive radio technology [3]

1.2 Spectrum Management

Coexistence between the primary and the secondary networks and the heterogeneous quality of service (QoS) requirements of the cognitive radio users forced the development of new spectrum management techniques to achieve solutions to many associated design challenges.

- Spectrum Management challenges

1. Interference Avoidance:

The secondary network must work seamlessly regardless of the existence of the primary network but at the same time must not interfere with it; the data transmission must be done effectively to not interfere with the primary network and efficiently as to achieve the maximum spectrum utilization.

2. QoS Awareness:

The secondary network must provide a suitable band for the secondary users based on their specific requirements. These challenges are met by implementing the cognitive radio cycle.

The cognitive cycle as shown in Figure 1.4 redrawn from [3], performs four main tasks: spectrum sensing, spectrum decision, spectrum sharing and spectrum mobility.

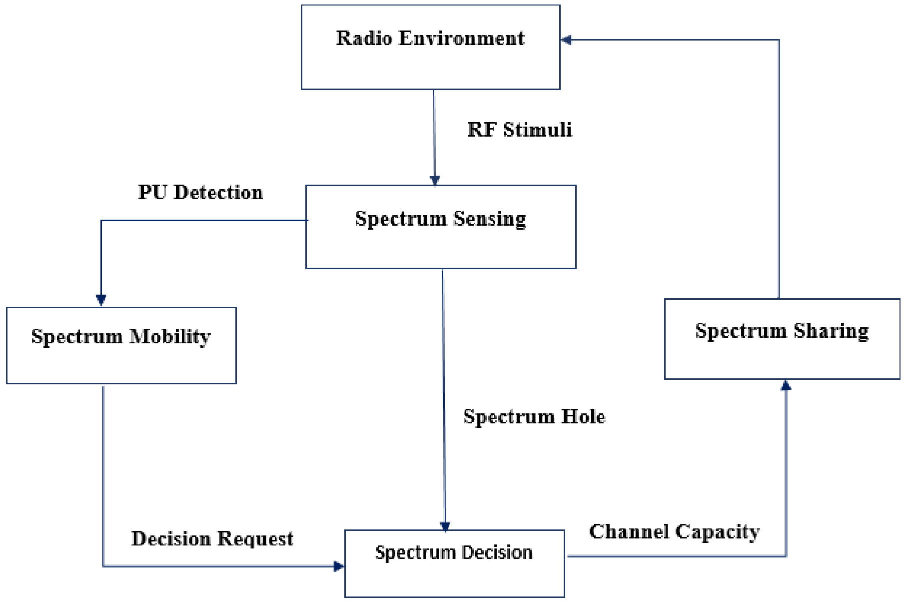


Figure 1.4: Cognitive radio cycle.

1.2.1 Spectrum Sensing

The first and arguably the most important step in the cognitive cycle is spectrum sensing. This is where the cognitive radio network scans the spectrum looking for white spaces or holes that are not used by the primary users and can be used by the secondary users to transmit their data and hence enhance the spectrum utilization.

Many different schemes to detect the existence of primary users' existence have been introduced in the literature; some of them are based on detecting the primary users' transmitters to identify this spectrum portion as busy while others are based on detecting the leakage power of the primary receiver, as this will indicate an ongoing communication in the primary network. Matched filter detection, energy detection, and feature detection are some examples of the first kind while the direct receiver detection method is a type of spectrum sensing based on the leaked power from primary user receivers [5].

- Spectrum Sensing Challenges

One of the spectrum sensing challenges is the location estimation of primary receivers. This is a challenge because there are no interaction between the primary and the secondary networks. Another issue is the detection of primary users in an environment in which a large number of both primary and secondary users reside which makes the ability to spot spectrum holes a difficult task. Spectrum-efficient sensing algorithms are constantly modified to find the most efficient method to balance between the sensing time and the spectrum utilization; a greater sensing time leads to minimize the error in estimation but at the same time reduces the spectrum utilization and vice versa [6].

1.2.2 Spectrum Decision

After all the available bands have been identified in the sensing step, the spectrum decision step aims to optimize the process by selecting the best band to satisfy the minimum quality of service required by the secondary users while maintain a no interference policy to the primary users. This can be done by channel characterization based on the current channel estimation and primary users' activity modeling; this includes channel identification, channel capacity estimation, channel interference estimation and spectrum selection [6].

- Spectrum Decision Challenges

Researchers are looking into cooperation and adaptability in cognitive radio networks, which is still an open area of research. Transmission parameters must be optimally adapted to use the certain spectrum bands; even at low SNR, the achieved data rate can be maintained by changing the modulation schemes and using Multiple Input Multiple Output (MIMO) techniques. In addition, spectrum decision mobility over licensed and unlicensed bands is another challenge in cognitive radio networks [6].

1.2.3 Spectrum Sharing

The third component in the cognitive cycle is optimum sharing of available spectrum holes between competing secondary users based on their individual requirements. Spectrum sharing is very useful in terms of saving energy, which can be achieved by utilizing lower frequency bands that will decrease the transmitted power. Exploiting other regions of the spectrum that are underutilized can provide a greater capacity and this can be advantageous by reducing the number of active base stations which will enhance the system power efficiency [6].

- Spectrum Sharing Challenges

Using shared common control channel between all the secondary users depends on the topology. This channel is also used by the primary users and must be vacated immediately when the primary users arrives. Due to the nature of cognitive radio the operating frequency change continuously, this is referred to as a dynamic radio range property. The research on spectrum sharing techniques considers the channel as a basic spectrum unit. In many of the research about spectrum sharing, researchers considered the assumption that the secondary users know the location and transmission power of the primary users to calculate the interferences appropriately [6].

1.2.4 Spectrum Mobility

The last step in the cognitive cycle is the spectrum mobility. After the secondary user occupies the channel, it must be aware of the activities of primary users. In case of a return of the licensed user to use it, the unlicensed user must leave the occupied channel and hop to another channel; this is called a spectrum handover. As in the handoff of cellular networks, the transition between channels must be fast and seamless to maintain a good performance of the network [6].

- Spectrum Mobility Challenges

Available vacant channels change continuously over time and space. Maintaining a QoS over all these challenges in all the cognitive cycle steps is a major design concern. Figure 1.5 show the spectrum framework for cognitive radio networks [6].

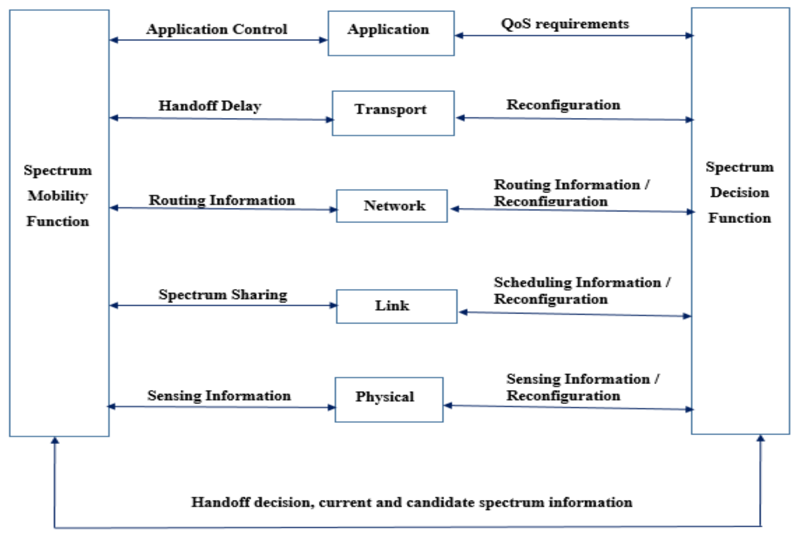


Figure 1.5: Spectrum management framework for cognitive radio networks

1.3 Cognitive Radio Network Architecture

The cognitive radio network components are divided into two main groups: The primary (licensed) network and the secondary (dynamic spectrum access) network. The primary network users are the licensed user to use the spectrum at any time and must not be affected by secondary users.

The secondary network is not licensed to use the spectrum and hence it must have additional functionality to match these requirements. Since the secondary users can access both licensed and unlicensed bands (Spectrum Heterogeneity), the operations in each portion of the spectrum must be different in a way, which adds another layer of complexity to the cognitive users, as the secondary users need to have an adaptive media access control protocol (MAC) to roam seamlessly from one network to the other [8].

In the licensed band, the main task done by the unlicensed users is to perform an efficient spectrum sensing to detect the activity of the primary users, and the capacity of the secondary users depend on the level of interference. If at any time the primary user returns, the secondary user must immediately evacuate the channel (spectrum mobility). While in the unlicensed bands, all the users are the same and no one has a priority over the other unless stated by a certain policy, and the main task in these bands is to share the available spectrum efficiently and effectively [8]. A cognitive radio network architecture is shown in Figure 1.6 redrawn from [6].

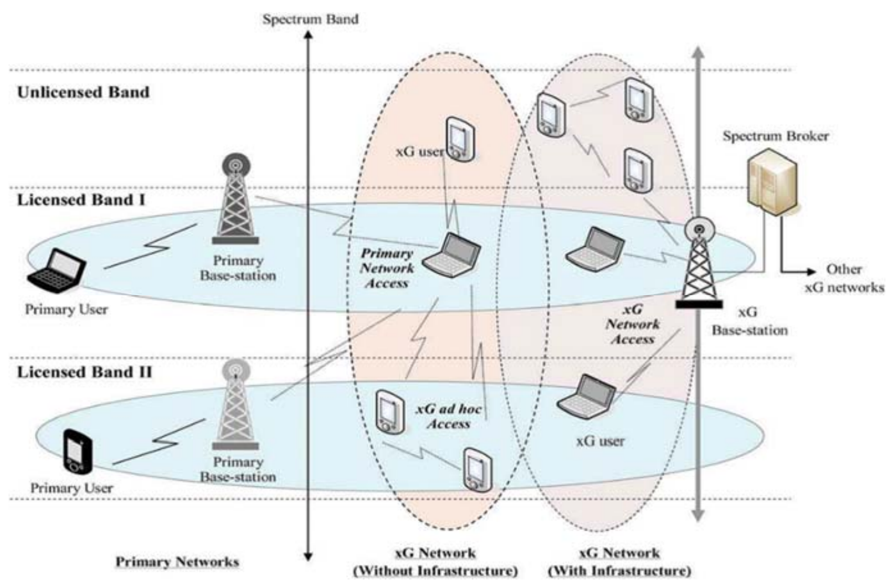


Figure 1.6: Cognitive radio network architecture

Figure 1.7 demonstrates the concept of spectrum sharing between primary and secondary networks.

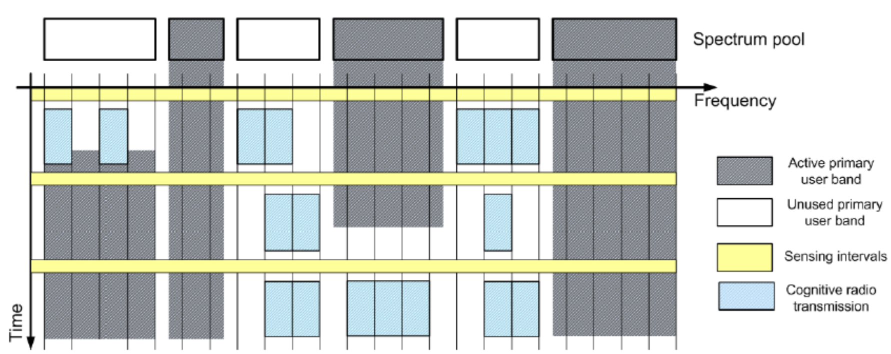


Figure 1.7: Spectrum sharing in cognitive radio networks

Optimizing the sensing interval is important to enhance the performance of the cognitive users and many researchers have proposed methods to achieve that. In this thesis, we concentrate on the spectrum sharing step in the cognitive cycle and therefore the sensing time is assumed to have negligible effect on the capacity of the secondary networks.

1.4 Cognitive Radio Networks Channel Models

Communication over wireless channels is very challenging due to various effects, such as the geographical and topological characteristics of the area and the communication nodes design. A combination of these components may lead to a degradation in the system performance due to fading, multipath propagation and shadowing. Signal to noise ratio, SNR is a common measuring parameter of the system performance [9]. The signal refers to the received power while the noise is caused by many parameters. In Additive White Gaussian Noise (AWGN) channels, the noise is a result of the thermal noise at the receiver side only. On the other hand, fading channels suffer from the impact of multipath propagation and shadowing. Fading is categorized into slow and fast fading. In slow fading, the time duration of the fading is smaller than the average time in which the fading is correlated, otherwise it is considered to be fast fading. Fading can be also categorized into frequency selective and flat fading [9]. If all of the spectrum components are affected the same way, the fading is considered non-selective or flat fading, this occurs when the transmitted signal bit duration is smaller than the channel coherence time (narrow-band systems). On the other hand, frequency selective fading occurs when the spectrum components are affected by different weights and the transmitted signal bit duration is greater the channel coherence time (wide-band systems). In this thesis, only slow-flat fading channels are considered [10].

In the urban environment, the transmitted signal suffers from various obstacles in their way to the receiver. These obstacles cause a reflection, deflection and refraction in the signal, and as a result of this, the receiver gathers multiple versions of the signal from different paths over time, this is referred to as multipath propagation. In this thesis, Rayleigh and Nakagami fading channels are taken as a statistical behavior of the multipath fading [10].

1.4.1 Rayleigh Fading Channel

Multipath fading with no direct line of sight (LOS) is statistically described with Rayleigh distribution. The received signal envelope is given as [9]:

$$P_r(r) = \frac{r}{\sigma^2}\, e^{-(\frac{r^2}{2\sigma^2})} \qquad r \geq 0 \tag{1.1}$$

where r is the received signal voltage and σ^2 is the variance of the channel distribution

The instantaneous signal of the Rayleigh channel is exponentially distributed and is given as [9]:

$$P_\gamma(\gamma) = \frac{1}{\bar{\gamma}}\, e^{-(\frac{-\gamma}{\bar{\gamma}})} \qquad \gamma \geq 0 \tag{1.2}$$

where γ is the received signal power and $\bar{\gamma}$ is the average SNR of the Rayleigh faded channel.

The received signal in the Rayleigh fading channels suffers from high variations; this is of high importance in cognitive radio networks as the misdetection of the primary users will lead to collision with the cognitive users.

1.4.2 Nakagami-m Fading Channel

The received signal envelope in Nakagami channels is given as [9]:

$$P_R(r) = \frac{2\, m^m\, r^{2m-1}}{\Omega^m\, \Gamma(m)}\, e^{-(\frac{mr^2}{\Omega})} \qquad r \geq 0 \tag{1.3}$$

where $\Omega = E(R^2)$ and m is the fading parameter and is given as $\frac{\Omega^2}{(r^2-\Omega)^2}$.

Rayleigh fading is considered a special case of Nakagami fading by setting $m = 1$, and when m is large, the Nakagami channel tends to behave as a non-fading or AWGN channel. In other words, as the fading parameter increases the fading effect becomes less and less until it vanishes at large values of m.

The instantaneous SNR of the Nakagami channel is gamma distributed and is given as [9]:

$$P_{\gamma}(\gamma) = \frac{m^m \, \gamma^{m-1}}{\bar{\gamma}^m \, \Gamma(m)} \, e^{-(\frac{m\gamma}{\bar{\gamma}})} \qquad \gamma \geq 0 \tag{1.4}$$

where γ is the received signal voltage and $\bar{\gamma}$ is the average SNR of the Nakagami fading channel.

1.5 Thesis Organization

The objective of this thesis it to study the performance of spectrum sharing in cognitive radio networks and to show the performance of a new spectrum allocation technique based on the Hungarian algorithm that provides QoS assurance to the secondary users. In what follows, we present the thesis outline and its main contributions.

Chapter 2 provides the necessary background and presents a summary of the existing models of spectrum allocation models of the cognitive radio network. It highlights the motivation for developing new models to cope with the diverse quality of service requirements

In chapter 3, different cognitive radio networks models in the AWGN and under perfect sensing mode are studied. The performance of the models was measured with the total spectrum utilization and with secondary users' data throughput. The degradation of throughput due to primary users' activity is explored by varying the arrival rate of the primary users in a given spectrum band. This chapter provides an insight to the benefits of cognitive radio networks in increasing the spectrum utilization.

The study of cognitive radio models performance is extended in chapter 4 to cover the system models under Rayleigh and Nakagami fading channels. This will provide more realistic models in wireless communication than the AWGN channel. The effect of imperfect sensing is also studied by applying non-collaborative sensing represented by the energy detection scheme. Furthermore, collaborative sensing using square law combining technique is investigated. The effect of the primary user's SNR and the fading parameters were discussed.

In Chapter 5, a heterogeneous network model is introduced to study the QoS assurance of secondary users in cognitive radio networks. An allocation process in centralized base stations is discussed in details and a spectrum allocation algorithm based on the Hungarian algorithm is proposed. A comparison between the First Come First Served (FCFS) algorithm and the proposed algorithm under AWGN and fading channels reveals the outperformance of the proposed algorithm compared to FCFS.

The heterogeneous network performance in terms of the total capacity and the achieved data rate are the main consideration of Chapter 6. For each application, its contribution to the total network capacity and its average data rate is presented.

Chapter 7 concludes the work and provides suggestions for possible future works.

Chapter 2: Literature Review

2.1 Introduction

Research in Cognitive Radios encompasses many areas of interest starting from the research in spectrum sensing techniques through spectrum decision and sharing and finally to the research on spectrum mobility. In this chapter, the motivation behind spectrum sharing that assures QoS is discussed. The preceding efforts in the cognitive radio in general and sharing techniques and models in particular are also presented in details.

2.2 Research Motivation

Cognitive radios consists of a high level of complexity in all of its operations steps. The continuous interactions between all the network elements (licensed and unlicensed) have created a huge research opportunities in order to develop procedures, algorithms and protocols to achieve the promised outcomes of the cognitive radio [11]. Wireless networks are a dynamic and unpredictable medium in nature and the lack of instantaneous and full predictive knowledge of its behavior may lead to degradation in the expected performance and QoS [12].

This leads to one of the thesis motivations, which is the study of cognitive radio under different channel models; AWGN, Rayleigh and Nakagami models in particular. The effect of imperfect sensing using non-cooperative (energy detector) and cooperative sensing (square law combining technique) on the system performance is also addressed to show a clear image of cognitive radio systems.

As cognitive users' devices with different applications that require varying QoS i.e. (chat, audio, video and web browsing) are connected online, an algorithm that allocates the best available channel for their requirements while achieving the maximum spectrum allocation is required; this is the motivation for the proposed allocation algorithm presented in this thesis.

2.3 Preceding Efforts

In this section, we review some of the related research on the area of cognitive radio in general and the research in spectrum sharing in particular. Mitola and Maguire presented the first description in cognitive radio in 1999 [13]. They have introduced the concept of radio etiquette, "Radio etiquette is the set of RF bands, air interfaces, protocols, and spatial and temporal patterns that moderate the use of the radio spectrum". They have stated that the cognitive radio must have knowledge of this etiquette in addition to the propagation and network modeling and the application scenarios that automatically leads to the satisfaction of varying user needs. This knowledge redefines the responsibilities and capabilities of the radio nodes from blind nodes to intelligent nodes that are aware of their surroundings and are always adapting their protocol stack to the varying requirements of the network nodes and working in different ways to achieve these requirements. Smart radios are the foundation stone for the realization of cognitive radio.

In 2005, Haykin described the cognitive radio as a smart wireless communication system that is cognizant of its surrounding environment and uses this knowledge to learn, build and adapt to the statistical variation in the inputs, which aims to provide a reliable communication anytime, anywhere and provide an efficient utilization of the radio spectrum [14]. In his paper, Haykin tackled three main cognitive tasks: radio analysis, channel estimation & modeling and dynamic spectrum management, which represent the first three tasks of the cognitive cycle [14].

A profound understanding of any system behavior can be extracted using appropriate modeling; these models must have two characteristics in order to be considered a “realistic” model: the system must be general and specific at the same time!

The model must be general to be applied to various problems, yet specific to the needs and specifications of the current implementation. This can be carried out by designing a simple model and see if it can capture all the system characteristics and properties. If true then we try to make it simpler until the point it is not reliable to be implemented, and the model prior to this will be implemented [15].

Different approaches of spectrum sharing in cognitive radio have been proposed throughout the years from joint power allocations, spectrum pricing and using contract theory. The authors of [16] introduced a power control algorithm based on game theory for cooperative cognitive radio networks where they used the throughput and power to represent the utility function. They have achieved the Nash equilibrium analytically and by simulation. A joint rate and power control algorithm is derived in [17] and the authors perspective was to maximize the link utility function, and they have shown the algorithm performance through simulations.

The authors of [18] and [19] studied the spectrum sharing problem using spectrum pricing. In the former paper, the authors investigated the impact of increased number of secondary users with different channel preferences on the system performance, while the latter focused on cooperative pricing model with competitive pricing and used the Nash equilibrium as a solution to the problem.

In [20], the authors proposed a joint power control and resource allocation model for co-channel deployed femtocells in macrocell networks that aims to minimize the total power consumption and guarantee QoS for both femtocell and macrocell users. The authors proposed a centralized scheme based on the Hungarian algorithm to solve the formulated optimization problem and the simulation results showed that the proposed scheme allocated both power and frequency to femtocells effectively while reducing the power consumption considerably.

The authors of [21] proposed a new adaptive channel allocation algorithm for cognitive radio networks with Orthogonal Frequency Division Multiplexing (OFDM) systems using the Hungarian algorithm. The algorithm aims to maximize the total bit rate of cognitive users under the constraint that the secondary users' transmission power must be below a certain threshold and the interference at the primary users is below the maximum acceptable value. The proposed algorithm improved the system throughput compared to other algorithms based on computer simulations.

The authors of [22] proposed an allocation scheme based on the Hungarian algorithm that work with different channel conditions using a backpressure approach. The proposed scheme assigns the available resources firstly to users with larger waiting traffic opportunistically, after that, the remaining available resources are allocated to other users to achieve fairness and maximize the throughput of the network. The authors of [23] investigated and modeled the channel allocation problem in a single cellular cell suffering interference from multiple device-to-device (D2D) communications. The allocation scheme was implemented using the Hungarian algorithm to maximize the number of D2D communications and to provides an optimal aware of interference to the cellular communication. The allocation scheme succeeded to enhance the number of D2D communications while minimizing the interference to the cellular network.

Another approach for spectrum sharing technique was presented in [24]. The authors investigated the problem of maximizing the total throughput of multiple secondary users in a multi-channel sensing-based cognitive radio network under various traffic conditions. Two dynamic spectrum access algorithms (Hungarian and Greedy) were proposed under non-cooperative spectrum sensing. The simulation results showed that as the number of available channels increases the Hungarian algorithm provides a better allocation results than the greedy algorithm.

In [25], the authors proposed a new scheduling scheme for MAC-layer sensing in cognitive radio networks based on the secondary users channel state and primary users activity. The spectrum sensing problem was modeled as an optimization problem and solved using the Hungarian algorithm. The proposed algorithm succeeded to provide a considerable tradeoff between the fairness among secondary users and the cognitive radio network throughput. The authors of [26] investigated the problem of downlink video streaming for multi-users in cognitive radio networks, where each secondary user is allowed to access only one channel at a time. The problem of secondary users Quality of Experience (QoE) maximization was formulated as a maximum weighted matching problem and was solved using the Hungarian algorithm to provide optimal channel assignment. The simulation results showed the outperformance of the proposed algorithm compared to other schemes in terms of number of available channels and the QoE achieved.

In [27], the authors investigated the resource allocation for underlay cognitive radio networks, where the primary users do not exist and thus the secondary users do not cause any interference to them. The authors compared two schemes, the sum energy efficiency based scheme that formulated a sum energy efficiency maximization problem and then solved by the Hungarian algorithm and a resource allocation scheme based on the stable matching that considered the choices of primary and secondary users.

In [28], a channel allocation scheme for two-way relay cognitive radio networks was proposed. The authors modeled the network as a classical weighted bipartite graph, which was solved by the Hungarian algorithm to provide an optimum relay selection and channel allocation. The authors' strategy was based on utilizing some of the secondary users as a relay to the primary users communication, maximizing the signal to interference plus noise ratio (SINR) for the secondary users and minimizing the SINR at the primary users The simulation results showed that the proposed allocation scheme outperformed the conventional power allocation and relay selection algorithms. The authors in [29] proposed a new channel allocation scheme with cooperative spectrum sensing as a sensing strategy. The authors implemented an iterative Hungarian algorithm to optimize the channel allocation. The authors showed that the proposed scheme succeeded to enhance the sensing performance of the system.

In [30], the authors proposed an innovative channel sharing scheme that aims to minimize the interference caused by the secondary users that affects the ongoing communications of the primary network. The authors formulated the sharing problem as an assignment problem and the Hungarian algorithm was implemented to provide an optimal solution under the constraints of minimizing the interference to the primary users. The authors have shown that the proposed scheme succeeded to reduce the interference to the primary users compared to other schemes. For all the above-mentioned schemes, the Quality of Service (QoS) requirements for different applications and secondary users were not considered. In this thesis, a spectrum sharing algorithm that focuses on the secondary users' QoS requirements is presented.

A centralized cognitive radio network model is considered where all the cognitive cycle decisions are done there. The network is simulated under different channel models to reflect different environments in which the system may exist. The spectrum broker, which is the central entity responsible for allocating the channels, receives all the required channel information, i.e. the existence of the primary user and the channel SNR. It also receives the requests from the secondary users to access the spectrum; the secondary users send their QoS requirements in terms of SNR to the system broker.

The proposed allocation algorithm is based on the Hungarian algorithm in order to provide an optimum spectrum sharing solution among the secondary users. It gathers all the information mentioned above and matches the SUs applications with the available channels that have the nearest SNR that is higher than the required SNR. The algorithm approach provides QoS assurance for the cognitive network and a power saving strategy for the secondary users.

2.4 Conclusion

A comprehensive review of the spectrum allocation schemes was given in this chapter. The motivation behind the research in the area of spectrum sharing was discussed and the need for an allocation technique that guarantee QoS for secondary users is presented. The Hungarian algorithm is famous for providing an optimization allocation for resources in various types of applications, and wireless communications is not an exception of that. It was shown that, the Hungarian algorithm was used as an optimization algorithm in cellular, Ad-hoc, D2D and cognitive radio networks. Given that, it was considered as a base model to our proposed allocation algorithm that was briefly discussed in this chapter.

Chapter 3: Cognitive Radio Networks under Perfect Sensing

3.1 Introduction

In this thesis, four cognitive radio models are considered starting from an ideal spectrum sharing case in this chapter and ending with the usage of the modified Hungarian algorithm introduced in chapter 5. For all the models in this chapter, perfect sensing of the primary users is assumed and the probabilities of false alarm and misdetection are assumed to be negligible.

3.2 Ideal Model

In this model, a centralized cognitive radio network that consists of N number of secondary users compete for the access of up to K available channels. The simulation of this model will shed the light on the relationship between the total spectrum utilization and the secondary users' data throughput will illuminate the benefits of cognitive radio.

Spectrum utilization of this model is directly related only to the number of available and requested channels as other parameters were considered to be perfectly implemented. If the number of available channels identified after the perfect spectrum sensing is greater than the number of requested channels by the secondary users then a low spectrum utilization is to be expected. Spectrum utilization will increase as the number of requested channels increase until it reaches the number of available channels and in this case, the spectrum will be fully utilized (ideally).

On the other hand, the throughput of the secondary user (measured as a percentage of the data sent to the total number of data) is expected to be the other way around. When the number of available channels is greater than the number of the requested channels, all the data is ideally sent and received and therefore we expect a 100%

throughput for all secondary users. The throughput will decrease if the number of available channels is less than the number of needed channels and this value will reach zero if all the spectrum is utilized by the primary users.

3.3 Probabilistic Model

In this model, the existence of the primary users in each time slot and channel is generated randomly based on the ratio of the total number of primary users to the total number of users (primary and secondary users). The existence of the secondary users and different QoS requirement are generated randomly. QoS for the secondary users is generated as a random number between 1 and 4 that represents the number of channels the secondary user needs to send its data. The simulation model will give an insight into the relationship between the number of available and requested channels and the spectrum utilization and secondary users' data throughput.

It is expected to gain high spectrum utilization up to full utilization of the total spectrum if the number of spectrum holes are greater than the cognitive users' demand and vice versa. The users' data throughput as illustrated before has an inverse relationship with the spectrum utilization as we are considering on the cognitive users' throughput only. If the primary users' throughput is considered then it will have an obvious direct relation with the number of occupied channels and evidently will have an impact on the channel conditions.

In this model, a full secondary users' buffer is assumed, perfect spectrum sensing and minimum satisfying channel conditions.

3.4 Poisson Model

3.4.1 Poisson distribution

In probability theory and statistics, the Poisson distribution, is a discrete probability distribution that gives the probability of a given number of events occurring in a fixed interval of time and/or space. It is widely used when these events average occurring rate is known and that the events are independent from each other; the occurring of an event at a certain time does not have any effect on the behavior of events in the future. This process is a continuous time Markov process.

3.4.2 Definition

A discrete random variable X is said to have a Poisson distribution with parameter $\lambda > 0$, if, for k = 0, 1, 2… the probability mass function of X is given by

$$f(k;\lambda) = P_r(X = k) = \frac{\lambda^k e^{-\lambda}}{k!} \tag{3.1}$$

where

$e \equiv \text{Euler's number}$

$k! \equiv \text{Factorial of k}$

$\lambda \equiv \text{Mean and Variance value of X}$

If for every $t > 0$ the number of arrivals in the time interval $[0,\ t)$ follows the Poisson distribution with mean λt, then the sequence of inter-arrival times are independent and identically distributed exponential random variables having mean $1/\lambda$.

3.4.3 Model Assumptions

- The probability of a primary user entering the network between $t \rightarrow t + \Delta t$ is given as $\frac{\lambda^k e^{-\lambda}}{k!}$, where λ is a constant, independent of the time, independent of the earlier number of arrivals and represents the average number of primary users.
- The number of arrivals in non-overlapping intervals are statistically independent.
- Only one primary users arrival can occur during a time slot t

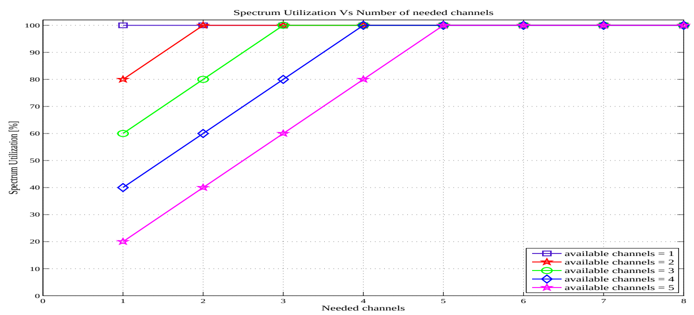
In this model, the number of primary users is generated using a Poisson distribution function of minimum value of 1 and a maximum value equal to the total number of channels in the network. If the number of primary users is higher than the total number of channels, this will lead to very rare opportunities for secondary users to find vacant channels. The number of requested channels moves on a range for each run with a constant value of the mean number of the primary users. This model is more realistic than the previous two models. Though it is assumed that all secondary users have the same QoS requirements and all secondary users are treated as summation of one entity in the calculations. As in the second model, the simulation results will show the relationship between the mean number of primary users, the total spectrum utilization and the secondary users' data throughput for different number of requested channels.

3.5 Simulation Results

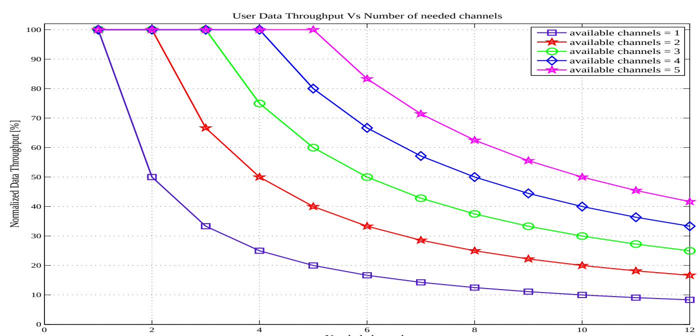
Figures 3.1 - 3.2 represent the effect of secondary users' as well as the primary users' activity on the system performance, i.e. the total spectrum utilization and the secondary users' data throughput. Figure 3.1 shows the effect of secondary users' requirements on the system performance. It is clear from the figure that for the same number of white spaces or available channels, the network (including primary users) utilization may reach a 100% of the available capacity with the increase in secondary users' activity in an ideal situation.

On the other hand, the data throughput of the secondary users drop with their higher demand for available channels. This is because when the number of available channels is less than the requirement number, the secondary users must compete for the limited number of available channels.

Figure 3.1 also illustrates that for the same number of required channels, the spectrum utilization decreases with the increase of available channels that is because when the number of available channels is higher than the secondary user requirements this leads to spectrum holes that are not utilized. Data throughput of secondary users increases with the increase of available channels, which is expected because in this case all secondary users will send their data without competing with other secondary users. In general, Figure 3.1 shows the inverse relationship between the total spectrum utilization and the data throughput of secondary network.



(a)

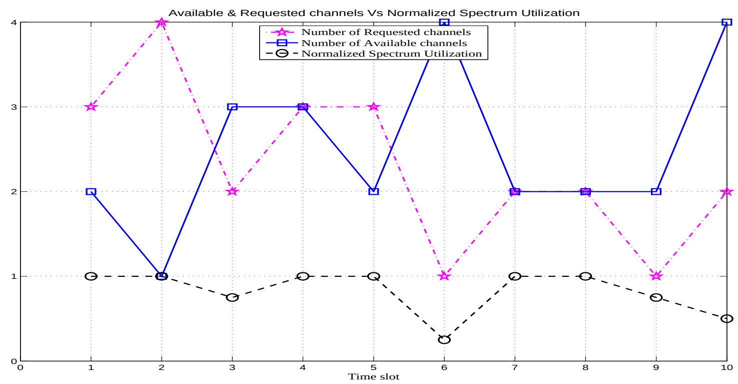


(b)

Figure 3.1: Effect of SU activity on system performance

Figure 3.2 shows the relationship between the normalized to 1 spectrum utilization and secondary user data throughput with the number of both the available and requested channels.

When the number of available channels is higher than the number of needed channels the data throughput will reach 100% -normalized to 1 in the graph- as all secondary users' data are transmitted, while the spectrum utilization drops because there are some spectrum holes that were not utilized. On the other hand, when the number of requested channels are higher than the available channels, the spectrum utilization will reach a 100% ideally, as most of the spectrum will be utilized by the primary user and the rest will be used by some of the secondary users. The secondary networks' throughput will drop as a result of lacking free channels.



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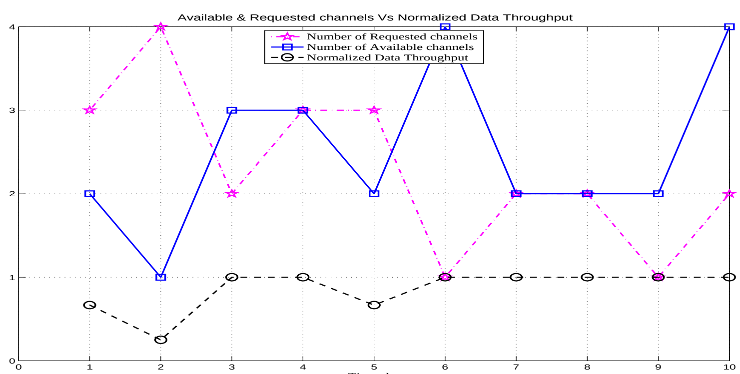
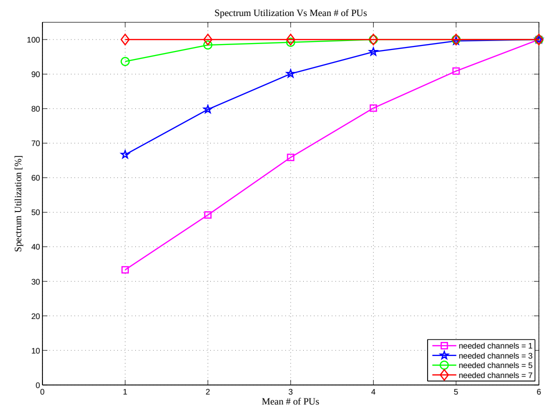


(b)

Figure 3.2: Effect of available & requested channels on system performance

The effect of primary users' activity (mean number of primary users) on the total system utilization and the data throughput of the secondary users is depicted in Figure 3.3. As the mean number of primary users increases, the spectrum utilization increases to reach ideally 100% where the primary users will be the dominant participants utilizing the spectrum. This means that secondary users will be assigned a smaller portion of the spectrum leading to a drop in their data throughput, which reaches zero when there are no spectrum holes left by the primary users. For the same mean number of primary users the spectrum utilization increases with higher demand from the secondary users (needed channels) as the white spaces are utilized. On the other hand increasing the demand of the secondary users beyond the available channels leads to degradation in the data throughput of the secondary users.



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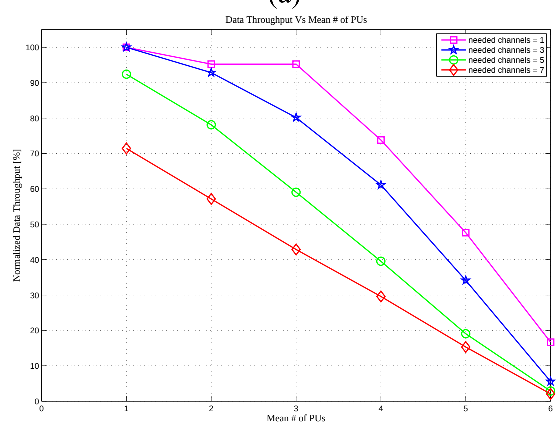

(b)

Figure 3.3: Effect of PU activity on system performance

3.6 Conclusion

In this chapter, different cognitive radio networks models in the AWGN and under perfect sensing are studied. The performances of the models were measured in terms of the total spectrum utilization and the secondary users' data throughput. It was found that, as the number of available channels decreases, the total network utilization increases due to the primary users' activities and the secondary network throughput decreases. The effect of primary users' activities (mean number of primary users) on the total system utilization and the data throughput of the secondary users were also discussed in this chapter. The degradation of throughput due to primary users' activities are explored by varying the arrival rate of the primary users in a given spectrum band and it was shown that increasing the primary user's activity in the network will increase the total spectrum utilization and at the same time decreases the secondary users' throughput.

As these results may seem predictable but it provides a basic cognitive radio model that will be further developed in the following chapters.

Chapter 4: Cognitive Radio Networks under Imperfect Sensing

4.1 Introduction

Spectrum sensing is extremely important step in the cognitive cycle. Channel model was shown to have a great effect on the sensing performance; therefore, the effect of different sensing techniques in different channel models on the secondary users' throughput is discussed in this chapter.

4.2 Non-cooperative Sensing in Cognitive Radio Networks

In this section, non-cooperative sensing in AWGN and fading channels using energy detector is discussed.

4.2.1 Non-cooperative Sensing in AWGN Channels

AWGN channel is the ideal type of wireless channel where the total noise at the receiver is only a result of the white noise and no effect of other factors such as fading is considered. Performance of cognitive radio networks in AWGN channels is measured using four basic parameters, the probability of misdetection P_{md} , the probability of false alarm P_f, the probability that the primary user is using the channel $P(H_1)$ and the probability of a vacant channel $P(H_0)$. The probability of misdetection is the probability the primary user exists but not detected. The probability of false alarm is the probability that a flag was raised indicating the existence of the primary user while in fact it does not occupy the corresponding channel. These probabilities are given as [31]

$$P_{md} = 1- Q_S\left(\sqrt{\frac{2\gamma}{\sigma^2}}, \sqrt{\frac{\lambda}{\sigma^2}}\right) \tag{4.1}$$

$$P_f = \frac{\Gamma(S,\lambda/2\sigma^2)}{\Gamma(S)} \tag{4.2}$$

where γ is the SNR,λ is the threshold and σ^2 is the variance of the channel. $\Gamma(.)$ is the incomplete gamma function [32], N is the half number of samples, Q_S is the generalized Marcum function [33].

4.2.2 Non-cooperative Sensing in Fading Channels

In Nakagami fading channel, the probability density function (pdf) of the SNR follows the gamma distribution and is given as in equation (1.4):

$$f_\gamma(\gamma) = \frac{1}{\Gamma(m)} \left(\frac{m}{\bar{\gamma}}\right)^m \gamma^{m-1}\, exp(\frac{-m}{\bar{\gamma}}\,\gamma) \tag{4.3}$$

where $\bar{\gamma}$ is the average SNR in the fading channel and m is the Nakagami fading parameter.

The probability of false alarm in Nakagami channels is the same as in AWGN given in equation (4.2), since the false alarm probability is the probability that the received signal is above a certain threshold while the primary user is does not exist. The probability of detection over Nakagami fading channel is given by [32]:

$$P_{d,Nakagami} = \frac{1}{\Gamma(m)} \int_0^\infty Q_S\left(\sqrt{(2\gamma)}, \sqrt{\lambda}\right) (\frac{m}{\bar{\gamma}})^m\, \gamma^{m-1}\, exp\left(\frac{-m}{\bar{\gamma}}\,\gamma\right) d\gamma \tag{4.4}$$

The probability of detection in Rayleigh channels can be found easily by setting $m = 1$ in the above equation

$$P_{d,Rayleigh} = \int_0^\infty Q_S\left(\sqrt{(2\gamma)}, \sqrt{\lambda}\right) (\frac{1}{\bar{\gamma}})\ exp\left(\frac{\gamma}{\bar{\gamma}}\right) d\gamma \tag{4.5}$$

4.3 Cooperative sensing in cognitive radio networks

In this section, cooperative sensing using square law combining technique is discussed in AWGN and fading channels.

4.3.1 Cooperative Sensing in AWGN Channels

Applying non-cooperative spectrum sensing may affect the performance of the cognitive radio network in terms of probability of detection and the probability of false alarm, especially when the primary users' received SNR is low. This encouraged researchers to apply cooperative sensing technique to improve the primary users' detection results. In this thesis a parallel distributed sensors with data fusion is used to simulate the network performance in terms of throughput. In this model, the fusion center will gather the information from all the sensors and combine them to examine the existence of primary users. As an example of the soft combining techniques, Square Low Combining technique (SLC) is applied to the network model and the performance of the network is compared against non-cooperative sensing.

The probability of misdetection and probability of false alarm in AWGN channels with collaborative sensing is the same as in AWGN given in equations (4.1) and (4.2) just by replacing N by kN where k in the number of collaborative sensors and is given as [31]:

$$P_{md} = 1 - Q_{kS}(\sqrt{\frac{2k\gamma}{\sigma^2}}, \sqrt{\frac{\lambda}{\sigma^2}}) \tag{4.6}$$

$$P_f = \frac{\Gamma(kS,\lambda/2\sigma^2)}{\Gamma(kS)} \triangleq G_{kS}(\lambda) \tag{4.7}$$

4.3.2 Cooperative Sensing in Fading Channels

Under identical independent Nakagami fading channels, the pdf of the combined SNR using SLC method follows the gamma distribution and is given by [30]:

$$f_{\sum\gamma}(\gamma) = \frac{1}{\Gamma(km)} \left(\frac{m}{\bar{\gamma}}\right)^{km} \gamma^{km-1} \, exp(\frac{-m}{\bar{\gamma}} \gamma), \gamma \geq 0 \tag{4.8}$$

where $\bar{\gamma}$ is the average total SNR, k is the number of sensors and m is the Nakagami fading parameter.

The probability of false alarm in Nakagami channels is the same as in AWGN given by (4.2), since the false alarm probability is the probability that the received signal is above a certain threshold while the primary user does not exist. The probability of detection over Nakagami fading channel is given by [31]:

$$P_{d,Nakagami} = \frac{1}{\Gamma(m)} \int_0^\infty Q_{kS}\left(\sqrt{(2k\gamma)}, \sqrt{\lambda}\right) \left(\frac{m}{\bar{\gamma}}\right)^{km} \gamma^{km-1}\, exp\left(\frac{-m}{\bar{\gamma}}\, \gamma\right) d\gamma \quad (4.9)$$

The probability of detection in Rayleigh channels can be found easily by setting m = 1 in the above equation

$$P_{d,Rayleigh} = \int_0^\infty Q_S\left(\sqrt{(2k\gamma)}, \sqrt{\lambda}\right) \left(\frac{1}{\bar{\gamma}}\right)^{k} \gamma^{k-1}\, exp\left(\frac{\gamma}{\bar{\gamma}}\right) d\gamma \quad (4.10)$$

The performance of the cognitive radio network represented as the secondary users' spectrum utilization under fading channels and non-cooperative sensing is depicted in Figure 4.1. It is clear from the figure that as the primary users' received SNR increases, the spectrum utilization increases where it reaches a total spectrum utilization at 15dB received primary user' SNR. In deep fading channels with m = 0.5 fading parameter, this percentage drops to about 65%, the spectrum utilization increases to about full capacity when $m = 5$. Figure 4.1 also shows the deep effect of bad channel conditions on the system performance using traditional non-cooperative sensing.

The performance of the network using SLC collaborative sensing technique under Nakagami fading channels with fading parameter $\mathrm{m} = 2.3$ is shown in Figure 4.2. The effect of number of collaborative sensors is clear. For a primary user's received SNR of 10dB, the spectrum utilization under AWGN is about 100% where this percentage decreases to about 60% using one sensor. Increasing the number of sensors effectively boosts the system performance and only an amount of four sensors makes the fading channel appearing as an AWGN channel

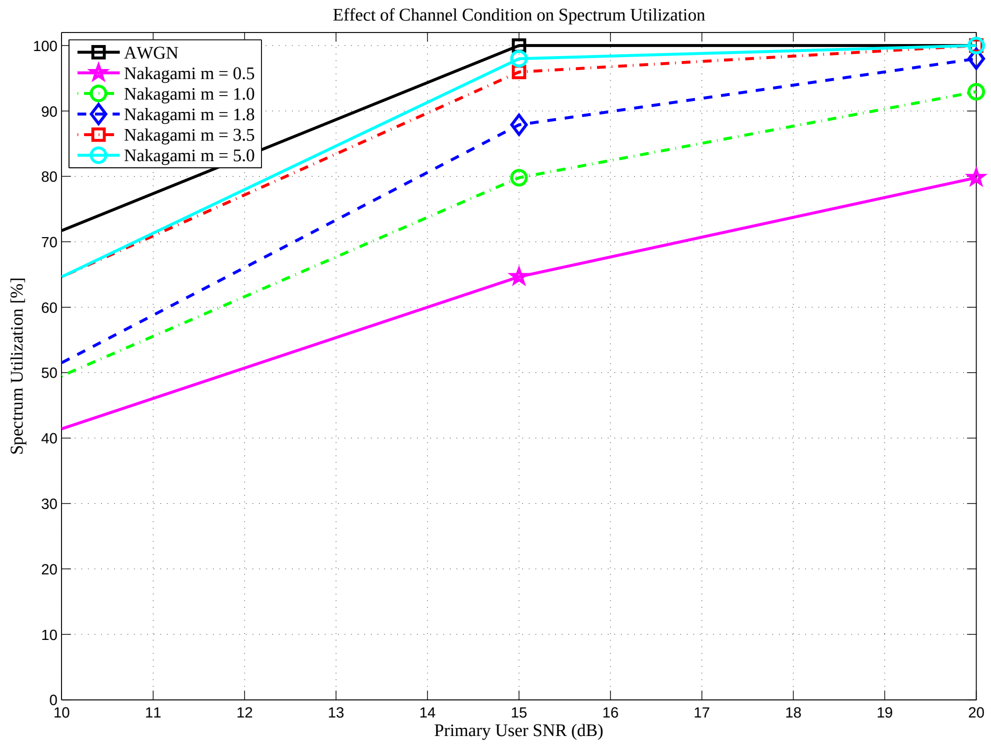

Figure 4.1: Effect of channel conditions on spectrum utilization

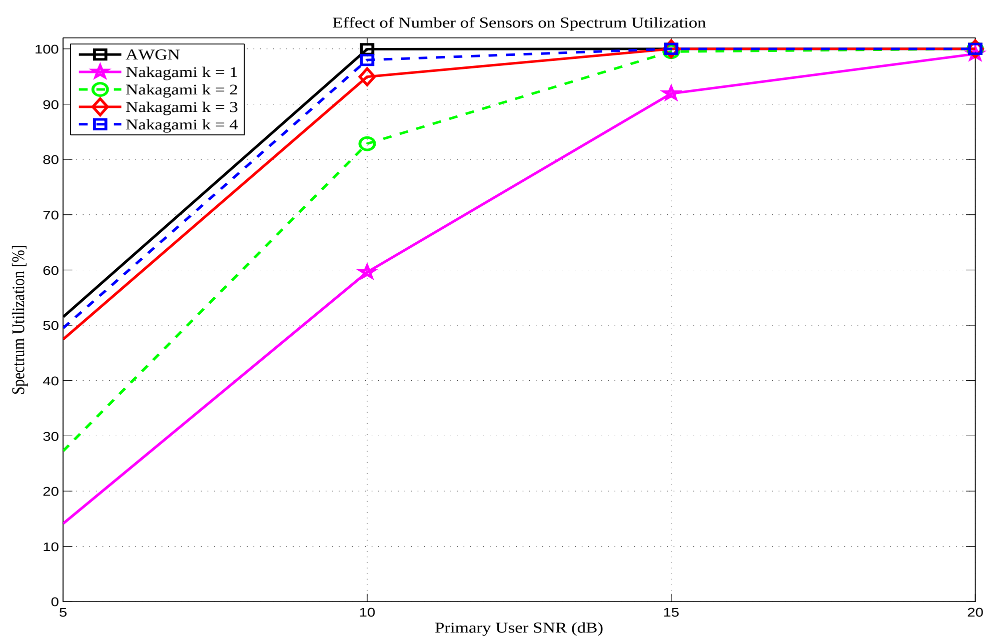

Figure 4.2: Effect of number of sensors on spectrum utilization

4.4 Conclusion

The effect of the received primary user's SNR on the cognitive radio network is presented in this chapter. High primary users' SNR results in a better estimation of the activity of the channel and lowers the probability of misdetection; this leads to a higher spectrum utilization. Channel conditions were also discussed in this chapter. As the channel suffers from only thermal noise, the spectrum utilization is higher compared to channels that suffers from fading for the same primary user's SNR. Those conclusions are summarized in Table 4.1.

Table 4.1: Effect of channel conditions on spectrum utilization

	Spectrum Utilization (%)				
PU's SNR (dB)	Rayleigh	Nakagami (m=1.8)	Nakagami (m=3.5)	Nakagami (m=5)	AWGN
10	50	50	65	65	70
15	80	87	95	98	100
20	92	92	100	100	100

The advantage of applying cooperative sensing compared to the non-cooperative sensing is also discussed, as the number of cooperating sensors increases the network throughput increases. More sensors will provide a valuable information of the network regarding the activity of the primary users.

Chapter 5: Spectrum Sharing in Heterogeneous Network Model

5.1 Introduction

In this chapter, we discuss in details the cognitive radio model used in the development of the spectrum sharing technique in heterogeneous networks, and demonstrates how the proposed algorithm works and concludes with computer simulations to show the performance of the proposed algorithm.

5.2 Centralized Cognitive Radio Network Model

In this model, all decisions are carried out by a centralized entity with enough processing power to provide service for all the users in the dual network (primary network and secondary network) which will simplify the design of the end users' network. Throughout the thesis, it will be referred to as Cognitive Radio Base Station (CRBS). In this scenario, the centralized base station is responsible for the cognitive radio cycle from the spectrum sensing to the spectrum mobility stages.

Cognitive radio base station in the absence of the secondary users, acts as an ordinary base station to provide service to primary users and its operation is quite similar to the current base stations of the cellular networks. The additional process is a real time sensing of the spectrum holes and the existence of the secondary users. The base station registers the spectrum holes and waits for a request for an available channel from a secondary user.

When a secondary user requests a channel for its data transmission, it must provide its QoS requirements to the cognitive radio base station that will provide an optimal channel allocation. A real time spectrum sensing is crucial to the success of the cognitive radio as it will increase the spectrum utilization instantly and it will provide a dynamic prediction model of the channel occupation characteristics in a specific area, which is very useful in adapting the spectrum sensing time in order to reduce the processing power. The cognitive radio base station continues to scan this perimeter and if a primary user has data to send it must ask permission from the CRBS, which will demand the secondary user to leave the occupied channel.

5.3 Cognitive Radio Base Station Model

The first operation of Cognitive Radio Base Station is to sense the spectrum as mentioned earlier. The result of the spectrum sensing is stored in a 3-D matrix; one dimension represents the time, the second dimension represents the frequency of the channel and the third dimension represents the primary user's ID. If a primary user is occupying the first channel (F1) at the first time slot (T1), a "1" will be inserted into the matrix in the (1, 1) or otherwise this positon is filled with 0 and this process will continue for M primary users, N secondary users and K channels until all the matrices are created. The spectrum sensing matrix dimension must be dynamic according to the spectrum sensing time and as described earlier we assume no effect of the sensing time on the secondary network performance. Two matrices for primary and secondary users are generated based on the model. Figures 5.1 and 5.2 show a simplified matrix.

	F_1	F_2	F_3	F_4	F_5	F_6
T_1	1	0	0	1	0	1
T_2	0	1	0	0	1	0
T_L	1	0	1	0	0	0

Figure 5.1: PU-1 sensing matrix

	F_1	F_2	F_3	F_4	F_5	F_6
T_1	1	0	1	1	0	1
T_2	1	0	0	0	1	0
T_L	0	0	1	0	1	0

Figure 5.2: SU-1 sensing matrix

	F_1	F_2	F_3	F_4	F_5	F_6
SNR	SNR_1	SNR_2	SNR_3	SNR_4	SNR_5	SNR_6
Data Rate	R_1	R_2	R_3	R_4	R_5	R_6

Figure 5.3: Channel's QoS matrix

The cognitive radio base station database has another table built in it, which is the channel quality of service table. As the CRBS scans the spectrum, it records also the channels' characteristics like the SNR and records them into the channel QoS Table.

5.4 Spectrum Allocation Optimization

5.4.1 Bipartite Graph

Allocating the spectrum holes to the secondary users can be depicted as an assignment problem, that can be solved partially or completely using bipartite graph and the Hungarian algorithm. In the bipartite graph, set A represents the secondary users and set B represents the available channels (W, X, Y, Z) where each secondary user (A, B, C) from set U must be only connected to a maximum of one channel from set V. If a channel from set V is assigned to a secondary user from set U, then it cannot be assigned to another secondary user. An illustration of bipartite graph is shown in Figure 5.4.

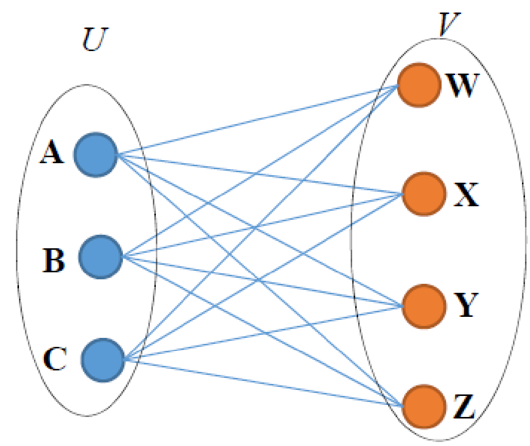

Figure 5.4: Bipartite Graph

Every edge of the bipartite graph has a cost and many optimization algorithms were developed to solve this assignment problem. To find the optimum solution to the above bipartite graph an optimization algorithm must be considered which will assign each secondary user to only one available channel in case of a complete matching or provides a maximum matching in case of incomplete matching. The total cost of this assignment must be minimized.

The main steps of the Hungarian Algorithm are summarized as following, [34]**:**

1. Represent number of SUs (N) in the rows, number of channels (K) as columns, and cost as C matrix.

2. Find row minimum (Δw)

3. Subtract each element by Δm (i.e.,$C_{st} = C_{st} - \Delta w$) from each row of the cost matrix.

4. Subtract each element by the row minimum Δn (i.e., $C_{st} = C_{st}$ -Δn) from each column of the cost matrix.

5. Cover all the zeros in the matrix with minimal number of lines. If L lines are used to cover the entire zeros and if $L = n$, go to step 8. Else, continue.

6. If $K < N$, add the minimum of the uncovered element h to every uncovered element. Subtract h from all elements which don't have any line passing through it and add h if a number has 2 lines passing through it and the remaining elements remain unchanged then move back to step 4.

7. The solution is now obtained as each row and column have only one zero.

8. Apply the assignment to the original matrix.

5.4.2 Cost Function

The cost assigned to each edge of the bipartite graph were derived to guarantee that each secondary user gets a channel that satisfies its minimum QoS requirements. In this work, we introduce a cost function based on the minimum required signal to noise ratio, which will provide a QoS assurance and power efficiency at the same time (Green Cost Function). Cost function is provided as:

$$C_i^j = \frac{SNR_i - SNR_j}{SNR_j} \tag{5.1}$$

where ${C_i}^j$ is the cost for assigning channel i to secondary user j , SNR_i is the energy per bit to noise power spectral density ratio for channel, SNR_j is the minimum required energy per bit to noise power spectral density ratio for secondary user j. Besides assuring the QoS for secondary users, this cost function provides power efficiency to secondary users by choosing the channel with the closest SNR to their QoS requirements.

The maximum achieved data rate of the secondary users depends on the channel' SNR and the bandwidth of the channel. In this thesis, the maximum channel bandwidth needed is about 60 KHz for video applications as will be explained further in section 5.6, this is a small bandwidth and therefore our main concern will be the SNR of the channels.

After obtaining the cost of all edges between the secondary users and the channels, these values will form the matrix that is the basis to solve the assignment problem. If all the channels satisfy the secondary users' minimum requirements, the Hungarian algorithm is applied directly to the matrix and the optimized solution is obtained but if one or more channels fails to meet the minimum QoS requirements of one or more secondary users then a slightly modified approach is used as described in section 5.5.

5.5 Proposed Spectrum Sharing Algorithm

In this section, a description of the proposed algorithm is presented, and its constraints are explained mathematically.

1. Generate the cost matrix.

2. If all the channels meet the minimum QoS requirements apply the Hungarian algorithm to the cost matrix else go to step 3.

3. For all rows find the minimum element value and subtract this value from all row elements.

For all columns find the minimum element value and subtract this value from all column elements.

5. For all rows, find the number of zeros in each row.

6. If number of zeros in all rows is greater than 1, assign the first secondary user to the first acceptable channel.

7. Prohibit this user from accessing other channels and prohibit other secondary users from accessing this channel.

8. If the number of zeros in a row equals one, assign the secondary user with the only acceptable channel.

9. Repeat from step 5 until all secondary users are assigned to the best matched available channel (perfect matching) or until no channels can be matched due to requirement constraints.

In case of special cost matrix the algorithm reacts according to the specified case; e.g. if one available channel is the only option for more than one secondary user it is assigned to the use with the minimum identification number. Another special case occurs when two or more edges have the same cost and both of them satisfy the data rate requirements. In this case, the secondary user with the minimum highest required data rate will be assigned the available channel to achieve a higher spectrum utilization. A pseudo code for the proposed algorithm is shown below:

1: $\mathrm{C} \leftarrow$ Cost Matrix

2: **for all** $\mathrm{C}_{i,j}$ do

3: check $\mathrm{C}_{\mathrm{SNR(i,j)}}$

4: **if** $\mathrm{C}_{\mathrm{SNR(i)}} > \mathrm{C}_{\mathrm{SNR(j)}}$, **then**

5: Allocate using Hungarian Algorithm

6: **else**

7: **for all** rows i

8: $\mathrm{m_i} = \min(\mathrm{i}, \mathrm{j})$

9: $\mathrm{C_{i,j}} = \mathrm{C_{i,j}} - \mathrm{m_i}$

10: Repeat from 7 **for all** columns j

11: $\mathrm{n} =$ number of zeros in each row

12: **if n** $\boldsymbol{\geq 0}$

13: $\mathrm{SU_i} \rightarrow \mathrm{C_i}$

14: **if** all channels not occupied

15: **Goto** 13

16: **else**

17: **end**

18: **end**

The proposed algorithm main object is to minimize the cost function, maximizes the number of occupied channels and maximizes the number of served secondary users. The algorithm abide the constraints that any user must be assigned only one channel and any channel must only be assigned to one user.

The proposed algorithm can be represented mathematically as:

$$Minimize\text{: } \sum_{i=1}^{N} \sum_{j=1}^{K} C_i{}^j \; x_i{}^j \tag{5.2}$$

$$Maximize \; \sum_{i=1}^{K} x_i{}^j \tag{5.3}$$

$$Maximize \; \sum_{i=1}^{N} x_i{}^j \tag{5.4}$$

Subject to:

$$\sum_{j=1}^{K} x_i{}^j \; \leq 1 \tag{5.5}$$

$$\sum_{i=1}^{N} x_i{}^j \leq 1 \tag{5.6}$$

$x_i{}^j \; \epsilon \; \{0,1\}$, where $x_i{}^j$ is the cost function

5.6 Heterogeneous Network System Model

As mentioned earlier, in centralized network model, the central base station is responsible for the main tasks of the cognitive cycle. Interweave cognitive radio network model works under the assumption of total absence of the primary user in the specific spectrum bands. The secondary users compete for the access of these channels as if they were reserved for them. Figure 5.5 below shows a basic model.

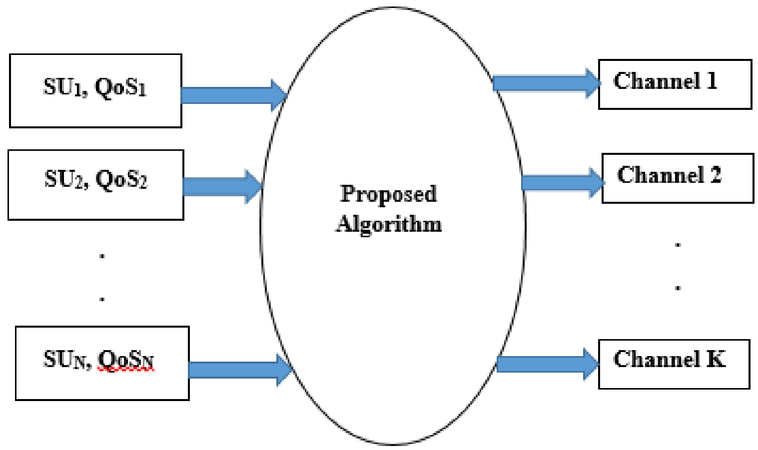

Figure 5.5: Heterogeneous basic system model

A centralized cognitive radio network of M primary users and N secondary users is considered. Each primary and secondary user has an identification number based on the time they join the network. The secondary users are competing for the access of K available channels. All the secondary users have data to send, though with different QoS requirements e.g. Internet chatting, voice over Internet, video over IP and web browsing as shown in Figure 5.6.

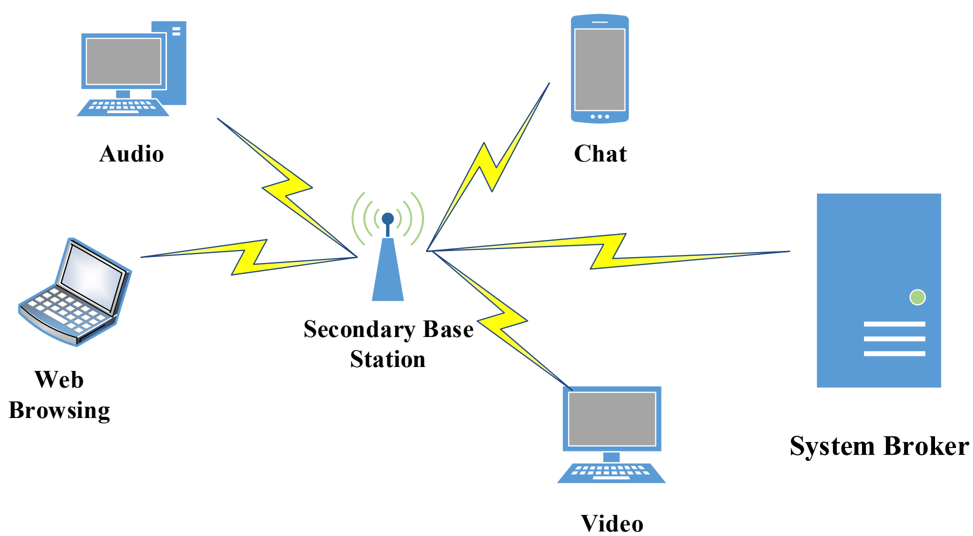

Figure 5.6: Heterogeneous network model

The radio spectrum is divided into channels with equal bandwidth and each channel has an identification number as well. The central entity periodically receives the signal to noise ratio and other channel parameters for each user, which forms the cost matrix. Spectrum sensing is assumed to be perfectly done and the probability of misdetection and the probability of false alarm are neglected. A matrix with available channels identification numbers and the corresponding signal to noise ratio to each available channel is formed. The central entity then applies the proposed algorithm to the cost matrix. Afterwards based on the proposed algorithm the central entity assigns each of the available channels to the best matched QoS requirement secondary user. The central entity relays this information to all the secondary users; if there is no match for the secondary user the central entity sends a message to the user asking it to wait and prohibits it from accessing the channels. The minimum QoS requirements for the used applications in the simulation are given in Table 5.1 [34].

Table 5.1: QoS requirements for different applications

Application (x)	**Data Rate (Kbps)**	**Minimum E_b/N_0 (dB)**	**Required Bandwidth (Hz)**
Web Browsing	30.5	8	10
Audio	56	11	15
Video	300	14	60
Chat	1	15	1

These requirements are based on using the differential phase shift keying (DPSK) modulation scheme. Channels with uniformly distributed energy per bit to noise power spectral density ratio ($\mathrm{E_b/N_0}$) are generated to simulate the wireless environment.

The i_{th} secondary user is transmitting in a different channel, denoted by its channel gain as g_i^s and the j_{th} primary user's transmission in this channel as g_j^p. The total noise in the $\mathrm{i_{th}}$ channel is denoted as N_i and the secondary users transmission power as P_i as shown in Figure 5.7. The received SNR_i of the i_{th} SU is written as

$$SNR_i = \frac{g_i^s \, P_i}{\sum_{j=1, j\neq i}^{N} g_j^s \, P_i + \sum_{j=1}^{M} g_j^p P_j + N_i} \quad , i = 1 \ldots K \qquad (5.8)$$

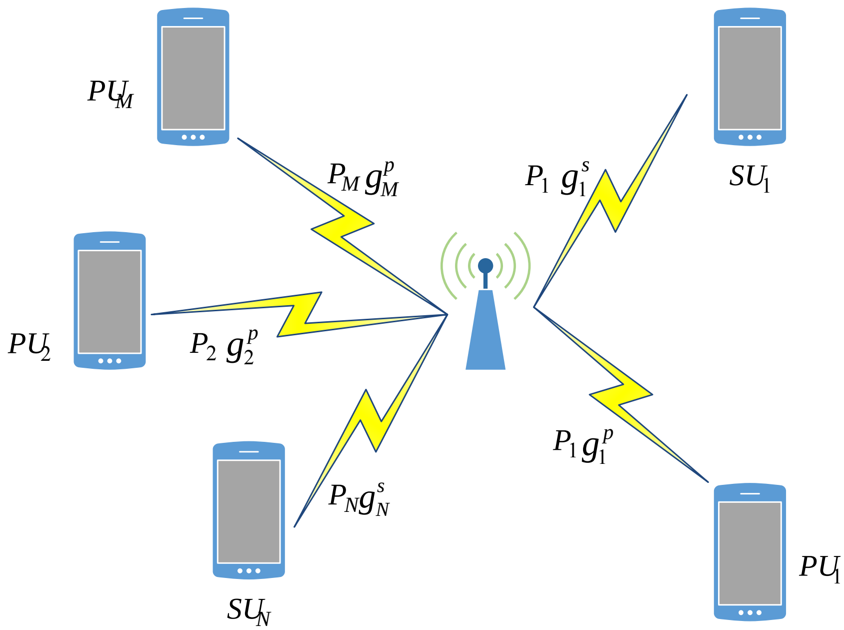

Figure 5.7: Interference model in cognitive radio network model

For the channel to be considered as satisfactory for a certain application x the following condition must be maintained

$$SNR_i \geq SNR_x$$

Figure 5.8 shows the heterogeneous network spectrum utilization based on the number of secondary users and the average required SNRs of the SUs applications for 4 available channels with average SNR of 14.5 dB. It is clear from the graph that at low required SNR, all the secondary users were assigned a channel and thus the utilization grew linearly from 25%-100% for 1 to 4 SUs and as the number of SUs exceeded the total number of channels the spectrum utilization settled at full utilization. On the other hand, as the required SNR increases, the spectrum utilization decreases as the number of available channels that satisfy the required QoS becomes more limited. Increasing the number of secondary users results in an increase in the spectrum utilization, which reaches about 95% for 6 SUs. Figure 5.8 illustrates the required SUs applications on the system performance, as the required SNR increases the spectrum utilization decreases and as the number of SUs increases the utilization increases as well.

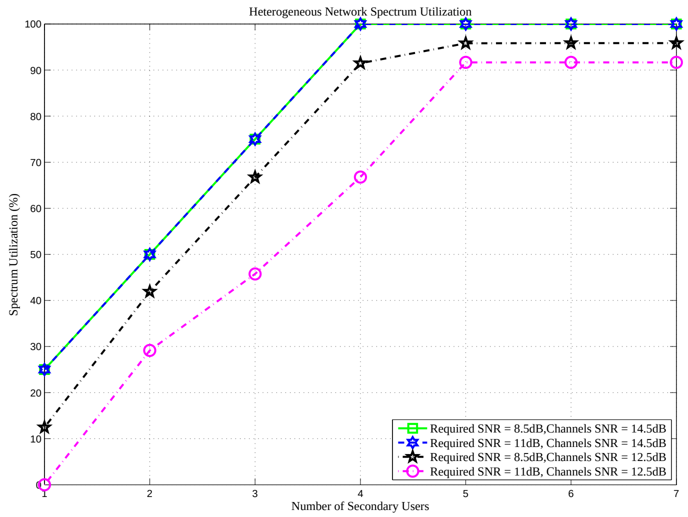

Figure 5.8: Spectrum utilization for different number of SUs

Figure 5.9 shows the effect of number of available channels and the channel conditions on the spectrum utilization bearing in mind that the required SNR is 11dB. The effect can be divided into 3 stages. When the number of secondary users is less than the number of available channels the spectrum utilization depends mainly on the number of available channels.

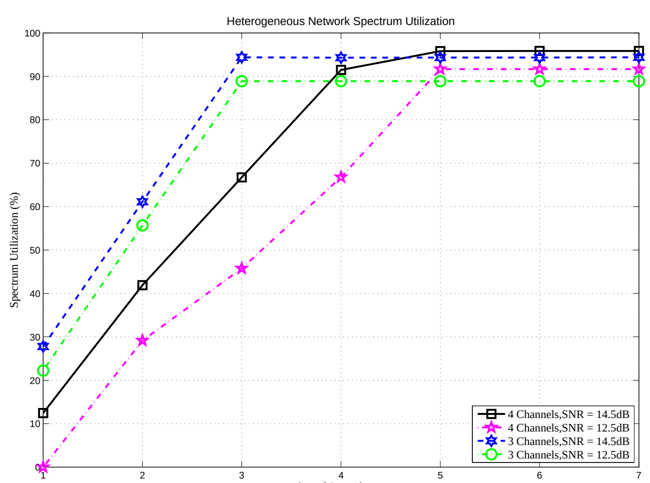

Figure 5.9: Spectrum utilization for different number of channels

The utilization decreases as the number of available channels increases and for the same number of available channels as the channel conditions improve the spectrum utilization increases as well. The spectrum utilization dependency takes a turn as the number of available channels and number of secondary users equal each other. At this point, the spectrum utilization depends mainly on the channel conditions. The utilization improves as the channels' conditions get better and for the same channels' conditions, less number of available channels will leads to a higher spectrum utilization. When the number of secondary users exceed the number of available channels, the spectrum utilization also depends greatly on the channel conditions, but as there are more pool of secondary users to allocate from, the higher the number of available channels, the higher the spectrum utilization.

Figure 5.10 demonstrates the effect of channel conditions and the QoS requirements of the secondary users' applications on the utilization of the secondary network. It is clear from the graph that as the channels' conditions improve, the spectrum utilization increases accordingly; the higher the average channels' SNR, the higher the utilization is until it reaches a full spectrum utilization. The QoS requirements of the secondary users also affects the spectrum utilization as shown in the graph. For the same average channel' SNR, the spectrum utilization decreases as the QoS requirements increases and vice versa. The graph shows the superiority of the proposed algorithm over FCFS algorithm in terms of the archived spectrum utilization.

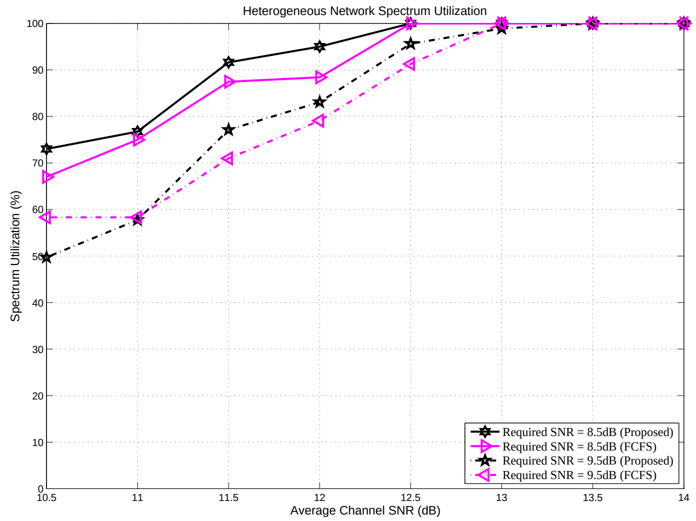

Figure 5.10: Comparison of allocation schemes in different channel conditions

Without losing generality and for simulation purposes, four secondary users with different QoS requirements (8, 11, 14, 15 dB) are requesting to access available channels with different channel parameters. The modified algorithm is applied to the system and the assigning results are presented. An illustrating example of the instantaneous assignment of the channels to the secondary users is shown in Figure 5.11. Figure 5.11 demonstrates many aspects of the proposed algorithm performance in AWGN and Rayleigh fading channels and against the FCFS algorithm represented as the achieved SNR for different secondary users' applications. The proposed algorithm succeeded to provide all the secondary users' their required SNR in AWGN channel. Under Rayleigh fading, the channels' SNR are much less compared to AWGN channels and therefore, some users got an SNR that is less than their requirements. From the first look, it seems like the FCFS algorithm provides a higher SNR than the proposed algorithm. Giving the graphs a closer examination reveals the importance of the proposed algorithm. Although at some times the FCFS may provide a higher SNR for the secondary users', but it does not guarantee the minimum requirements for them; this is clearly shown in the chart in Figure 5.11.

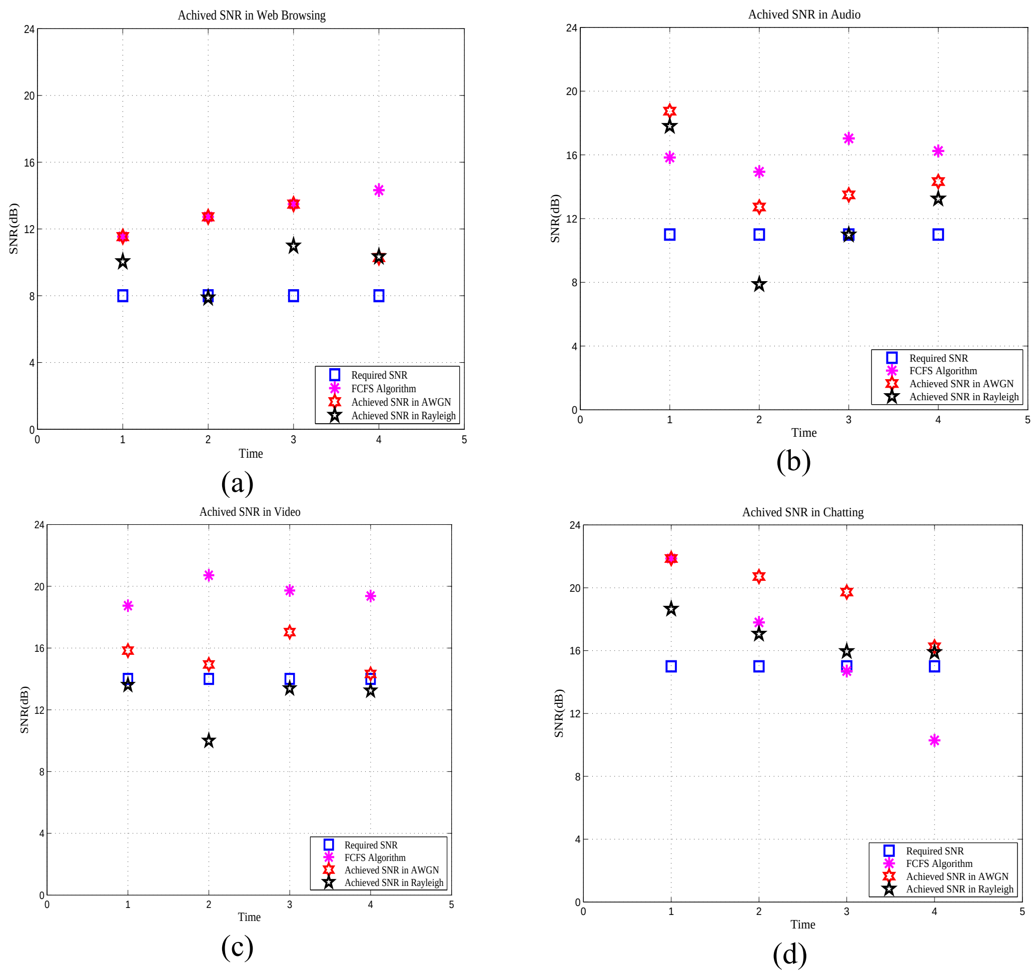

Figure 5.11: Proposed algorithm instantaneous assignment

The average achieved SNR under ideal channels using the proposed algorithm succeeded in meeting the minimum QoS for all applications as depicted in Figure 5.12. In Figure 5.12, the effect of Rayleigh fading channels on QoS is illustrated by comparing the achieved SNR to the minimum requirement. As expected, the achieved SNR in the Rayleigh fading channels were always smaller than the one in ideal channels and in some cases even less than the minimum QoS required by the secondary users' applications.

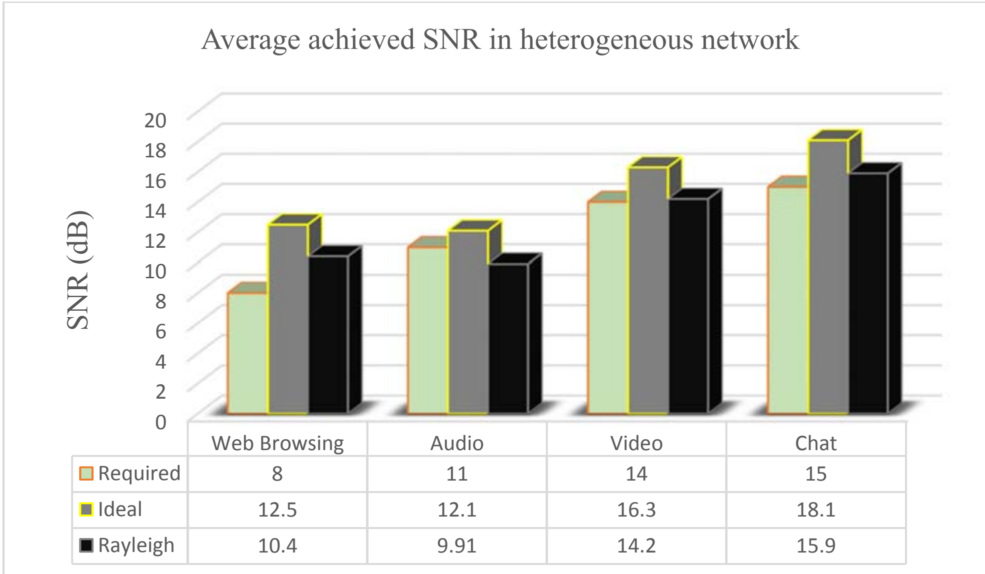

Figure 5.12: Average achieved SNR for applications

The simulation results in Figures 5.12 reveals the success of the proposed algorithm in terms of QoS assurance through SNR and overall spectrum utilization of the networks in the long time run with a success rate of more than 85% which reveals the advantage of the proposed algorithm.

5.7 Conclusion

In this chapter, the proposed channel allocation algorithm was applied to the heterogeneous cognitive radio model and its performance was compared to the FCFS algorithm in both AWGN and Rayleigh fading channels.

The effect of channels' conditions and the required QoS requirements of secondary users on the spectrum utilization are demonstrated. The spectrum utilization is proportional to the average channels' condition and inversely proportional to the secondary users' QoS requirement. As the average channels' SNR increases, more channels will be available for assignments which increases the spectrum utilization. Simultaneously, for the same channel's SNR, the lower the QoS requirements the higher the spectrum utilization is until a full spectrum utilization is achieved. The effect of channels' conditions have more effect on the spectrum utilization at low channels' SNR and the effect diminishes slowly as the channels' conditions improve.

The effect of the number of secondary users and the channels' conditions on the system performance is also investigated in this chapter. It is found that as the number of secondary users increases the spectrum utilization increases. It is also shown that, as the required average SNR's for the applications increases, the spectrum utilization decreases and for the same required SNR, a better channel condition will lead to a better spectrum utilization.

The two algorithms were compared by the average achieved SNR for each application and by the total spectrum utilization for each algorithm in which the proposed algorithm provided a higher SNR and spectrum utilization than FCFS.

Chapter 6: Performance Measures in Heterogeneous Network Model

6.1 Introduction

The allocation algorithm is described and its performance was measured in the sense of providing an optimum allocation for the secondary users to available channels. In this chapter, the performance of the algorithm is measured by the secondary users' network achieved capacity and data rate.

The capacity of the secondary user's network in AWGN channels in the absence of the primary users is given by Shannon's equation [35]:

$$C_0 = log_2(1 + \gamma_s) \qquad (6.1)$$

where γ_s is the SNR of the channel between the secondary transmitter and the secondary receiver.

On the other hand, when the primary users exists but the secondary users' fail to recognize its existence the capacity of the secondary networks is given as [35]:

$$C_1 = log_2(1 + \frac{\gamma_s}{1+\gamma_p}) \qquad (6.2)$$

where γ_p is the SNR of the channel between the primary transmitter and the secondary receiver.

The probability of the primary users is using the channel is given as $P(H_1)$ where the probability of a vacant channel is $P(H_0)$. The average capacity of the secondary network is given by [14]:

$$C = C_0(1 - P_{f)}\, P(H_0) + C_1\, P_m\, P(H_1) \qquad (6.3)$$

6.2 Capacity under Perfect Sensing

Under perfect sensing, both the probabilities of misdetection and false alarm are negligible and then the capacity of the secondary network is given as [14]:

$$C = C_0 = log_2(1 + \gamma_s) \tag{6.4}$$

The accumulative data rate of every application is represented in the Figure 6.1, where it is assumed that allocating a free channel to a certain application will guarantee its required data rate.

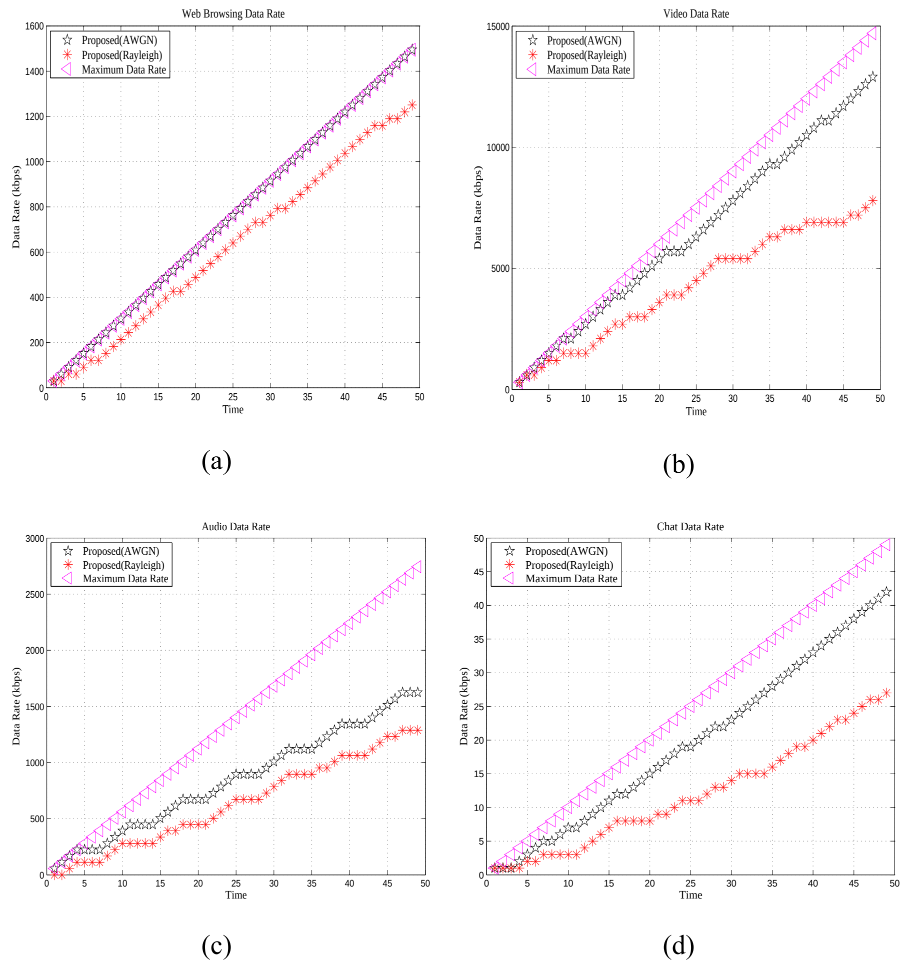

Figure 6.1: Applications' sum data rate

Figures 6.2 and 6.3 represents the average achievable rate for all applications using the proposed algorithm under AWGN and Rayleigh fading. It is clear from the graph that the proposed algorithm provided the required data rate for web browsing, audio, video and chat.

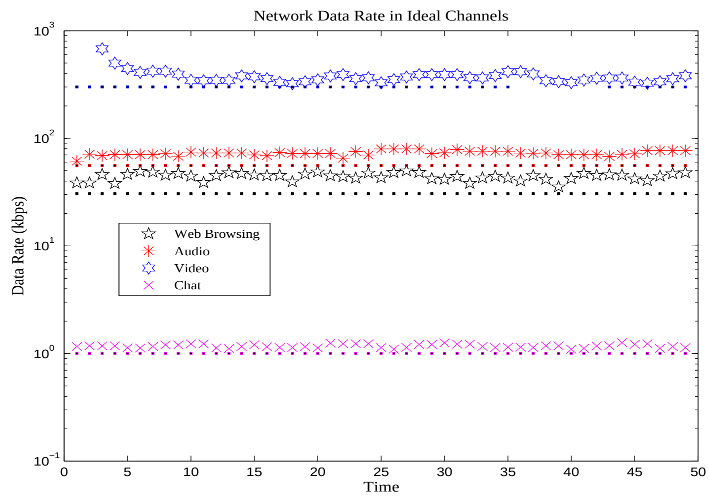

Figure 6.2: Average achievable rate in AWGN channel

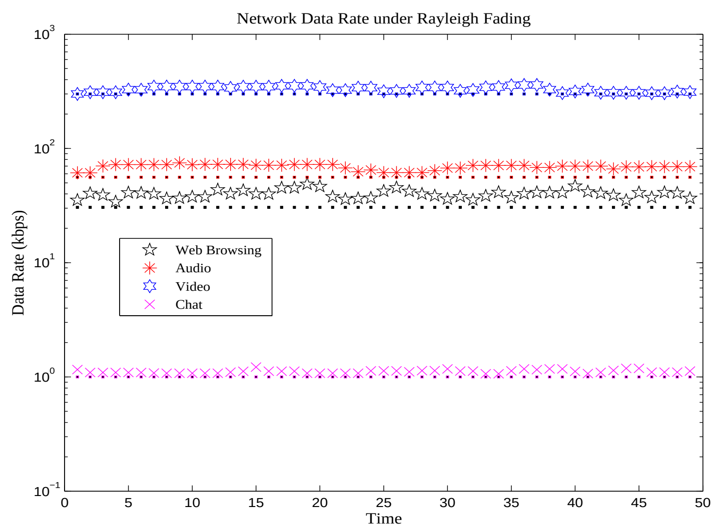

Figure 6.3: Average achievable rate in Rayleigh channel

6.3 Capacity under Imperfect Sensing

In the previous section, perfect sensing is assumed and therefore the capacity of the secondary network depend only on the channels SNRs and the transmission parameters as the secondary users transmit their data in absolute absence of the primary user.

If the activity of the primary user is sensed imperfectly, the probability of misdetection and false alarm affects the secondary network as their transmission may suffer from collision with the primary network transmission and even if collision never happened the channels' SINR would decrease due to the interference from the primary or secondary users. As mentioned earlier in Chapter 5, the channel SINR can be written as equation (5.2) where $\sum_{j=1,j\neq i}^{M} g_j^p\, P_j$ represnts the primary users' interference to secondary users' transmission. As the probability of detection increases, the secondary network is more aware of the activity of the primary users on channel and therefore the secondary users can send data over free channels. On the other hand, if the probability of detection decreases, the secondary network is considered blind of the primary network and this may cause a degradation of the performance of the network.

Figure 6.4 represents the average achievable rate for all applications using the proposed algorithm in AWGN channel with different probability of detection values with $P(H_1)$ = 60%. Figure 6.4 shows that for web browsing application, the total data rate with imperfect sensing is the same as under perfect sensing even under low probability of detection, this means that channel allocation for web browsing was not affected by the primary users' activity. This is due to the low QoS requirement of the web browsing that allowed it for more channel options to be assigned. For audio, the achieved data rate is considered the same on relatively high probability of detection, nevertheless when the probability of detection decreases, the rate decreases.

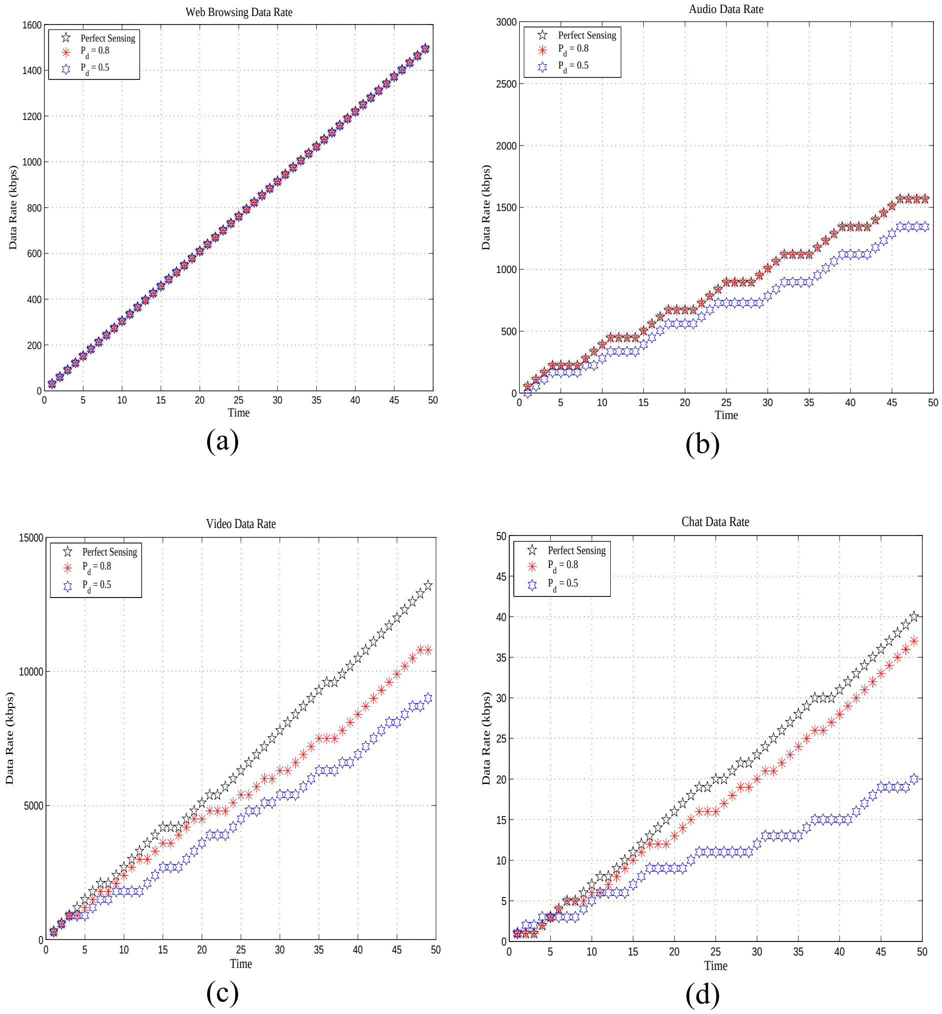

Figure 6.4: Applications’ sum data rate with imperfect sensing

Due to the high QoS requirements for the video and chat application (14 and 15 dB), any interference from the primary users, reduces the channels’ SINR which results in a fewer channels that satisfies their QoS.

Figure 6.4 shows clearly, as the probability of detection decreases, the achieved data rate for video and chat decreases significantly Table 6.1 shows the percentage of the achieved data rate for each application with different probabilities of detection.

Table 6.1: Network data rate with imperfect sensing

	$P_d = 1$	$P_d = 0.8$		$P_d = 0.5$	
Application	Data Rate (Kbps)		Percentage	Data Rate (Kbps)	Percentage
Web Browsing	1500	1500	100%	1500	100%
Audio	1600	1600	100%	1400	87.5%
Video	13000	11000	84.5%	9000	69.5%
Chat	40	37	92.5%	20	50%
Total	16140	14137	87.5%	11920	73.85

An interesting criteria of the proposed algorithm is embedded in Table 6.1, when $P_d = 0.8$, the percentage of data rate of the chat application is higher than the video application while when $P_d = 0.5$, the opposite happened as the percentage of the video is higher than the chat.

Higher probability of detection means lower interference from the primary users, which leads to higher SNR channels, and as mentioned in the proposed algorithm description the chat application is assigned the highest SINR channel, which is relatively available at this time.

On the other hand, when channel conditions are bad, less channels satisfy the QoS of the chat application and the vacant channel is assigned to the video application. Figure 6.5 shows the average data rate for all applications, and it is clear from the figure the effect of imperfect sensing.

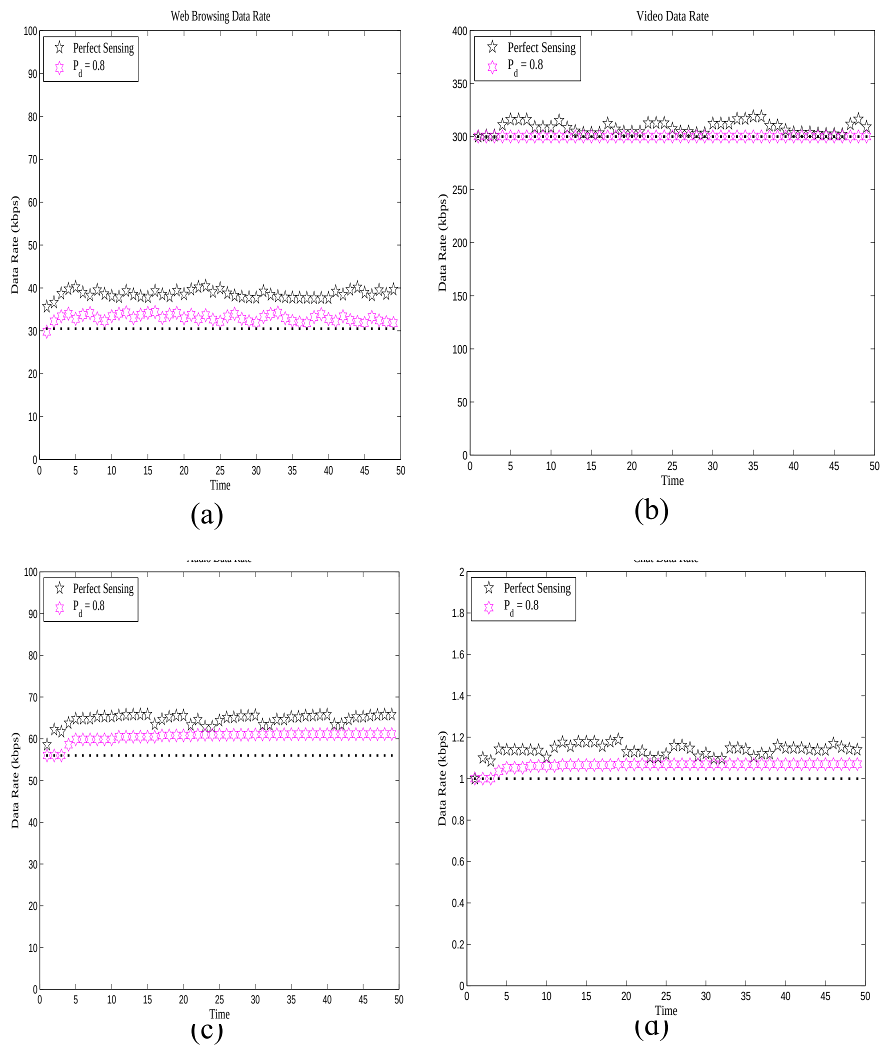

Figure 6.5: Applications' average data rate with imperfect sensing

6.4 Conclusion

The secondary network's performance in terms of the capacity and the average data rate for each application are presented in this chapter, the proposed algorithm succeeded on average to guarantee the QoS requirement for each secondary users' application. The effect of imperfect sensing on the system performance is investigated using simulation. As the system incorporates advanced spectrum sensing techniques that have higher probability of detection the cumulative applications data rate increases significantly.

CHAPTER 7: Conclusions and Future Work

In this chapter, a conclusion of our work in the thesis is summarized and suggestions for future work are presented.

7.1 Conclusions

In this thesis, cognitive radio networks under perfect, imperfect sensing is discussed, a spectrum allocation algorithm for heterogeneous networks in cognitive radio networks is proposed, and the performance of the algorithm is analyzed based on the spectrum utilization, capacity and data rate for secondary networks.

In Chapter 1, a background overview of the cognitive radio network is presented and its features regarding its architecture, spectrum management techniques and channel models is discussed. A literature review of the spectrum allocation techniques used in cognitive radio networks is examined and the motivation for developing a spectrum sharing algorithm that guarantee QoS for secondary users is discussed in Chapter 2. The Hungarian algorithm is famous for providing an optimization allocation for resources, that's why it was used as a base model to our proposed allocation algorithm that is briefly discussed in this chapter

In Chapter 3, different cognitive radio networks models in the AWGN and under perfect sensing are studied. The performance of the models was measured in terms of the total spectrum utilization and the secondary users' data throughput. It was found that, as the number of available channels decreases, the total network utilization increases due to the primary users' activity and the secondary network throughput decreases. The effect of primary users' activity (mean number of primary users) on the total system utilization and the data throughput of the secondary users was also discussed in this chapter. The degradation of throughput due to primary users' activity is explored by varying the arrival rate of the primary users in a given spectrum band and it was shown that increasing the primary user's activity in the network will increase the total spectrum utilization and at the same time decreases the secondary users' throughput.

The study of cognitive radio models performance is extended in Chapter 4 to cover the system models under Rayleigh and Nakagami fading channels which are more realistic models in wireless communication than the AWGN channels. The effect of imperfect sensing is also studied by applying non-collaborative sensing and collaborative sensing techniques using energy detecting and square law combining techniques, respectively.

The effect of the received primary user's SNR on the cognitive radio network is presented in this chapter. High primary users' SNR results in a better estimation of the activity of the channel and lowers the probability of misdetection; this leads to a higher throughput of the cognitive network. As the channel suffers from only thermal noise, the secondary users' throughput is higher compared to channels that suffers from fading for the same primary user's SNR. As the number of cooperating sensors increases the network throughput increases which proves the advantage of applying cooperative sensing; more sensors will provide a valuable information of the network regarding the activity of the primary users.

In Chapter 5, a heterogeneous network model is introduced to study the QoS assurance of secondary users in cognitive radio networks. An allocation process in centralized base stations is discussed in details and a spectrum allocation algorithm based on the Hungarian algorithm is proposed. In this chapter, the proposed allocation algorithm was applied to the heterogeneous cognitive radio model and its performance was compared to the FCFS algorithm in both AWGN and Rayleigh fading channels. The effect of channels' conditions and the required QoS requirements of secondary users on the spectrum utilization is demonstrated. The spectrum utilization is proportional to the average channels' condition and inversely proportional to the secondary users' QoS requirement. As the average channels' SNR increases, more channels will be available for assignments which increases the spectrum utilization. Simultaneously, for the same channel's SNR, the lower the QoS requirements the higher the spectrum utilization is until a full spectrum utilization is achieved. The effect of channels' conditions have more effect on the spectrum utilization at low channels' SNR and the effect diminishes slowly as the channels' conditions improve.

The effect of the number of secondary users and the channels' conditions on the system performance is also investigated in Chapter 5. It is found that as the number of secondary users increases the spectrum utilization increases. It is also shown that, as the required average SNR's for the applications increases, the spectrum utilization decreases and for the same required SNR, a better channel condition will lead to a better spectrum utilization.

The two algorithms were compared by the average achieved SNR for each application and by the total spectrum utilization for each algorithm in which the proposed algorithm provided a higher SNR and spectrum utilization than FCFS.

The secondary network's performance in terms of the capacity and the average data rate for each application are presented in Chapter 6. The proposed algorithm succeeded on average to guarantee the QoS requirement for each secondary users' application. The effect of imperfect sensing on the system performance was investigated. As the probability of detection increases by applying advanced spectrum sensing techniques, the total applications data rate increases significantly as the cognitive network will be more aware of the primary users' activity.

7.2 Future Work

In this section, we discuss directions for future work, which can be summarized as follows: In this thesis, we assumed the cognitive radio network models suffer only slow flat fading. The research can be extended for systems under fast and selective fading.

In our work, we have assumed that the sensing time has no effect on the system performance, studying the effect of varying the sensing time and applying different sensing techniques is a possible extension to the current research.

The proposed algorithm allocates the vacant channels based only on the QoS requirements for applications; an option to prioritize the applications will provide more flexibility to the algorithm. Some applications require high QoS requirements, video streaming as an example; developing the cost function to accommodate not only the SNR but also other specific applications' requirements is a possible research direction.

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