QoS based Route Management in Cognitive Radio Networks

By

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Abstract

QoS based Route Management in Cognitive Radio Networks

Saed Alrabaee

Cognitive radio networks are smart networks that automatically sense the channel and adjust the network parameters accordingly. Cognitive radio is an emerging technology that enables the dynamic deployment of highly adaptive radios that are built upon software defined radio technology. The radio technology allows the unlicensed operation to be in the licensed band. The cognitive radio network paradigm therefore raises many technical challenges such as the power efficiency, spectrum management, spectrum detection, environment awareness, the path selection as well as the path robustness, and security issues.

Traditionally, in the routing approaches in the wired network, each node allows a maximum load through the selected route while traditionally in the routing approaches in wireless network, each node broadcasts its request with the identification of the required destination. However, the existing routing approaches in cognitive radio networks (CRN) follow the traditional approaches in wireless network especially those applied for ad hoc networks. In addition, these traditional approaches do not take into account spectrum trading as well as spectrum competition among licensed users (PUs).

In this thesis, a novel QoS based route management approach is proposed by introducing two different models; the first model is without game theory and the second model is with game theory. The proposed QoS routing algorithm contains the following elements: (i) a profile for each user, which contains different parameters such as the unlicensed user (secondary user, SU) identification, number of neighbors, channel identification, neighbor identification, probabilities of idle slots and the licensed user (primary user, PU) presence. In addition, the radio functionality feature for CRN nodes gives the capability to sense the channels and therefore each node shares its profile with the sensed PU, which then exchanges its profile with other PUs, (ii) spectrum trading, a PU calculates its price based on the SU requirements, (iii) spectrum competition, a new coefficient α is defined that controls the price because of competition among PUs and depends on many factors such as the number of primary users, available channels, and duration of the usage, (iv) a new function called QoS function is defined to provide different levels of quality of service to SUs, and (v) the game theory concept adds many features such as the flexibility, the dynamicity in finding solutions to the model and the dynamic behaviors of users. Based on the previous elements, all possible paths are managed and categorized based on the level of QoS requested by SUs and the price offered by the PU. The simulation results show that the aggregate throughput and the average delay of the routes determined by the proposed QoS routing algorithm are superior to existing wireless routing algorithms. Moreover, network dynamics is examined under different levels of QoS.

Acknowledgement

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

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Chapter 1: Introduction

Cognitive Radio Network (CRN) is a revolutionary technology, which aims at enhancing the efficiency of spectrum usage. In a cognitive radio network, there are two kinds of users; the unlicensed users (secondary users, SUs) have the possibility of using large amounts of unused spectrum in an efficient way while reducing interference with other licensed users (primary users, PUs) [1]. Moreover, the spectrum can be traded between PUs who are the spectrum owners, and SUs who are the spectrum leasers, in order to maximize the utility (profit) of primary users while maximizing the utility (QoS level) of secondary users. There might be more than one primary user that offers an affordable price as well as a good quality spectrum and therefore, the competition will be advantageous to the primary users and secondary users. However, secondary users in cognitive radio networks (CRN) require the ability to deal with different frequency bands and effectively adapt their configuration to changes in the radio environment without interrupting the normal operation of the spectrum owner. The radio nature, mobility nature, channel availability, and PUs' presence behavior of PUs may vary with locations, time and frequency bands. This is what sets cognitive radio networks apart from other wireless networks.

In this thesis, the spectrum management, which consists of spectrum trading between PUs and SUs, and spectrum competition among PUs on one side and among SUs on the other side, and the related routing issues, are addressed. As a result, two models are proposed; the first being the model without applying the game theory concept, and the second being the model with applying the game theory concept. Each model is applied into the proposed QoS routing algorithm. In the first model, new dynamic equations are introduced in order to control the behaviors of users in the network. In the second model, game theory is used to control the dynamic behavior of primary users as well as secondary users. Basically, both models are applied into the proposed QoS routing algorithm in order to improve the network performance. In this chapter, the definitions of CRN as well as the game theory concept are reviewed. The motivation of the proposed work is presented. The objectives and contributions of this research are listed. Finally, an organization section is added to describe the structure of this thesis.

1.1 What is the Cognitive Radio Network (CRN)

Nowadays, there is an unexpected explosion in the demand for wireless network resources. This is due to the dramatic increase in the number of the emerging web-based services. For wireless computer networks, limited bandwidth along with the transmission quality requirements for users, make quality of service (QoS) provisioning a very challenging problem. Many factors motivate the development of new algorithms and protocols to exploit the limited available spectrum. These factors include spectrum scarcity, the inefficiency in the spectrum usage and the remarkable increase in the number of devices that contend for spectrum [1-3]. The unlicensed users (secondary users) have the possibility of utilizing the large amount of unused spectrum in a smart way while reducing the interference with other licensed users (primary users). Moreover, cognitive radio networks are smart networks that automatically sense the channel and adjust the network parameters accordingly. Cognitive radio is an emerging technology that enables the dynamic deployment of highly adaptive radios that are built upon software defined radio technology. The radio technology allows the unlicensed operation to be in the licensed band. The cognitive radio network paradigm therefore raises many technical challenges such as the power efficiency, spectrum management, spectrum detection, environment awareness, distributed spectrum measurements, the route selection as well as the route robustness, and the security issues like the unauthorized intrusion and malicious users.

1.2 What is Game Theory

Game theory is a part of applied mathematics which is concerned with how rational objects make decisions in a situation of conflict. It is a rich mathematical tool that helps us to understand, to analyze, and to model the interaction among rational entities. Game theory has been largely used in Economics. It has also been used in other disciplines such as Biology, Political science, Engineering, and Philosophy. One of the main areas in Engineering where game theory has been applied is data communication networking. [4, 5]. During the late 1940s, cooperative game theory had come into being, which analyzes optimal strategies for groups of individuals, assuming that they can enforce collaboration between them so as to jointly improve their positions in a game. In early 1950s, J. Nash developed a new criterion, known as Nash equilibrium, to characterize mutually consistent strategies of players. During the 1950s, many important concepts of game theory were developed, such as the concepts of the core, the extensive form games, repeated games, and the Shapley value. During the 1960s, Bayesian games were proposed. Application of game theory to biology, i.e., the evolutionary game theory, was introduced by J. M. Smith in the 1970s. Recently, game theory has been used in the communication area [6-8]. In particular, it has been used to model and analyze resource allocation problems in a competitive environment, and more. In addition, it has also been used for security issues. The cognitive radio network becomes the focal part in the wireless network and game theory has also been applied to cognitive radio networks [9-12].

1.3 Motivation and Application

Cognitive Radio Network (CRN) has been widely studied to solve the frequency scarcity problem through dynamic spectrum access [1]. Traditionally, rigid allocation policies by FCC have severely hindered the efficient utilization of a scarce spectrum. Hence, dynamic spectrum access, with the aid of cognitive radio technology [2], has become a talented approach by breaking the paradigm and enabling wireless devices to utilize the spectrum adaptively and efficiently. Emerging wireless technologies such as cognitive radio network (CRN) make dynamic spectrum allocation a reality. CRNs are able to provide greater flexibility and access to spectrum, and improve the spectrum utilization by searching and utilizing radio resources efficiently. However, there are several open research challenges that motivate our work. These challenges include:

1- Spectrum Trading: The spectrum in CRN is a limited natural resource and there are no ways to increase it. In order to solve the spectrum scarcity problem, new solutions for spectrum management should be presented. Unfortunately, the static nature of the previous schemes prevents them from utilizing the unused spectrum efficiently. In this thesis, the new algorithm is developed to manage the spectrum portions as well as to classify these portions according to proposed QoS levels. As a result, the spectrum is traded, which allows SUs to access the unused spectrum using overlay by paying a price.

2- Spectrum Competition: Recently, there has been an incredible increase in the number of electronic devices that demand spectrum access. In order to manage the competition among these huge numbers of users, a new factor is proposed, which is called Competition Factor and game theory is incorporated to ensure the flexibility of this work. Users can access the unused spectrum dynamically by using the proposed game theory schemes.

3- Quality of Services (QoS): despite the fact that the research in cognitive radio has been increased in recent years, QoS area on cognitive radios network is still immature. This point motivates our work to consider the QoS in this work. Therefore, three QoS levels are proposed in our work by defining a new function called a QoS level function. The first level represents the delay, the second level represents the primary user presence, and the third level represents Expected Transmission Count (ETX). The significance of the QoS levels will be described in detail later.

4- Routing Management: in cognitive radio network the vital issues that affect the network performance are the node mobility, the primary users' presence, and the availability of spectrum or channel. These issues degrade the network performance. The traditional routing algorithms such as shortest hop, ad-hoc on-demand routing protocol (AODV), and greedy algorithm are less efficient in terms of delay and throughput when they are applied in cognitive radio networks. This motivates us to find solution to improve the network performance.

5- Game Theory: recently, game theory concept has been used in the communication area [12]. Basically, it has been used to model and analyze resource allocation problems in competitive area and it has also been used for security issues. The cognitive radio network is the focal part in the wireless network and game theory has also been applied to cognitive radio networks [9]. Hence, the applying of game theory concept to our proposed model is another objective of this work.

1.4 List of Challenges

This thesis consists of two models; the first model is without game theory and the second model is with game theory. In the latter model, a Nash Equilibrium (NE), which is the solution of the proposed model, is obtained. The challenge in doing so is that, since prices can take values from a continuous set, the strategy sets of primaries are unaccountably infinite. So it is not *a priori* clear whether a Nash Equilibrium exists, and there is no standard algorithm for finding a Nash Equilibrium. In the first model, new equations are introduced to balance the PU's revenues and the QoS for SUs. The proposed models are designed to provide a scheme to help the PUs to adapt to the changing spectrum market conditions which include traffic load at PUs, spectrum price offered and current cost of spectrum. In addition, due to many characteristics of cognitive radio network (CRN) such as the complexity of cognitive radios network, mobility nature, and primary user presence, developing routing algorithm in such networks becomes one of the greatest challenges. The main challenges for routing algorithm in Cognitive Radio include:

1) Spectrum: When an efficient route algorithm solution is to be designed, the algorithm must be aware of the surrounding physical environment to take more precise decisions.
2) Quality: the routing solution is greatly influenced by PUs' behavior. So, the quality measurement of end to end route should be tied with path stability as well as path availability.
3) Maintenance: It might require restoring the failure path by using the effective signaling procedures. Meanwhile it is required to achieve minimal effect on the quality of routing. To avoid the maintenance in the proposed algorithm, the profile for each user, which consists of all information related to the spectrum or channel, gives the ability to predict the health of the path in advance.
4) Cost: Balance the PU's revenues and the QoS for SUs. A scheme is proposed to help the PUs to adapt to the changing spectrum market conditions, which include traffic load at PUs, spectrum price offered and current cost of spectrum.

Specifically, the primary differences and challenges between routing of CRNs and routing of other wireless network such as ad-hoc or sensor was discussed by [3] and it can be summarized as follows:

1) Link availability: CRN links are available under idle duration of the primary user(s) so that Dynamic Spectrum Access (DSA) can effectively fetch such opportunities, after successful spectrum sensing. Links in the CRN can vary much more rapidly because link available duration is only a fraction of the inter-arrival time for traffic and signaling packets.
2) Unidirectional links: Typically wireless networks have bi-directional links, because radio communication is half-duplex. However, in CRNs, unidirectional links are more likely to be the case due to the fact that a CR node may just have an opportunity to transmit in one time duration and there is no guarantee to allow the opportunity for transmission from the other direction.
3) Heterogeneous wireless networks: In contrast to typical wireless ad-hoc or sensor networks, CRNs are generally formed by heterogeneous wireless networks (co-existing primary systems and CR nodes to form ad-hoc networks). However, CR links might be available for an extremely short duration and the successful networking lies in cooperative relaying among such heterogeneous wireless networks. It is not good in terms of security because it is not possible for a CR node to get a secure certificate within the short opportunistic window.
4) Efficiency: It can find some frequency spectrum, which is not occupied or only partially occupied. The unlicensed user, called secondary user (SU) or cognitive user (CU), can have access to such a spectrum, and the utilization will be improved greatly.

1.5 Problem Statement

A CRN allows SU to operate on the vacant parts of the spectrum allocated to PU. Due to the nature of radio networks, the users have the ability to sense the licensed channels. As a result, many SUs can sense the same channel (spectrum), which opens the door for the competition between SUs on the one side and between PUs (spectrum owners) on the other side. For primary users, the competition is to get more demand. In addition, the mobility of nodes, either PU or SU, could affect the network topology as well as the network performance. Moreover, the possibility of new users to join the network and the ability to sense the existing spectrum, make the routing in radio environment a problematic. The problem can be divided into three parts: the first part is to find efficient and dynamic equations for spectrum management. The second part is to obtain the Nash Equilibrium for each proposed game scheme. The third part is to apply the both models (with/without game theory) into proposed QoS based route management algorithm.

1.6 Objectives and Contributions of the Proposed Research

This section includes in detail the objectives and contributions of this work. Some research questions are presented to guide us to specify our objectives precisely.

1.6.1 Research Objectives

The major objective of this work is to propose new schemes to manage the spectrum efficiently and to maximize the network performance. In the first part, the objective of the first phase is to manage the spectrum and to control the behavior of SUs while of the second phase is to select a path as per SU's requirement and to give the SU a choice to specify its level of QoS. In the second part, the game theory concept is used to model the dynamic behaviors among PUs and the relation between PU and SU is modeled. To achieve this goal methodologies and mechanisms are developed to enable our system to interact with changes in wireless environment. Efforts will be geared towards the following tasks:

1) To design a new QoS based Route Management algorithm that achieves the following objectives:
    - To increase throughput of CRN by reducing the communication overhead and broadcasting in the CRN by defining a profile for each user.
    - To decrease the delay in the cognitive radio network by providing path with more idle slots in each link in the path. Efficient equations are introduced to calculate the delay in the link.
    - The mobility of SUs should also be considered properly by updating the proposed profile table periodically.
    - The presence of PUs should also be considered properly by providing a new constraint called probability of PU presence.

2) To develop the functions for the spectrum trading competition. These functions include:
    - Base Station Cost paid by a primary user to the base station.
    - Intermediate Cost paid to each intermediate node in the selected path.
    - Price Function calculated by primary user based on SU requirements as well as the previous costs.
    - Profit Function calculated by PU to get the net revenue of its service.
3) To consider the requirements of SUs while maximizing the revenue of PU.
4) To provide different levels of QoS that gives the chance for SU to choose the best one for its requirement.
5) To provide different options for path based on SU's requirement as well as the price.

6) To propose game theory schemes in order to model the dynamic behaviors of PUs and SUs. Three kinds of game models are proposed; the first scheme is to model the competition among PUs, the second scheme is to model the relation between PU and SU, and the third scheme is to model the spectrum selection among SUs. The proposed schemes are described in detail in Chapter 4.

1.6.2 Key Contribution

Much research has been conducted on the CRN especially for spectrum trading, spectrum competition, and routing algorithm. Most of this research focuses on spectrum trading and spectrum competition without considering the routing issue. To the best of our knowledge, there is no game theory framework ever proposed for routing in cognitive radio network from the system point of view. Therefore, the goal is to propose a complete system where spectrum trading, spectrum competition, QoS levels, path selection, routing algorithm, and game theory are considered. With this goal in mind, the contributions on different aspects of cognitive radio network are presented as follows:

- A new scheme for trading free spectrum to SUs is proposed. In spectrum trading, the objective of a PU is to maximize its revenue, while that of a SU is to get a service from this spectrum.
- A new factor called the Competition Factor for the spectrum competition among PUs is introduced. This factor relates to many parameters such as the availability of spectrum, the number of primary users, the usage period, and the number of secondary users.
- A multiple levels of QoS are proposed to get more quality service; a function called QoS level function is introduced, which relates to the spectrum.

- A new idea of defining profile for each secondary user is introduced that contains the user ID and parameters of its channel.
- Manage all profiles in a table called Profile Table. This helps in finding the best choice for SU.
- Apply both models, with and without game theory, for routing algorithm in cognitive radio network and measure the network performance.

1.7 Thesis Outline

The rest of the thesis is organized as follows: The literature review of the pricing, the spectrum trading, the spectrum competition, and the QoS routing in CRN are discussed in Chapter 2. The system requirements for the QoS routing algorithm are defined in Chapter 3. The system models with/without game theory are described in Chapter 4. The performance evaluation is presented in Chapter 5. The conclusion of the thesis and future work is presented in Chapter 6.

1.8 Summary

In this Chapter, the cognitive radio network and the concept of game theory were presented. In addition, the motivations, the objective, and the contributions of this thesis were highlighted. Moreover, the challenges were listed and the problem statement was defined. In next Chapter, literature reviews of pricing techniques, spectrum trading, spectrum competition, QoS routing, and game theory in CRN is introduced.

Chapter 2: Background and State-of-the-art

Earlier works on the fundamentals for this work is reviewed in this chapter. Firstly, both the static scheme and the dynamic scheme of the pricing techniques are studied. Secondly, the state of the art in spectrum trading and competition on cognitive radio network are reviewed. Thirdly, related area of routing in cognitive radio network is reviewed. The chapter is concluded with a presentation of the state of the art to fusing game theory in cognitive radio network.

2.1 Background

2.1.1 Pricing Techniques

In this section, the concept of price is introduced followed by the description of static and dynamic price and a review of pricing in cognitive radio network.

2.1.1.1 Introduction

Pricing is one technique that can be used for the design of a mechanism to adjust the usage of radio resources by the wireless nodes by amending their costs. However, the price technique is considered a control tool whereas the behavior of nodes is controlled by changing the price of path or spectrum according to the node's actions. In our model many factors based on secondary user's requirements will affect the price function such as the spectrum allocation, the path robustness, the path availability, the path stability, the path quality, and the throughput as well. Moreover, whenever the secondary users adjust their requirements the price function will be changed as well. By having such a function, selfish or malicious user in the network is prevented. If the secondary user uses the path for sending a specific number of packets and then the secondary user decides to increase the number of sent packets, the price function will increase the price as a result of this action to prevent the secondary user from the selfish actions and give chance for other users to utilize the path. Thus pricing plays an important role in the interaction of primary users and secondary users. In cognitive radio networks, secondary users are price takers who behave strategically considering the price and the competition they face, and primary users are price makers who would like to maximize their own revenue. The pricing schemes can be classified as either static pricing or dynamic pricing.

2.1.1.2 Static Price

It is a set of fixed prices to allocate the network resource, such that the network revenue (or utility) can be maximized. It is also called one-shot pricing. The network parameters keep unchanged in the considered time. Figure 2.1 shows the categories of pricing schemes [13].

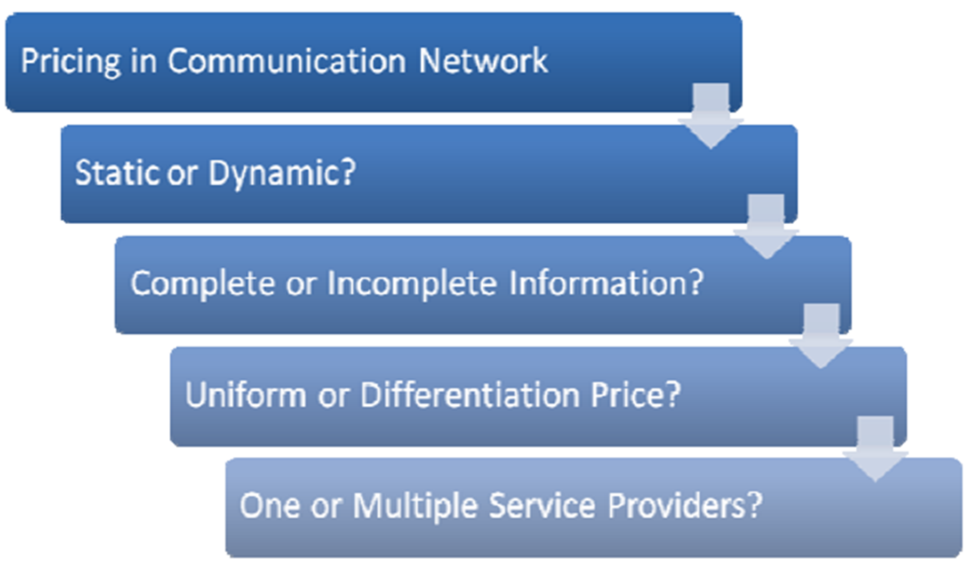

Figure 2.1: Categories of pricing schemes [13]

The most frequently used model in static pricing literature is Stackelberg game scheme [14, 15], which is a two-stage leader-follower game. In the first stage, the service providers announce prices, and in the second stage, the users respond by choosing a service quantity. Both users and the service provider are assumed selfish and rational. The task of users is to maximize their surpluses by choosing the right quantity of service, while the service provider tries to make a wise decision of prices to induce a desired resource allocation, such that its revenue can be maximized.

2.1.1.3 Dynamic Price

In contrast to static pricing schemes, dynamic pricing schemes are much more complicated, which consider the evolution of the pricing system in a sequence of time slots. The pricing strategies are adaptively changing according to the environment variations (e.g. network resource, user population and demands, network topology, channel conditions, etc) [13, 16, and 17]. Despite the complexity, service providers prefer dynamic pricing schemes for the adaptation and flexibility of managing the network resource in the dynamic network environment, such that higher profits can be obtained. Though static pricing is still dominant in most of the networks today, dynamic pricing schemes are of both academic and practical significance, since it will be a promising solution for service providers that face the increasingly intensive competitions and the resource (e.g. bandwidth) shortage.

2.1.1.4 Pricing in cognitive radio network

The following works addressed the issue of pricing in a cognitive radio network. The auction mechanism was applied to the problem of spectrum sharing among users using spread spectrum signaling to access the channel [18-20]. However, the issue of equilibrium among multiple operators and the dynamics of spectrum bidding in a competitive environment were ignored. Competition among the cognitive radio entities in a spectrum sharing environment can be modeled as either non-cooperative game or cooperative game [21-24]. Specifically in cognitive radio network, the price technique was introduced in different fields such as the use of the power resource by charging it to users [25], which is done by adding a cost component to the payoff function to add fairness to the network. The price also was introduced for resource allocation in [26] where utility/pricing strategy is defined that meets the objective to maximize the SUs capacity, and the protection for PUs by means of outage probability.

In [27] the authors proposed solution for spectrum trading, by using pricing technique in a cognitive radio network where multiple primary users race with each other to offer spectrum access chances to the secondary users. However, in [27] pricing scheme is used where each of the primary user targets to maximize its payoff under its quality of service (QoS) constraints. Figure 2.2 shows the price scheme proposed in [27]. Consider a wireless system with multiple primary services (total number of primary services is denoted by N) operating on different frequency spectrum F_i and a secondary service which serves a group of secondary users willing to share these spectrum with the primary services. In the scheme, the price was used to control the quantity and to maximize the payoff of primary users. However, the primary service searches for the equilibrium by adjusting the price offered to the secondary service so that the profit is maximized.

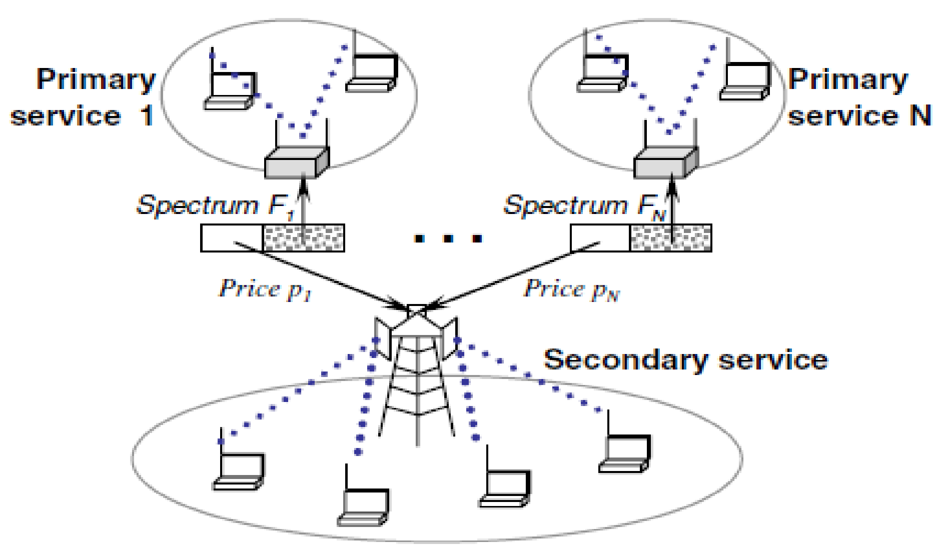

Figure 2.2: System Model for Spectrum Sharing [27]

In [27], as shown in Figure 2.3, a spectrum based on cognitive radio wireless system with one primary user and N secondary users is also considered. The primary user is willing to share some portion of the spectrum with secondary user. However, the primary user controls secondary users for the spectrum by putting a price per bandwidth. By having the price function the primary user can control the total requested bandwidth for secondary user.

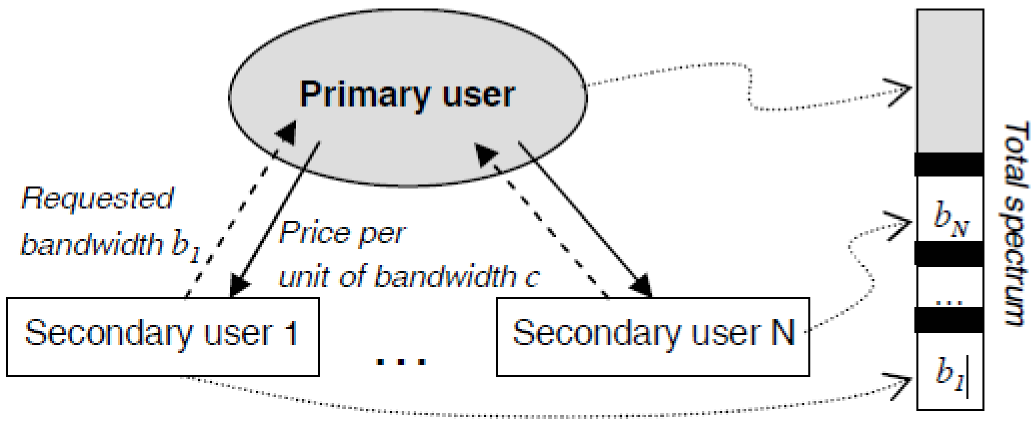

Figure 2.3: System Model for Spectrum Trading [27]

In Figure 2.3, a dynamic game is offered in which a secondary user adapts its spectrum sharing strategy by noticing only the marginal profit which is a function of spectrum price offered by the primary user. In [28] the price was discussed in competitive cognitive radio network where the secondary users adjust their transmission power level to maximize their payoff. However, the primary users will be in charge of cost of the secondary users in order to enhance their own revenue. They model the behavior as a non-cooperative game model and then find the Nash equilibrium. Primary users (PUs) transmit the available spectrum to the base station over the bandwidth allocated, while the secondary users (SUs) request spectrum from the primary service provider (i.e., the base station) and pay for their uplink transmissions.

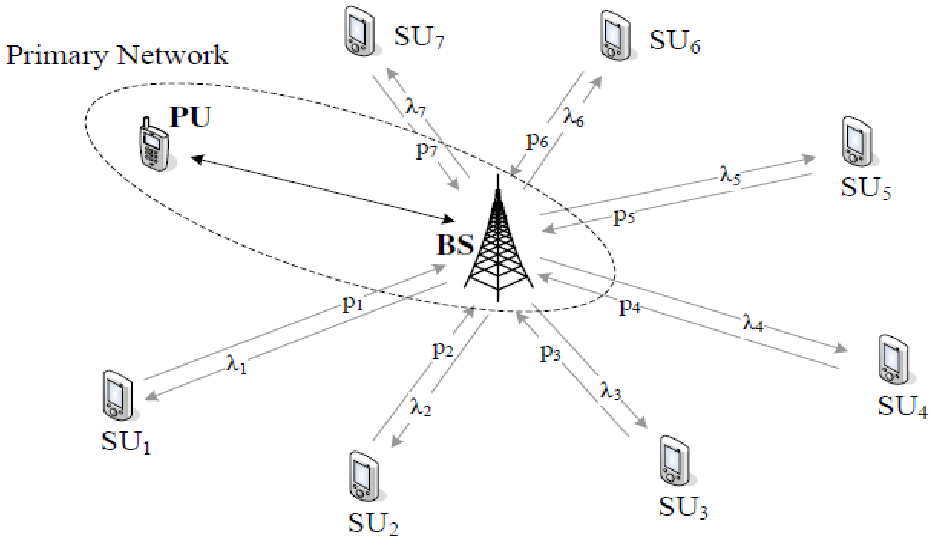

Figure 2.4: System Model for Spectrum Trading [28]

Figure 2.4 shows a number of cognitive secondary users. The base station charges the secondary user the amount per unit of transmit power on its uplink channel. For a secondary user, the payment can be seen as its cost of accessing the primary network. For the primary user, the payment can be seen as the compensation of its potential service quality degradation caused by the interference of secondary user. From previous discussions, the network pricing is a cross disciplinary research area and requires deep understanding of both networking technology and microeconomics. Basically, as it is shown in this section, pricing in cognitive network is based on many fields such as spectrum allocation, power control, and transmission control. In this thesis, the pricing technique is used for routing in cognitive radio network.

2.1.2 Spectrum Trading and Spectrum Competition

The spectrum can be traded between primary user and secondary users. The goal of this spectrum trading is to maximize the profit of primary users. Basically, the spectrum trading opens the competition's door either among PUs or among SUs. The following works addressed the problem of spectrum management, which consists of both spectrum trading and spectrum competition in cognitive radio network. In the cognitive radio network, spectrum trading is successfully formulated by economic models and competitive and cooperative pricing schemes are developed in [29]. In [30], hierarchical spectrum sharing is formulated as a unified market. Specifically, the pricing mechanism for the bandwidth allocations between the systems equates the supply to the demand. In [31], the consumers' demand function is modeled and the Walrasian prices calculated which equate the demand to the supply of each goods.

In [32], the authors addressed the problem of spectrum sharing in a cognitive radio network where multiple primary and secondary strategic-users are involved. In addition primary users (PUs) would like to offer part of their spectrum to secondary users (SUs) to make extra revenue. Following process is applied in Figure 2.5: PU decides the amount of the bandwidth to lease, SU decides the amount of bandwidth to use, and AP collects all the strategies and makes proportional allocation.

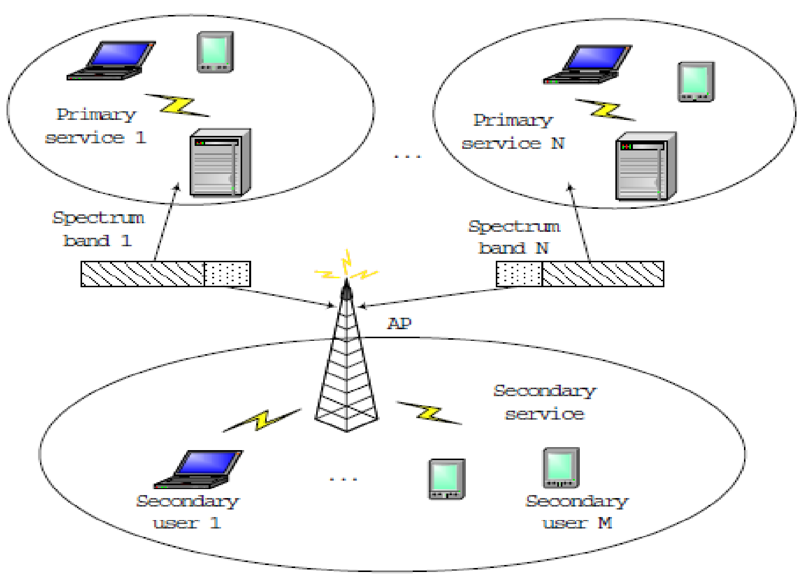

Figure 2.5: System Model for Spectrum Sharing [32]

In [33], a model consisting of multiple primary service providers (PSPs) is proposed, which have some amount of unutilized bandwidth, and multiple secondary users (SUs) that require spectrum bands. Moreover, a new network element, called Telecommunication Coordinating Authority (TCA), is introduced in the proposed model. The TCA has the responsibility to control the satisfaction of all users in the PSPs' networks by simultaneously limiting interference and maximizing cognitive capacity as shown in Figure 2.6.

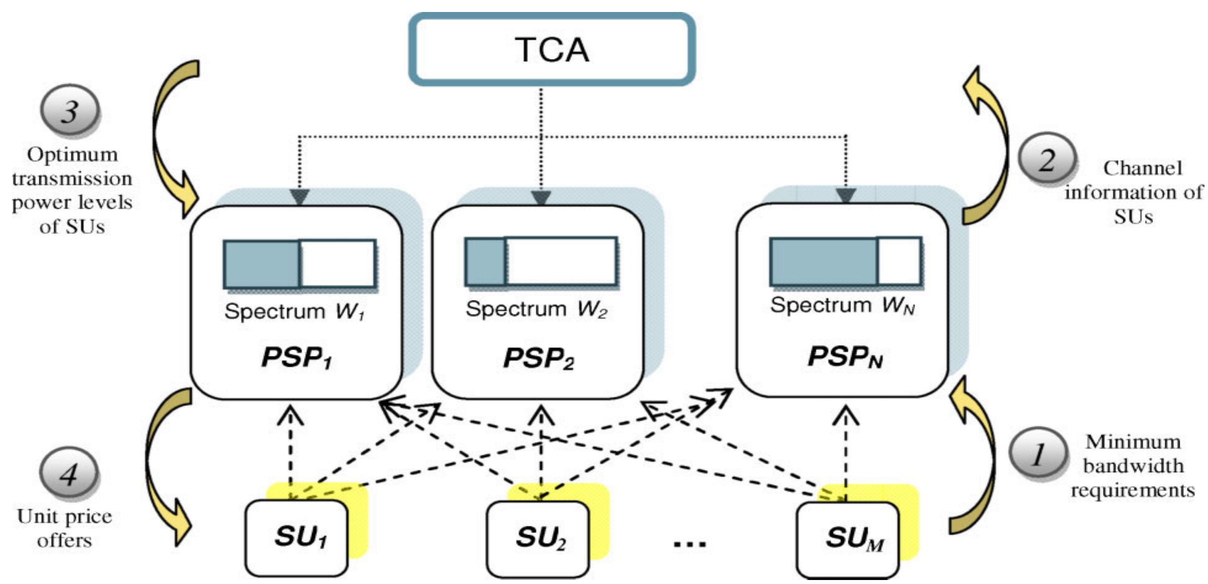

Figure 2.6: System Information Flow [33]

Figure 2.6 shows the flow is activated by the declaration of minimum desired bandwidth of SUs. The messages are broadcasted to PSPs periodically, in order to prevent multiple individual attempts. A game-theoretic modeling approach for a multiple-seller and multiple- buyer system has been proposed in [34] mainly by adopting the spectrum trading problem to the variations in price and quantity offered by the different primary users or primary service providers in order to maximize their utility functions. In addition, each user computes the bid that maximizes his profit function as shown in Figure 2.7.

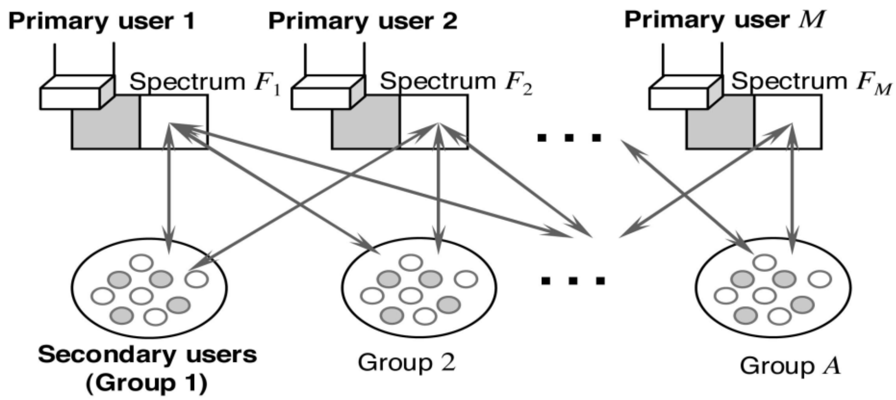

Figure 2.7: Spectrum Trading Model [34]

In [35], the authors proposed a dynamic spectrum allocation algorithm named market equilibrium and game (MEG). The market in their model consists of two submarkets: multiple primary service providers (PSPs) and a dynamic spectrum allocation server (DSAS) from the high submarket, while the low submarket is composed of the DSAS and a number of secondary users as in Figure 2.8.

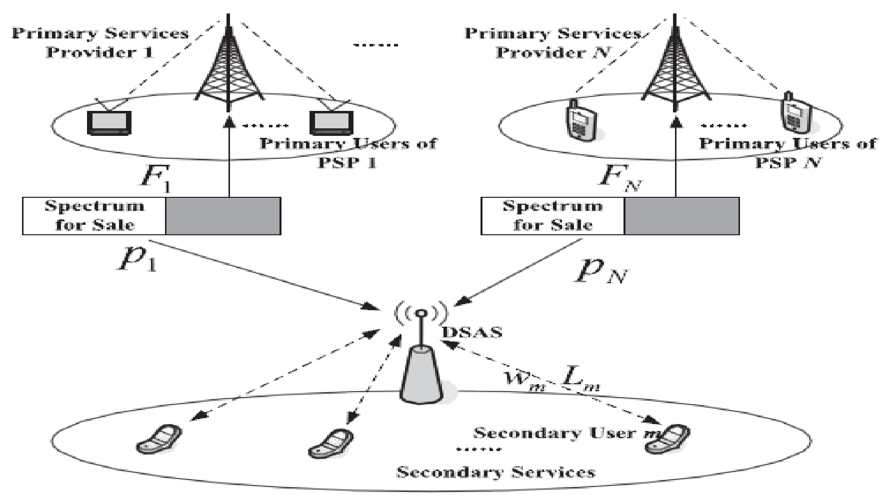

Figure 2.8: Two Level Secondary Spectrum Market [35]

The previous research mentioned in Sections 2.1 and this Section 2.2 apply different game frameworks to spectrum trading, spectrum competition, and some of them formulate price models as game theory framework. There are no approaches that consider the effect of applying game theory into the quality of service based routing. In addition, the previous works do not consider different levels of QoS. The previous research is summarized in Table 2.1.

Reference No.	Spectrum Trading	PUs' Competition	SUs' Competition
29	√	√	
30	√	√	
31	√		√
32	√	√	
33	√		√
34	√		
35	√	√	

Table 2.1: Summary of Research Literature on Spectrum Management

To the best of our knowledge, there is no model that addresses the spectrum trading between PU and SU, the competition among PUs, and the competition among SUs together in one research work. This thesis proposes as part of spectrum management, the spectrum trading between PU and SU, the competition among PUs, and the competition among SUs.

2.1.3 Routing in Cognitive Radio Network

The most important issue in the network layer is routing. It is considered in Cognitive Radio Network as a challenging task due to the mobility of cognitive radio users (secondary users), the primary user's presence, and the cognitivist functionality for each SU. In this section, an overview of routing issues in cognitive radio network and literature review for the routing techniques in cognitive radio network is presented.

2.1.3.1 Routing Issues in CRN

The routing issues are the obstacles in the network which prevent the maximization of the utilization of resources. However, the routing issues change according to routing metrics, which are defined as values that are assigned to the links in a path and are used by routing algorithm to select the path between the source and destination. However, these weights usually reflect the cost of using that link in the path. The following are the routing issues:

- Spectrum Knowledge: It is considered as the most important issue in CRN where the users in the CRN shall sense the spectrum. The secondary users must have local or global knowledge about the spectrum.
- Overhead: It is the excess of the allowable number of transmissions that reduce the efficiency as well as the throughput of the whole network. Before the secondary user starts using the spectrum there is overhead for some bandwidth consumed for reporting sensing results from secondary users (SUs).
- Link Failure: It is caused due to unexpected conditions. It requires extra power signal in order to recover the link. A link failure can occur in a CRN due to many reasons, such as a primary user becomes active or an intermediate secondary user moves to other place making no node available to replace the moved node.
- Mobility Handling: In a CRN, a secondary user can move or join to other place at any time. Therefore, once a path is established and if some intermediate node moves to another location, it requires switching to other node and re-establishing a path.

- Best Path Selection: Nodes (users) look for the best path in terms of many parameters according to the QoS of the application, which may be either data or voice. In a CRN, the secondary user may have many different paths based on many factors such as the possibility of primary user to be active, the bandwidth capacity, the robustness and stability of path.

The routing metrics that relate to these issues must be taken into consideration and are summarized in Table 2.2.

	Spectrum Knowledge [36,37]	Overhead [38]	Link failure [39]	Mobility Handling [40]	Best path selection [41]
Delay	√	√	√	√	√
Link Capacity	√	√			
Interference	√		√	√	√
Power efficiency	√	√	√		√
Throughput		√			√
Link robustness			√		
Link stability				√	
Cost					√

Table 2.2: Routing Metrics Related to Routing Issues

The proposed algorithm in this thesis considers i) delay, ii) link capacity, iii) throughput, iv) link robustness and stability, and v) cost.

2.1.3.2 Routing Techniques in CRN

In most of the research papers, routing protocols are classified into spectrum aware-based (full spectrum knowledge or local spectrum knowledge [36]), multi-path based, and traditional routing (local coordination-based, reactive source-based and tree-based routing techniques [37]) as shown in Figure 2.9.

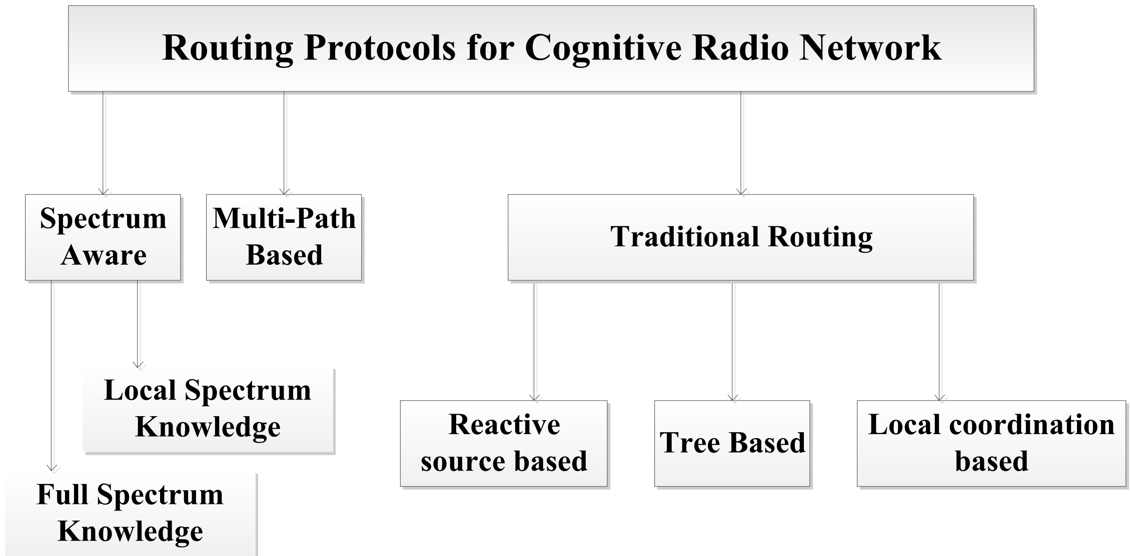

Figure 2.9: Routing Protocols for Cognitive Radio Network

Each category in Figure 2.9 is described as follows. In spectrum aware routing, the nodes (users) select the route based on spectrum knowledge [36, 37]. In full spectrum knowledge, nodes should be aware of all other nodes. These nodes may be represented by a graph, or mathematical programming tools may be used to represent them. On the other hand, in the routing schemes that are based on local spectrum knowledge the information about spectrum availability is locally constructed at each secondary user through a distributed protocol.

In multi path routing, the multi-paths are discovered first and then the node selects one route (path) among multiple routes (paths) according to different metrics selected such as delay, throughput, and link availability. The multi-path routing algorithm makes the network more dynamic while increasing the efficiency. The multi-path routing for CRN was addressed in [38], which uses dynamic source routing mechanism for route discovery. Moreover, [38] is based on broadcasting an RREQ message with the user's ID, next hop, and hop count. Each intermediate node updates the fields in the RREQ message and the destination responds with a RREP message on the path that satisfies the metrics chosen. Through multi-path routing [38] one achieves higher throughput as well as better resiliency.

In reactive source based routing within traditional routing category, the source specifies the path of data. Hence, the path to destination is computed by the source. The reactive source for CRN was addressed in [39], where the route is selected in order to achieve the bandwidth demand based on the probabilistic definition. In tree based routing a centralized routing scheme is considered, which is controlled by a single network entity. The tree based routing was addressed in [40]. It uses two schemes: the first scheme is based on end to end throughput metric and the other is based on the least load. It requires the nodes to register with the centralized entity. The local coordination based routing begins when nodes estimate the load of the flow. However, nodes choose the flow based on neighborhood interface, and is addressed in [41]. The above routing protocols with their related issues are summarized in Table 2.3.

	Spectrum Aware	Multi-Path	Traditional Routing		
			Reactive Source	*Tree based*	*Local Coordination*
Spectrum Knowledge	√	√	√		
Mobility Handling	√		√		√
Overhead	√	√		√	
Best Path selection	√	√	√	√	√
Link failure		√	√		√
Solutions	[36, 37]	[38]	[39]	[40]	[41]

Table 2.3: Summary of Routing Protocols

2.2 State of the Art

2.2.1 Routing Models in CRN

Routing is a vital yet not intensely studied area of research in CRNs [1]. There is only a limited work for the QoS routing in CRN. In [42], DORP, a routing and spectrum assignment scheduling algorithm is proposed to achieve lower switching and back off delay. However, the algorithm is under the assumption that the node has two transceivers, one is traditional and the other is a cognitive radio, which means that each node has data to transmit and must know the frequency band choice of every node along the route to destination. This is costly in terms of energy consumption and it requires having global information. In [43], a routing and spectrum selection for cognitive radio networks that computes paths from a source to a destination by considering the activity of primary users is proposed. The work in [43] does not cover the issues of channel assignment and delay control. In [44], RACON, a novel algorithm based on the capturing of any spatial locality of link disconnection for multi-hop in CRN is proposed, but the problem in [44] is the assignment of ID to the nodes, as well as the selection of efficient strategies. For the following works, they do not consider the route stability. In [45] the authors propose a routing metric that accounts for the available channels and hop count. In [46-48], the switching delay is considered. The unpredictable behavior of primary users is considered in [49]. Recently, a cooperative green routing model with an energy-efficient consideration algorithm is proposed in order to reduce the power consumption [50]. More recently, a routing algorithm for route robustness and spectrum allocation is proposed [51-53]. As a result, the issues in the previous works are considered in our model.

2.2.2 Game Theory in CRN

Recently, game theory has been used in the communication area [4-8]. Basically, it has been used to model and analyze resource allocation problems in competitive area and it has also been used for security issues. The cognitive radio network becomes the focal part in the wireless network and game theory has also been applied to cognitive radio networks [8-12]. Table 2.4

shows the correspondence between each element in a cognitive radio network with each element in game theory.

Elements of a game	Element of a CRN
Players	Nodes (Secondary and Primary users)
Actions	Change parameters
Payoff	Throughput, Delay, Bandwidth, Interference, etc.

Table 2.4: Cognitive Radio Network based on Wireless Networking Game

2.2.2.1 Game Theory for spectrum trading and competition in CRN

Game theory is a useful tool that can be used for spectrum management in cognitive radio network [54]. In [55], they modeled the competitive dynamic spectrum leasing by using the concept of game theory. Specifically, one level is between primary user and spectrum broker and the other level is between secondary user and service provider. The players of this game are the secondary users and their strategies are defined in terms of selection of a particular service provider. In [25], a game-theoretic cooperative spectrum sensing was proposed for cognitive radio network. In particular, they studied the interactive decision of selfish secondary users on cooperative spectrum sensing. The players of this game are the secondary users and their strategies are defined in terms of selecting frequency of channel. In [56], a non-cooperative game is formulated for spectrum trading in cognitive radio network. In this game, the players are the secondary users, and their strategies are for buying spectrum from the primary user. In [57], a game theoretic price competition was proposed in cognitive radio network. Specifically, they analyzed price competition in CRNs jointly considering both bandwidth and spatial reuse. The competitive spectrum leasing in a primary market was analyzed using auction methods in [58].

2.2.2.2 Game Theory for other issues in CRN

Due to the nature of cognitive radio network any change in environment will trigger the network to re-allocate the spectrum resources; the game theory was used as an important tool to analyze, model, and study the interactions. In cognitive radio network, some of the game theoretic models were presented in [59], which has identified potential game models for power control, call admission control, and interference avoidance in cognitive radio networks. Several methods have been proposed for dynamic spectrum access using game theory [60]. In [60], the channel allocation problem is modeled as a repeated game. In this, the players are secondary users and their strategies (actions) are choosing a channel. In [60] two classes of payoff were presented according to which cognitive radios adapt their transmissions. The first class corresponds to selfish behavior. The second class corresponds to cooperative behavior. The benefit of a game theory model in CRN is summarized as follows: the network users' behavior and actions can be analyzed; game theory provides us the equilibrium (solution), and the non-cooperative game theory gives us the ability to derive efficient distributed approaches. Basically, as shown in Table 2.5, the solution for most game models is Nash equilibrium, which means that each player has no chance to increase its utility by unilaterally deviating from this equilibrium.

Issue in CRN	Game Model	Solution	Reference
Power Control	Non-cooperative	Nash equilibrium	[59]
Interference	Potential game, Stackelberg game	Nash equilibrium	[61]
Spectrum Sharing	Cooperative	Nash equilibrium	[62]
Power Allocation	Potential game	Nash equilibrium	[63]
Spectrum access	Non-cooperative	Nash equilibrium	[64]

Security	Stackelberg	Nash equilibrium	[65]
Spectrum Trading	Supply and Demand functions	Market equilibrium	[66]

Table 2.5: Summary of Game Models for Issues in CRN

Table 2.5 shows the different issues in CRN that have been modeled by game theory. This modeling gives us the ability to understand the issue deeply and based on that the parameters of models are changed according to our requirements. Most game theoretic models were modeled for issues related to power and spectrum such as spectrum allocation, spectrum sharing, spectrum access, spectrum trading, power allocation, power control, and interference avoidance. The game theory models that are presented in previous two sub-sections could be one of the following kinds of game theory:

- Non-cooperative game: The users act to maximize their own payoff individually.
- Cooperative game: The users have mutual actions to gain shared benefits.
- Static game: It is deterministic, time independent, and is good for one period.
- Dynamic game: It is good for more periods and any change in the parameters of the system will affect the game.
- Repeated game: A group of agents engage in a strategic interaction over and over.
- Stackelberg game: It consists of a leader and a follower. Leader announces a policy and the follower chooses its policy based on leader's action.

To the best of our knowledge, there is no approach that uses the game theory concepts in routing. In this thesis, the game theory concept is applied to the routing algorithm to observe the network performance.

2.2.3 Literature review of QoS in Cognitive Radio Network

Even though cognitive radio has attracted increasing attention in recent years, research on cognitive radio network is still immature. QoS performance is one of the most sought research points for cognitive radio network. In [69], a QoS Routing approach called K-shortest widest paths Q-Routing algorithm is proposed by Alireza Esfahani et al. to improve end to end delay factor; however, the shortest widest path is sometimes not efficient. In [70] the authors proposed a power control strategy: fix the bit error rate and control the power to guarantee the optimal QoS, but the network performance was not studied. In [71], secondary users can achieve the available spectrum rapidly and reduce the time for spectrum switching which will improve capacity utilization and throughput, although it is costly. In [72], three QoS metrics are proposed which are used to evaluate the performance of the network: blocking probability, dropping probability, and failure probability but the PUs' presence was not addressed. In [73], He Qing et al. presented a routing algorithm based on QoS requirement for cognitive radio network which takes into account the effect of the bandwidth and delay; the efficiency of the network in terms of throughput was not addressed. In [74], the authors proposed an approach for impact on routing selection which was caused by channel capacity and interference arising from intra-flow contention. However [74] does not consider the mobility of network nodes. A strategy for QoS performance based on fuzzy logic control was studied by Al-Fuqaha et al. in [75]. The problem in [75] is that it is costly as well as it is more complex. This work proposes models that avoid the shortcomings in the previous works [69-75].

2.3 Summary

In this chapter, the concepts of the pricing techniques, the spectrum trading, the spectrum competition, the routing issue, and the game theory are reviewed for CRNs. It is concluded that the price is a very important control factor that can control the behaviors of nodes in the network. The spectrum trading and spectrum competition are still open for research due to the variety of CRN architectures. The routing issue plays a vital role in the network performance in terms of the throughput. The game theory concept is also a very important concept to give the model the flexibility and to find the solution dynamically. As mentioned in this chapter, the existing research groups deal with issues as follows: some groups deal with price and spectrums trading as one issue regardless of other issues, the other groups deal with routing issue, and some other groups apply the game theory concept to the spectrum trading and competition model. Hence, in this thesis, a game theory approach for routing in cognitive radio network based on spectrum management is proposed. In the next chapter, the system requirements of our model are reviewed. These requirements consist of SUs' requirements, spectrum sensing, spectrum allocation, PUs' requirements, and the QoS for SU.

Chapter 3: System Requirements

A multiple primary users and multiple secondary users exist in the system considered where a primary user buys spectrum from base station. The PU can lease a part of this spectrum to secondary users.

3.1 System Assumptions

In this paper, we consider an overlay model. In addition, users can exchange their profile information through a common control channel, as in [15], or in a distributed manner, as in [16]. Each PU has k channels assigned from the base station with a specific cost called Base Station Cost, which is described in the next section. In our model, the network consists of N primary users and M secondary users. Moreover, we define Sj as the spectrum size for renting, which is offered by PUj. A unique ID is defined for each channel. In terms of security, we assume that all the nodes (PU & SU) in the network are trusted nodes. Figure 3.1 illustrates the general system of the proposed models.

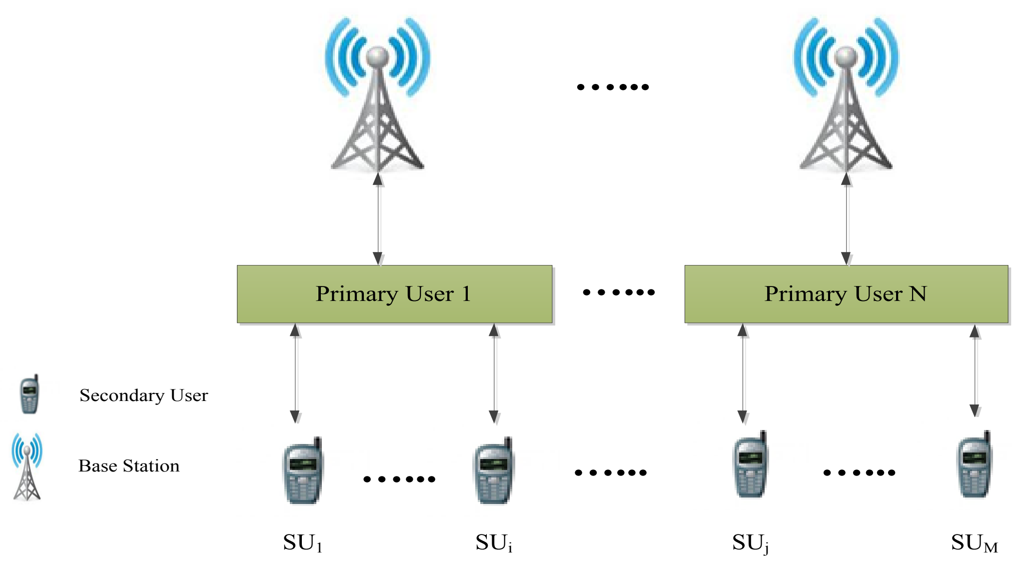

Figure 3.1: Multiple Primary Users Cognitive Radio Network

Basically, the only function of the base station is to allocate the spectrum to PUs at the beginning. The main components in our system are therefore the primary users and the secondary users. In this chapter, the secondary user's flow is defined. The mechanism of spectrum sensing as well as the spectrum allocation is reviewed. In addition, the spectrum market overview is presented and the primary user's requirements are presented as well. Finally, the QoS levels function are described and defined whereas this function consists of three levels.

3.2 Secondary User's Flow

The network consists of: spectrum owners (PUs) and consumers (SUs). Primary users have fixed mobility whereas secondary users are moving and changing their places arbitrarily. Each flow requires the capacity of one channel on each hop along the path between the source and the destination nodes for the duration of its service in order to fulfill its requirements. Once the flow gets accepted, a flow must have continuous service for the duration of its service time. After the service time has elapsed, the flow is deemed to have been completed successfully. However, in traditional wireless network the flow might be blocked. With cognitive radio functionality enabled, it can search for another way to service the flow instead of getting blocked. The network consists of N PUs and M SUs as shown in Figure 3.1. A PU is defined as a spectrum owner that may trade a spectrum to other users. Each PU has k channels assigned to it in advance and it offers an adaptable number of these channels to SUs. For each PU_i, S_i is the spectrum size for renting with its QoS requirements, and the price of spectrum. These parameters are changed over time corresponding to the network conditions, such as traffic load, spectrum demand, and spectrum cost. Basically, a dynamic spectrum allocation is considered where the PU can change the price and the size of the offered spectrum when needed due to the changes in network and the user's behavior. Game theory is used to help PUs to set the route parameters, spectrum size and price for all SUs based on their requirement. SUs can access a licensed spectrum if they rent the spectrum from a PU. From PUs point of view, the optimal resource management scheme is the one which maximizes their revenue. However, some constraints prevent PUs from maximizing its profit such as resource constraint and QoS for PUs.

In this work, the problem, how to manage the routing selection trading in the secondary spectrum market for satisfying both QoS levels of services for SUs and PUs as well maximizing the revenue of PUs, is addressed. PUs provide different QoS levels to SUs to maximize their profits while considering the trading constraint. Hence, the price of route access changes according to user requirement, and providing a service to new SUs whenever there is available spectrum may not maximize the PU's revenue. The PU has the choice of whether to accept the request or reject it and wait till a user with worthy reward requests. Therefore, the optimal resource management scheme is mandatory in our system. Basically, the problem of optimal resource allocation for satisfying multiple levels of QoS for multiple SUs is a challenging one in the design of our network. The main motivation in doing this is to adapt the services to the changes in the structure of the spectrum secondary market. Most of the research that has been conducted in this field assumes one type of service. Nowadays, with an explosion in the diversity of real-time services a better and more reliable communication is required. Moreover, some of these applications require firm performance guarantees from the PUs. After the source node selects the route, the payoff for the source can be calculated from the throughput experienced by the route. The path will consist of multiple nodes with each node experiencing different payoffs. The payoff of the intermediate node includes the cost incurred while forwarding the traffic from the source node. This cost can be the cost of battery power usage, the level of QoS, the usage period, and many other factors.

3.3 Spectrum Sensing

One of the most important findings from the measurements reported in [67] is that a large portion of the radio spectrum is not in use for significant periods of time in certain areas. Thus, there are a lot of spectrum holes, which are defined as a set of frequency bands assigned (licensed) to a user (primary user) but not utilized. However, the key idea of spectrum utilization can be drastically increased by allowing secondary users to access the spectrum holes that are unutilized by the primary user at certain time and space. Cognitive radio has been proposed as a means achieving such dynamics. A cognitive radio senses the spectral environment over a wide frequency band and exploits this information to opportunistically provide wireless links that can best meet the demand of the user, but also of its radio environments.

	Infrastructure cost	Legacy compatibility	Transceiver complexity	Positioning	Internet connection	Continuous Monitoring
Database Registry	High		Low	x	x	
Beacon Signal	High		Low	x		
Spectrum Sensing	Low	x	High			x

Table 3.1: Spectrum Identification Method

The cognitive-radio devices have two important functionalities: spectrum sensing and adaptation. Initially, before using the channel, SUs have to detect the activities of the primary users. Among different channel detection techniques, sensing-based access to the channel is favored because of its low employment cost and compatibility with the legacy of licensed systems [62]. As shown in Table 3.1, the first two approaches charge the primary systems with the task of providing secondary users with current spectrum usage information by either registering the relevant data (e.g., the primary system's location and power as well as expected duration of usage) at a centralized database or broadcasting this information on regional beacons [68].

A typical duty cycle of CR, as illustrated in Figure 3.2, includes detecting spectrum white space, selecting the best frequency bands, coordinating spectrum access with other users and vacating the frequency when a primary user appears. Such a cognitive cycle is supported by the following functions [82]:

- Spectrum sensing and analysis.
- Spectrum management and handoff.
- Spectrum allocation and sharing.

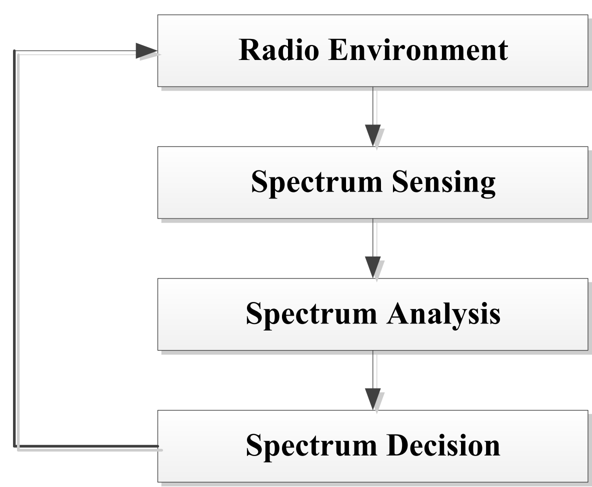

Figure 3.2: Spectrum Sensing Algorithm [82]

In our model, spectrum sensing solely relies on the secondary system to identify spectrum through direct sensing of the licensed bands. In this case the secondary system monitors a licensed frequency band and opportunistically transmits when it does not detect any primary signal. CR is defined as a radio that can autonomously change its transmission parameters based on interaction with the complex environment (radio scene, application and user requirements) in which it operates.

3.4 Spectrum Allocation

In most countries, the spectrum is allocated to PUs using auction theory. PUs compete to get the license for a spectrum. The competitive behavior among PUs was initiated by spectrum auctions held in 2000 and 2001. Auction theory achieved significant success for spectrum in some countries; however, it did not succeed in others [68]. In our work, game theory will be used to model the competition among PUs for the spectrum, among SUs to model the spectrum selection strategies, and between PU and SU.

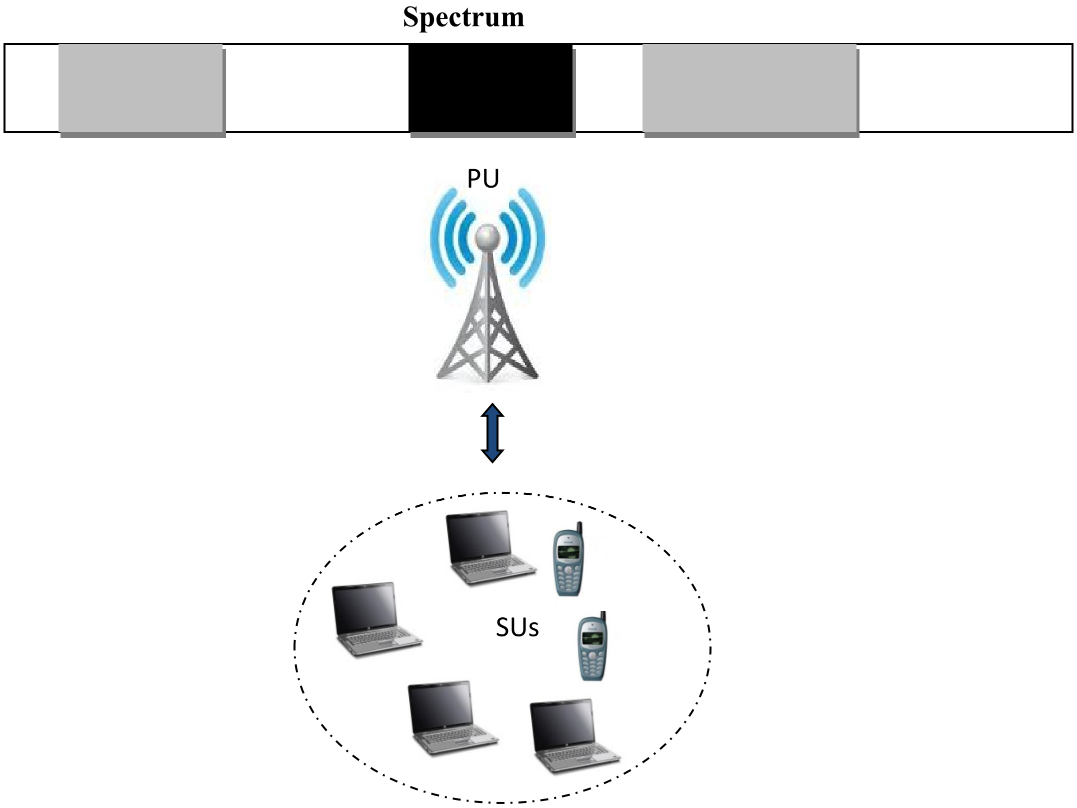

Figure 3.3: The Coupling between PUs and SUs

Traditional spectrum allocations schemes are usually long–term and PUs have exclusive right to access spectrum. Static allocation schemes of spectrum fail to utilize the unused spectrum even if the spectrum owner (PU) is willing to generate more revenue by renting the spectrum to

SUs. In order to utilize unused spectrum efficiently, a new concept of Dynamic Spectrum Allocation (DSA) is proposed. In DSA, spectrum will be allocated dynamically depending on need of the PUs and PUs can trade the unused spectrum. SUs are usually associated with one PU, i.e., get their services from one PU for a period of time. Hence, there is a strong coupling between the SU and PU as shown in Figure 3.3 that does not allow much flexibility to the SUs. Figure 3.3 shows the black holes and gray holes for the spectrum where the black holes are used and the gray holes are unused. However, in our work SUs can select the PU that provides the best quality of service (QoS) and offers the lowest price. SUs take into account several factors when connecting to a PU. These factors include users' preferences – quality of service (QoS), quality of experience (QoE), coverage, price etc. In our modeled spectrum market, SUs will be the customers of one of the PUs that provide the SUs authentication credentials, billing account and access to a spectrum. In our spectrum market there is no strong association between SUs and PU as a SU can choose any provider almost on a session by session basis. In addition to trade free spectrum, PUs use a multitude of access technologies, operating on both licensed and unlicensed bands, to serve an increasing number of customers. In the spectrum market, PUs have to support various services that have varied QoS requirements, for example, video and telephony services are more sensitive to delay than services such as file downloads that are affected by loss. With such loose coupling between PUs and SUs, several questions arise:

- How or which PU should be selected by a SU?
- What price per unit of resource should be offered by PUs such that profit is maximized?

By introducing all the PUs and SUs in a market environment, it becomes convenient to leverage the concept of prices of services to regulate the demands of SUs who consume resources (spectrum). With dynamic spectrum access in effect for PUs, loose coupling exists between PUs and SUs since a SU can be associated with any one of the PU. It is clear that a new economic model needs to be developed. A vast number of options are available for dynamic spectrum allocation.

In our spectrum market, PUs manage the allocation, usage, and pricing of the portions of the spectrum which is unused, or under-utilized. In such a dynamic setting, the question arises, how the spectrum will be allocated from the PU to the SUs and how PUs will determine the price of their services to the SUs? Each PU has to manage the free spectrum and trade the free spectrum and it knows how to obtain the spectrum back when needed. Free spectrum is used to offer services to SUs and generate revenue according to some business strategies.

3.5 Primary User's Requirements:

In this section, we present an overview of spectrum market and we define the primary user's constraints.

3.5.1 Spectrum Market Overview:

A PU can sell portions of the free spectrum to the unlicensed users (secondary users, SUs) who are willing to access the spectrum. SUs pay a PU for spectrum usage. To trade free spectrum, a PU disseminates the trading information to SUs. This information includes:

- The available spectrum.
- The metrics for route.
- The price to be paid to access the spectrum as well as access the route.

After receiving spectrum information and the proposed routes based on secondary user requirements, each SU decides whether to accept the deal or not. PUs allocate spectrum as well as set the path for its customer after receiving SU's approval.

3.5.2 Primary User's constraints:

In the spectrum market, the spectrum owners and the spectrum leasers correspond to the PUs and the SUs, respectively. In this market PU_i rents free spectrum of size $s_i \in S_i$ from its spectrum. PU_i has total available bandwidth of size S_i and charges price p_i (per user per unit time) to the SUs. In our model, the pricing for routing is considered. However, the secondary users send the primary user their requirements and based on that the primary user sets the price for the route. The secondary user has a choice to either accept or not as in Figure 3.4. With this market structure, SUs are free to choose and buy the spectrum that provides the best payoff in terms of performance and price.

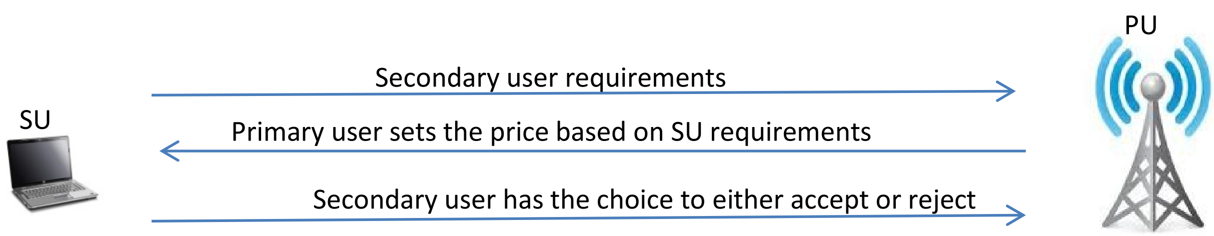

Figure 3.4: Handshaking between a Primary User and a Secondary User.

There are two levels of competition in the spectrum trading market. The competition in the first level is among PUs to sell the unused spectrum to the SUs. If the offered price by PU_i is high, SUs will deviate to buy spectrum opportunities from other PUs. Therefore, each of the PUs must carefully set spectrum prices based on the following:

- Competition with other PUs.
- Spectrum demand.
- PUs requirements.

Each PU must carefully set the price of the offered spectrum so that the payoff of the PU is maximized and the PUs' requirements are met. SUs compete to select the best offered spectrum in terms of spectrum price and quality. For example, if all SUs buy the spectrum from the same PU (i.e. the PU who offers the lowest price), the corresponding spectrum will get congested and the quality of the spectrum will be degraded significantly.

In this case, the PU will increase the price to get more profit because of spectrum demand. As a result, SUs will start looking for other PUs and they will compete to get the spectrum with lower prices and better performance. SUs stop looking for other PUs when the payoff becomes identical to the average payoff of the SUs.

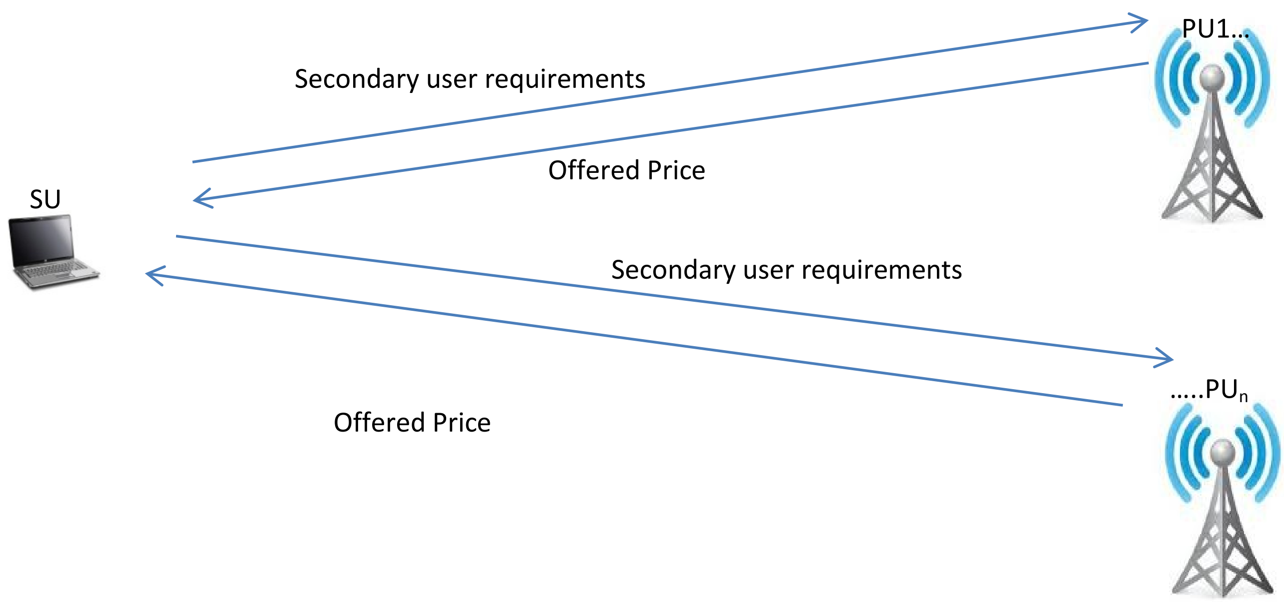

Figure 3.5: Handshaking between multiple PUs with one SU

It is shown in Figure 3.5 that the secondary user sends his requirements to all active primary users and then the primary user will respond by sending the offered price. The secondary user will choose one of the available prices. Undoubtedly, it will select the lowest one.

3.6 QoS for PUs and SUs

In this section, a literature review about QoS in cognitive radio network is presented, the metrics for QoS for SUs and PUs at each path are defined, define mathematical models to evaluate these metrics, propose adaptation algorithms to support QoS for both SUs and PUs, and define new strategies for PUs and SUs to negotiate based on their QoS.

3.6.1 QoS Levels for secondary users in our model

In this work, the QoS is classified to three different levels. A novel function is introduced to control the level of QoS and price. The QoS function $f(L_{QoS})$ is defined as follows:

$$f(L_{QoS}) = QoS_{level} * \ln(b). \tag{3.1}$$

where QoS_{level} may take a value of 1, 2 or 3, depending upon the QoS level requested, and b is the size of spectrum traded to the secondary user. The first level is the lowest level of QoS service, the second level is the middle level of QoS service, and the third level is the highest level of QoS service.

- The First Level contains the following metrics:
    - Delay
    - Transmission Rate
- The Second Level contains the following:
    - Level 1 metrics
    - Link robustness
- The Third Level contains the following:
    - Level 2 metrics
    - Expected Transmission Count (EXT)

3.6.2 QoS metrics in our model

In this section, the metrics in each level are described and how the metrics affect the performance of Cognitive Radio Network.

3.6.2.1 Delay and Transmission Rate

Delay is an important QoS parameter in any wireless network. It is well known that CRN users are expected to experience, by default, widely varied delays due to uncertainty of channel availability. Compared to existing wireless networks, delay analysis attains a complex scenario in CRN due to the presence of PUs. Delay constraint needs to be considered in determining the number of secondary users supported or number of channels to be sensed or number of radio interfaces required by a single secondary user. In [76, 77] the authors developed scheduling models for secondary network to analyze the performance of packet delivery time. Scheduling model in [77] considers different priority among SUs where they are forced to stay in the same channel.

To the best of our knowledge, delay in CRNs is the combination of two components: the information propagation delay and the queuing delay: The information propagation delay is the total amount of time that a packet spends in traveling over the intermittent relaying links in a CRN and is determined by the underlying communication capabilities of the network. The queuing delay is the amount of time that a packet spends in waiting for other packets to finish their transmission and is determined by traffic load and scheduling algorithms in CRNs. In our model, one more constraint is added to control the delay, the probability of channel availability, $Prob_k$:

$$Prob_k = n_{Id} * t_{Id} / (t_{busy} + n_{Id} * t_{Id}) \tag{3.2}$$

where n_{Id} is the total number of idle period, t_{Id} is the time of each idle period, and t_{busy} is the busy time of channel. Transmission rate is more related to the bandwidth of channel as well as the packet size. There is no constraint considered in this thesis to control the transmission rate because this metric will vary based on the offered bandwidth from the intermediate nodes (either SU or PU).

3.6.2.2 Link robustness

The "Link Robustness" metric is offered in this work for level 2 QoS. This metric is very important for maximizing the throughput and to guarantee the stability of service. Once the robustness is selected, the spectrum to be allocated on each link along the selected route is determined. In cognitive radio network, this metric means the presence of PU. In this work, the probability of PU presence is calculated as follows:

$$Prob_{PU} = P_{link} * Prob_k \qquad (3.3)$$

In equation 3.3, the previous constraint $Prob_k$ is added to guarantee level 1 of QoS within the level 2 QoS and P_{link} is the measurements of the loss probability.

3.6.2.3 Expected Transmission Count (EXT)

This metric is required for level 3 QoS, which is considered as the highest level and a higher price among other levels as well. The primary goal of the ETX design is to find paths with high throughput, in spite of losses. The derivation of ETX starts with the measurements of the loss probability, denoted by P_{link}, to calculate the expected number of transmissions. The cognitive radio network requires that for a transmission to be successful, the packet must be successfully delivered to each intermediate node until the destination node. ETX is calculated as follows [83]:

$$ETX(link) = 1 / (P_{link}) \quad (3.4)$$

$$ETX(Path) = \sum (ETX(link)) \quad (3.5)$$

3.7 Summary

In this chapter, three important parts were discussed; the first part is the secondary user requirements, the second part is the primary user requirements, and the third part is different QoS levels. The secondary user's flow was defined. The mechanism of spectrum sensing as well as the spectrum allocation was reviewed. In addition, the spectrum market overview was presented and the primary user's requirements were presented as well. Finally, the QoS levels function were described and defined where this function consists of three levels. Next Chapter describes the proposed models as well as the QoS based route algorithm.

Chapter 4: QoS based Routing Algorithm for CRN

In this chapter, the system model that consists of base station cost, intermediate node cost, price function, and profit function is introduced. The stages of our model are presented and the QoS based route algorithm is introduced with an example. Finally, all proposed equations are simulated. Two different approaches to describe the system modeled are presented. First, the model is described without game theory. Some of the steps of this model apply also to the model using concept of game theory, which is described next.

4.1 System Model without Game Theory

In this section, the equations of our model without using the concept of game theory are described.

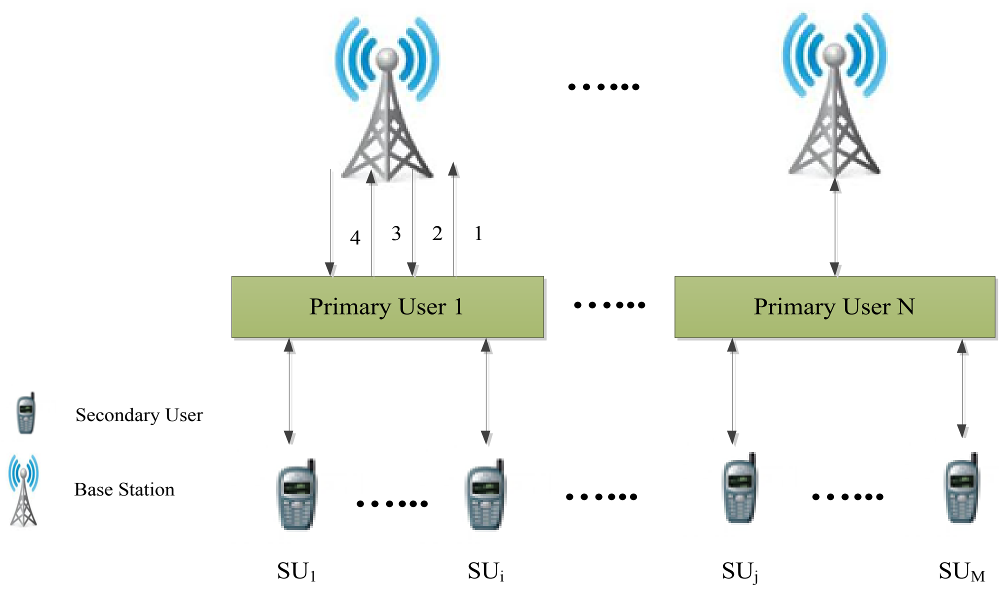

Figure 4.1: System Model between PU and Base Station

The stages of our model without concepts of game theory are shown in Figures 4.1 and 4.2 wherein the preliminary stage (Figure 4.1) is between the primary user and its base station, and the main stages (Figure 4.2) are between the primary user and the secondary user. The steps between a PU_i and its base station as shown in Figure 4.1 are: 1) PU_i requests base station for channel k_i that has spectrum S_i with bandwidth BW_i, 2) base station calculates the base station cost C_{BS} and sends it to the primary user, 3) PU_i may or may not accept the deal and sends its response to the base station, 4) base station based on PU's decision in the previous step will either allocate the spectrum or release the request.

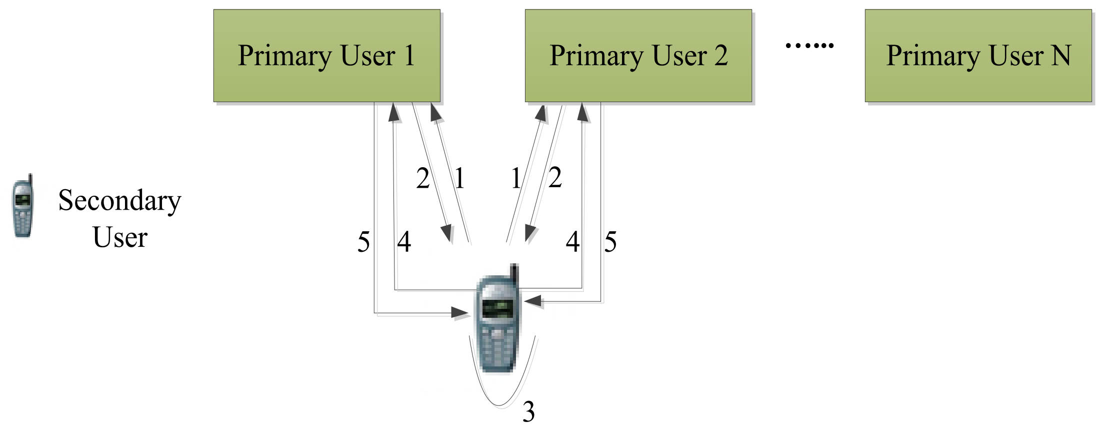

Figure 4.2: System Model between PU and SU

Figure 4.2 shows the following steps: 1) a secondary user requests primary users for channel or portion of channel with the requested spectrum size, the bandwidth size, as well as the level of QoS, 2) primary user checks the availability of spectrum for the QoS level requested, calculates the price considering other PUs as sellers, and sends it to the secondary user, 3) and 4) secondary user checks other offers received and chooses the best with least price offered and better QoS, 5) primary user responds to the secondary user's decision of accepting the primary user by allocating the spectrum; otherwise, the request is dropped. In the next subsection, spectrum trading is introduced.

4.1.1 Spectrum Trading between PUs and SUs

In spectrum trading, the main concern of PUs is to maximize their own revenue while supporting the QoS for SUs. PUs trade the extra (unused) spectrum to the SUs to maximize their revenue. For spectrum trading, one of the challenging issues is pricing. In our model, the design of the price function answers the following: how to set the spectrum price in a competitive environment where multiple sellers offer spectrum to the buyer, so that the sellers (e.g., primary users) are satisfied and their profits are maximized. The spectrum pricing in cognitive radio network is discussed in this thesis in Section 2.1. Moreover, the price in our model consists of:

- The initial stage occurs when the secondary user sends its requirements as well as the required level of QoS to the available PUs.
- In the second stage, after the PU calculates its price, it calculates α as in equation 4.8 and 4.9 to obtain the total price, which is then sent to the SU. This factor could be helpful in attracting more demands from SU.

The proposed price function is very dynamic and efficient because all the agents that could affect the service (e.g. path and spectrum) are considered. In the next subsection, the revenue functions are introduced.

4.1.2 Revenue Functions

The problem of competitive pricing in a cognitive radio network is addressed where the primary users offer spectrum access opportunities to a secondary user. This problem is formulated as an oligopoly market where few firms (PUs) compete with each other in terms of price in order to get the highest profit. For the primary user, the cost of renting the spectrum to secondary users is defined as a function of the quality of service (QoS), data transmission rate, and the spectrum size. This function is called P_{PU}, as shown in equations 4.5. For the intermediate secondary user, a spectrum cost function is established based on the spectrum size, which depends on the channel quality (QoS level). This cost is called intermediate cost C_{SU} as in equation 4.4. In addition we assume that PUs can get the channels from base station for a certain cost called C_{BS}, as in equation 4.1. The equations are introduced as follows:

Each PU would first pay a cost to base station to provide a channel for the SU. This cost will be a part of the price. The base station cost is calculated as follows:

$$C_{BS} = \log (BW_k) * k * t * P_{BS}. \tag{4.1}$$

where BW_k is the bandwidth of k channels provided by base station (BS) to the primary user, t is the time of using the k channels, and P_{BS} is the unit price specified by base station based on PU request. The price of each channel is defined by PU such that the profit of that channel is maximized. Hence, the profit earned by renting channels is as follows:

$$Profit = k * P_{total} - C_{BS} - C_{SU} \tag{4.2}$$

where k is the number of channels assigned to a SU, P_{total} is the offered channel price for SU as in equations 4.6a and 4.6b, C_{BS} is the base station cost as in equation (4.1), and C_{SU} is the cost paid to the intermediate nodes, defined in equation 4.4. A novel function to control the level of QoS and price is introduced. This novel function called the QoS function $f\,(L_{QoS})$ is defined as follows:

$$f\,(L_{QoS}) = QoS_{level} * \ln (b). \tag{4.3}$$

where QoS_{level} may take a value of 1, 2 or 3, depending upon the QoS level requested, and b is the total size of spectrum traded to the secondary user.

The C_{SU} is the cost, which is paid by the PU to rent spectrum from an intermediate node, and is defined as follows:

$$C_{SU} = f(L_{QoS}) * b_{SU} * P_{SU}. \quad (4.4)$$

where $f(L_{QoS})$ is the QoS function for the path selected, b_{SU} represents the size of the spectrum rented from intermediate nodes and P_{SU} is the unit spectrum price for intermediate nodes. The price function P_{PU} calculated by PU to increase its revenue is defined as follows:

$$P_{PU} = W * \ln(b) + \omega * P * b + \omega * f(L_{QoS}) \quad (4.5)$$

where W is the data transmission rate, b is the size of spectrum traded to the secondary user, ω is the number of customers (SUs that request one channel or more), P is the unit price for the spectrum traded, and $f(L_{QoS})$ is the function of QoS. The total and competitive price follows the next equations:

$$P_{total} = P_{PU} \quad ; \alpha = 1 \quad (4.6a)$$

when there is no competitive primary. If there is no available channel ($\alpha = 0$) $P_{total} = \infty$. The equation 4.6b is the normal case where there are some competitive primary users, some available channels, and a usage period.

$$P_{total} = \alpha * P_{PU} + A \qquad ; 0.1 < \alpha < 0.99 \quad (4.6b)$$

A is a constant that signifies the effect of a number of PUs and SUs on offered price. If the number of competitive PUs is higher than the number of SUs requesting spectrum, the offered price should be lowered. It is calculated as follows:

$$A = \chi - \theta. \quad (4.7)$$

where θ is the number of competitive PUs and χ is the number of customers (SUs that request one channel or more). In the following sub-section, the spectrum competition is described.

4.1.3 Spectrum Competition among PUs

In this model, there are multiple primary users that offer a spectrum to multiple secondary users based on their price. A PU competes with other PUs by offering a suitable price to the secondary users. A new coefficient α ($0 < \alpha < 1$), called competition factor is defined. A PU selects the value of this coefficient by considering the number of PUs offering that channel, the usage period of the offered channel, and the probability of its presence. The competition factor function is described in the following function (equations 4.8a, 4.8b, and 4.8c).

$$\alpha = 1, \quad \text{when the number of primary user} = 1 \tag{4.8a}$$

$$0.1 < \alpha < 0.99, \quad \text{the normal case} \tag{4.8b}$$

$$\alpha = 0, \quad \text{when there is no available channel} \tag{4.8c}$$

If no other PU offers the requested channel, $\alpha = 1$, which means the price remains same and is not adjusted. If there is no available channel, $\alpha = 0$, which means the price offered is 0. However, if there are a number of primary users with available channel for the request as well as the usage period of the offered channel, the PU chooses an appropriate value for α ($0.1 < \alpha < 0.99$) to reduce the total price as per the following equation.

$$\alpha = (\psi+\kappa+\chi+\tau) / ((\psi+\kappa+\tau)+\tau*\psi) \tag{4.9}$$

where ψ is the number of PUs offering the path, κ is the number of channels, χ is the number of SUs requesting a specific channel, and τ is the usage time of the channel. In Figure 4.3, the equation 4.9 is simulated to see the effect of competition factor. Figure 4.3 shows the effectiveness of α value due to the total price (offered); $\alpha 1$, $\alpha 2$, and $\alpha 3$ is used where $\alpha 3 > \alpha 2 > \alpha 1$. So when α is increased the total (offered) price will be increased. In addition, when the numbers of primary users becomes larger, the total price offered remains the same even if α is changed. The reason of not changing the total price when the numbers of primary users is large is that, as a market nature, the primary user cannot let the offered price decrease until it reaches zero. The cognitive nodes are randomly placed in 300x300 m^2 and the transmission range is 150 meters. The usage time considered is three hours. However, the number of cognitive nodes in CRN is changeable. The length of packet size is 64Kbit. The values considered for $\alpha1$, $\alpha2$, and $\alpha3$ are for example sake only.

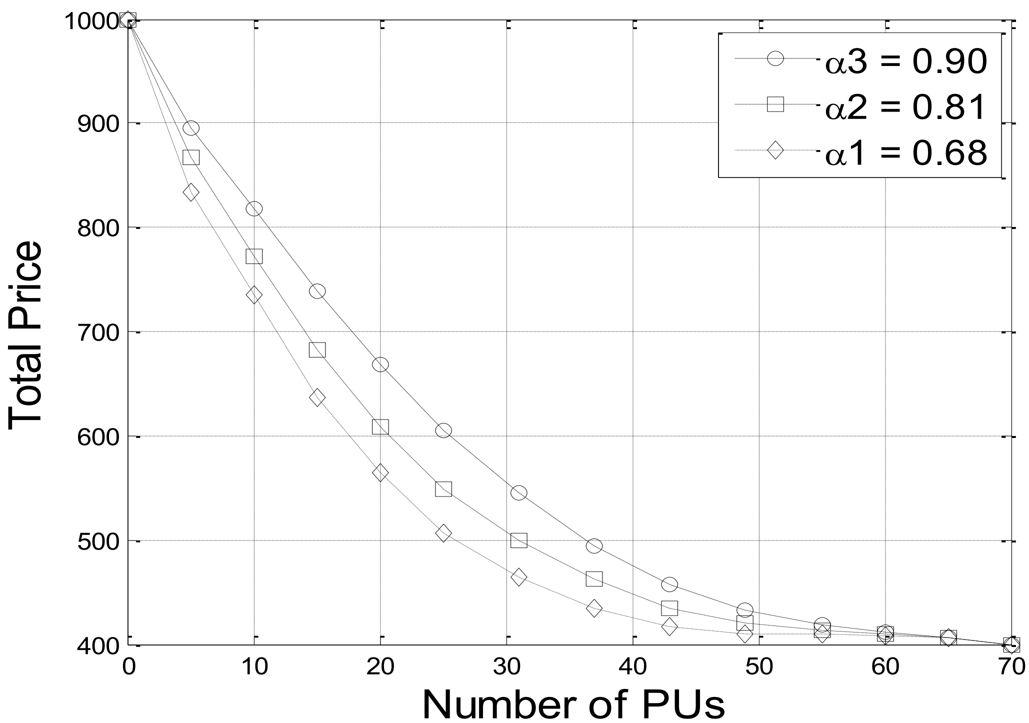

Figure 4.3: The Effectiveness of Competition Factor against Profit

Moreover, the parameters that the alpha value depends on are changed. The parameters are shown in Table 4.1.

Legend id	No. of SUs	No. of channels	Usage period in hour
X1	4	2	2
X2	14	4	5
X3	24	6	10

Table 4.1: Parameters used to simulate alpha equation in Figure 4.4

The parameters in Table 4.1 are used to simulate the alpha equation. Figure 4.4 shows how the alpha changes according to the parameters in Table 4.1. X_1, X_2, and X_3 are used as legends to represent the different values of parameters. The alpha values in X_1 is always greater than in X_2 and X_3 because the values of parameters in X_1 such as the number of SUs, the number of channels, and the usage period are less than the corresponding values in X_2 or X_3. The PU therefore has the liberty to choose the value of alpha to be higher. However, the values of α for X_2 and X_3 are not too different because when the values of parameters become high, the alpha value will not be that much affected.

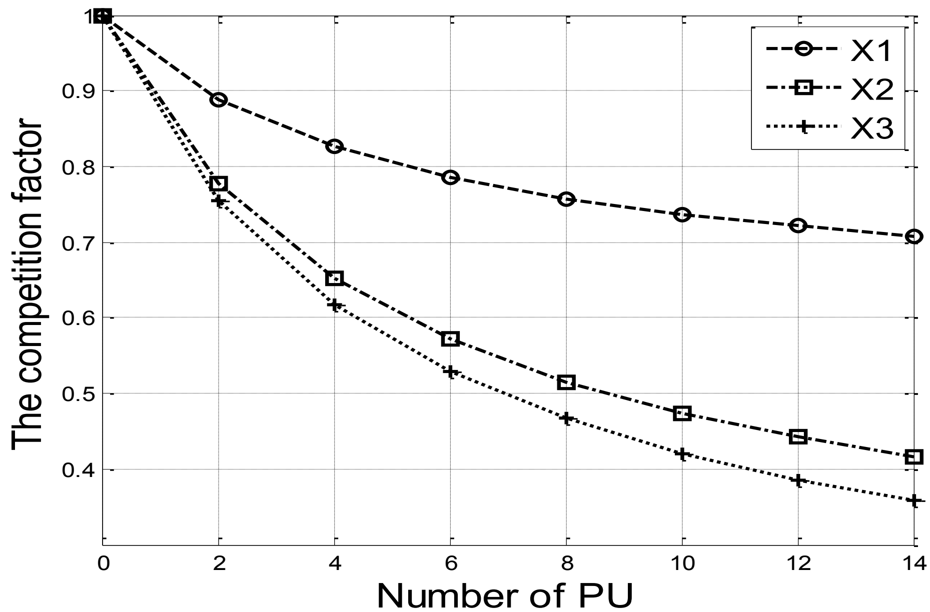

Figure 4.4: The Competition Factor based on Three Different Network Scenarios

4.2 System Model Stages

In this section, the various stages of our models are described. There are four stages; the preliminary stage, the first stage, the second stage, and the third stage. This section also describes the algorithm for our models, which is used to find a path for SU based on its requirements. In addition, this algorithm is used to calculate the price for the spectrum offered and the profit for PU is calculated as well.

4.2.1 Preliminary stage:

In the preliminary stage as in Figure 4.5, each SU shares its profile vector with its sensed PUs, which then exchanges their profiles among each other. Two kinds of profile are defined, the SU profile and the PU profile; each profile contains multiple records.

- Secondary User Profile: $Profile_{SUi}$ = {$Profile_{id}$, SU_{id}, k_{id}, PU_{id}, $neighbor_{count}$, [$neighbor_{id}$], $Prob_k$, $Prob_{PU}$, P_{link}, BW}, where $Profile_{id}$ is the ID for SUs' profile, SU_{id} is the secondary user id, [$neighbor_{id}$] is a vector that contains the list of SU's neighbor ID, k_{id} is id of channel, PU_{id} is the id of primary user that offers the channel k_{id}, $neighbor_{count}$ is the number of neighbors, and $Prob_k$ is probability of idle slots to busy slots as defined in the Chapter 3(equation (3.4)). $Prob_{PU}$ is the probability of PU presence, BW is the bandwidth of the channel (spectrum), and P_{link} is the probability for link robustness as defined in the Chapter 3(equation (3.5)).
- Primary User Profile: $ProfilePU_j$ = {$Profile_{id}$, $Profile_{SUi}$, PU_{id}, $Prob_k$, $Prob_{PU}$, P_{link}}, where $ProfileSU_i$ is the profiles from SUs, PU_{id} is the id of the PU profile sender.

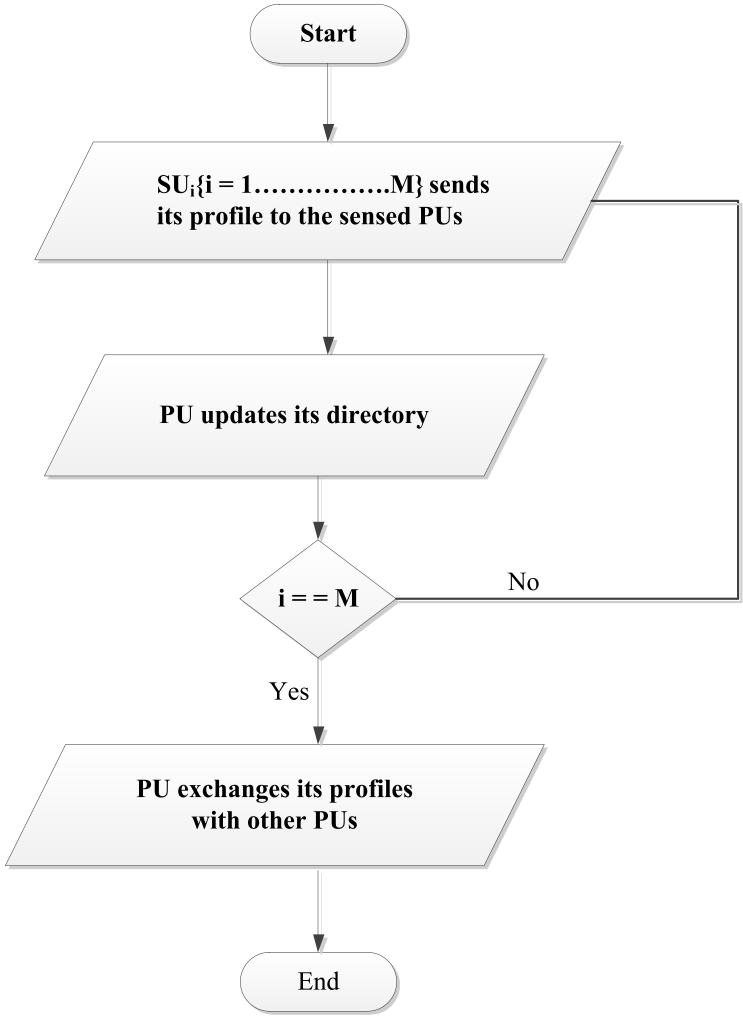

Figure 4.5: Flow Chart for Profile Exchange

4.2.2 The First Stage

In the first stage, a secondary user sends its request for a destination with the required level of QoS to each of its sensed PUs. In addition, each sensed PU checks the destination that is requested by SU, and checks the availability of spectrum along its path. Each sensed PU also checks the QoS level as per SU's requirements and computes the price according to the equations (4.6a or 4.6b). The flow chart of this stage is represented in Figure 4.6. The steps for this stage are as shown below:

- Step 1: checks the availability of the destination

- Step 2: check the availability of total spectrum
- Step 3: checks the SU requirements
- Step 4: If step 1, 2, or 3 not satisfied, PU sends to SU that the service is not available
- Step 5: if step 1, 2, and 3 are satisfied, it transfers to the second stage

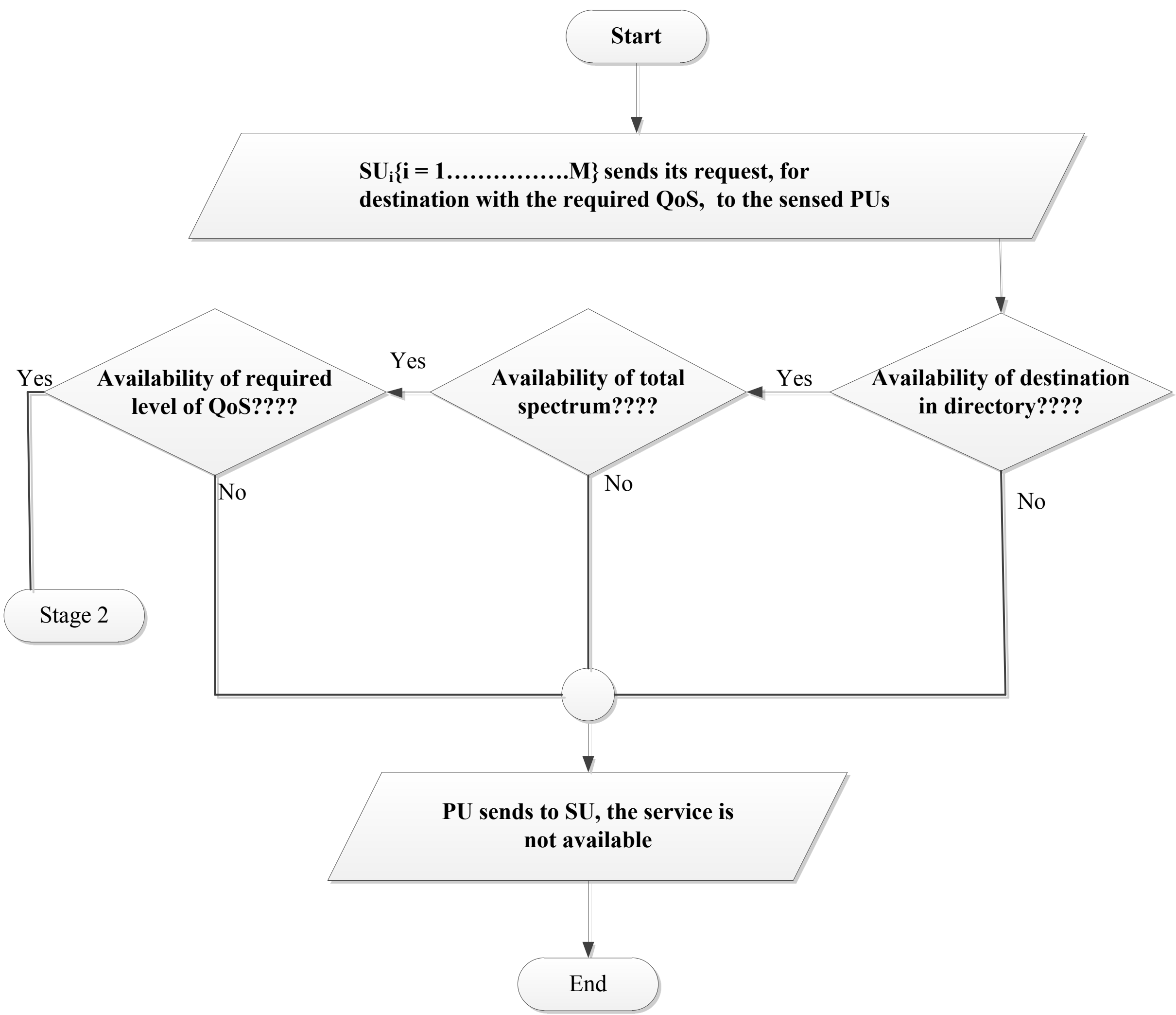

Figure 4.6: Flow Chart for the First Stage

4.2.3 The Second Stage

PUs adjust their price according to equation (4.6) considering other PUs in competition. Each sensed PU finally sends this price to SU. The flow chart of this stage is represented in Figure 4.7.

It is clear from Figure 4.7 that if there is no other PU, the $P_{total} = P_{PU}$; otherwise PU must select an appropriate value for α. The steps for this stage are as shown below:

- Step 1: check the intermediate cost C_{SU}, compute $f\,(L_{QoS})$, and compute P_{PU}.
- Step 2: check the number of competitive PUs and obtain α, to compute P_{total}
- Step 3: compute the price by taking into consideration of other PU
- Step 4: in step 3, once the P_{total} is computed, it sends to SU
- Step 5: it transfers to stage 3

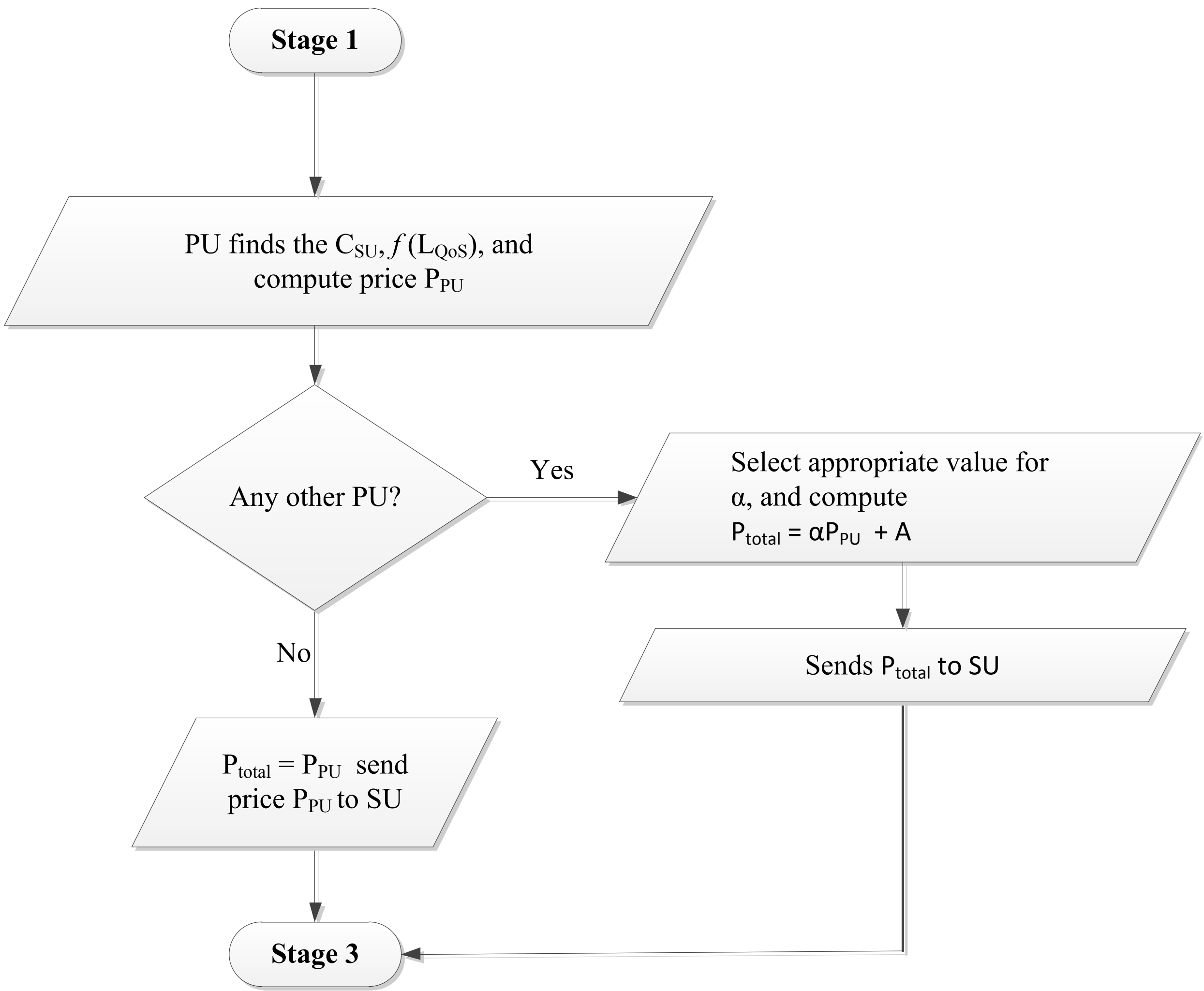

Figure 4.7: Flow Chart for the Second Stage

4.2.4 The Third Stage

The SU receives different prices from different PUs and will look for the lowest price for the level of the quality of service requested. Finally, the PU accepted allocates the spectrum and sends the path address to the SU. Figure 4.8 shows the flow chart for this stage. The steps for this stage are as shown below:

- Step 1: SU sets an initial value for the price (e.g. min = 0)
- Step 2: SU compares with the received price values; if the value received is less than min, the value of min is updated.

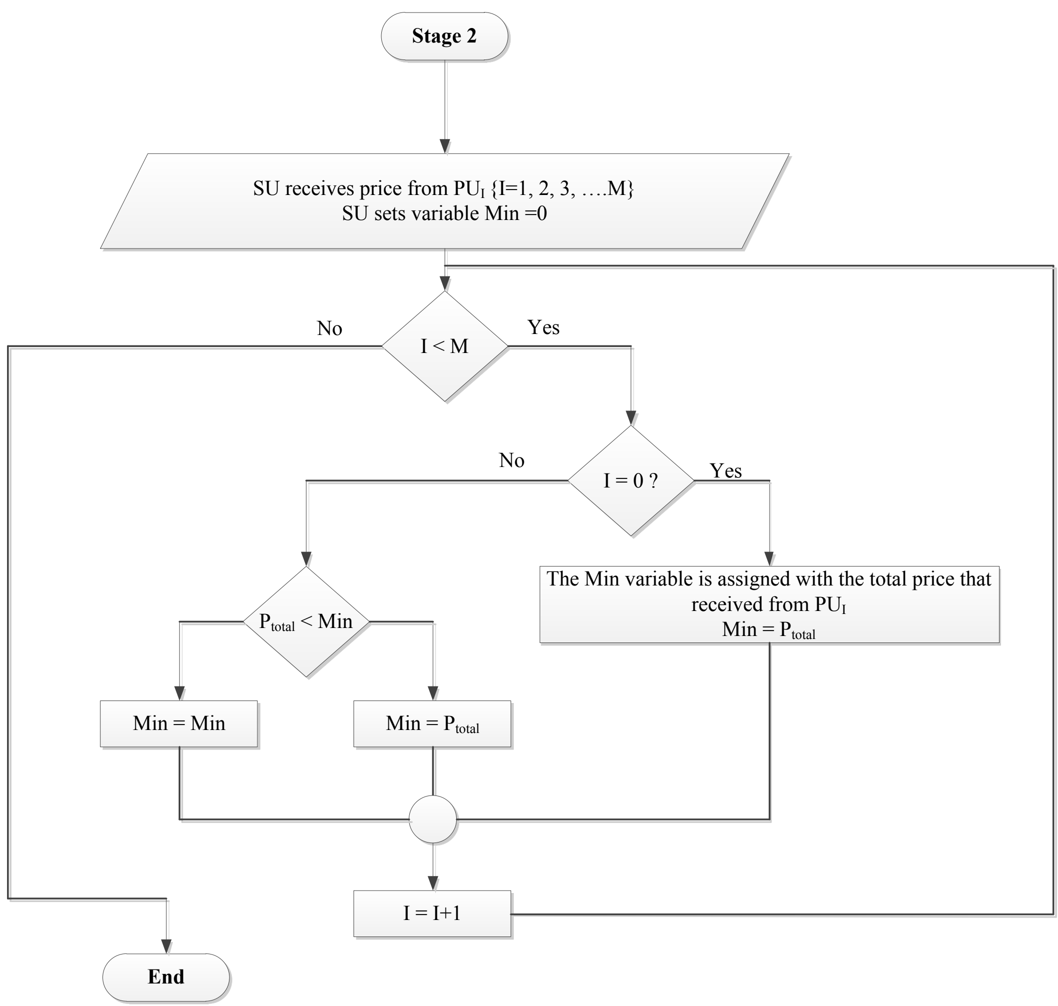

Figure 4.8: Flow Chart for the Third Stage

4.3 Route Management Algorithm

Algorithm shows the previous stages as pseudo-code, this algorithm describes profiles exchange, searching for the destination with QoS requested from SU, and calculating the costs as well as the profit.

Route Management Algorithm

Parameters:

// Profile that shows the channels with SU and parameters related to that channel such as bandwidth, PU owner, neighbors, and the probabilities of that channel.

$Profile_{SUj}$ ($Profile_{id}$, SU_{id}, k_{id}, PU_{id}, $neighbor_{count}$, [$neighbor_{id}$], $Prob_k$, $Prob_{PU}$, P_{link}, BW_k)

M: the set of SUs

N: the set of PUs

K: the set of channels

U: is the set of nodes in the network

T_P: profile table for PU

$L = \{l_1, l_2, l_3, l_4, \ldots\ldots\ldots, l_U\}$: the set of nodes,

$SU_j \in M$

$PU_i \in N$

$A_s \in$ L: source node

SU_d: destination node

V: Array to store the path

Request (R_{id}, SU_{d}, f (L_{QoS}))

// R_{id} the request id, SU_d is the destination id, and the *f (L_{QoS}) is QoS function.*

Response (RP_{id}, V [])

// RP_{id} is the response profile id, *V []* is the array of the intermediate nodes until destination

Functions:

Save (X1, X2, X3, X4, X5, X6 [], X7, X8, X9, X10), a function to save the parameters of profile into profile table.

$Save_{PU}$ (X11 []), a function to exchange the profiles only among PU

$Cost_1$ (X12 []), a function to calculate the price P_{PU} // 1 represents the QoS level

$Cost_2$ (X13 []), a function to calculate the price P_{PU} // 2 represents the QoS level

$Cost_3$ (X14 []), a function to calculate the price P_{PU} // 3 represents the QoS level

InterCost (X15 []), a function to calculate the intermediate cost

BaseStationCost (X16 []), a function to determine the initial base station cost

Total (X17 []), a function to calculate the total price P_{total}

Search (X18, X19 []), a function to find matching entry in the profile table for destination (SU_d)

Check (), a function to check the number of competitive PUs

Send (), a function to send the price to SU

Receive (), a function to check if an SU accepts the price.

Response (), a function to send the response profile from PU to SU, if SU accepts the deal

// Lines 1-9: Preliminary Stage

1: Begin
2: for each $SU_j \in M$
3: // we define for each SU belong to the network a profile called $Profile_{SUj}$
4: Save ($Profile_{id}$, SU_{id}, k_{id}, PU_{id}, $neighbor_{count}$, [$neighbor_{id}$], $Prob_k$, $Prob_{PU}$, P_{link}, BW_k)
5: end for
6: for each $PU \in N$
7: // basically, each PU exchange with each neighbor (PU) Profiles
8: $Save_{PU}$ ($Profile_{PU}$) // to exchange the profiles only among PUs
9: end for

// Lines 10-12: First Stage.

10: if Search (SU_d, f (L_{QoS})) = 0 // Search for SU_d and available spectrum,
// Search for level of QoS requested in profile table
11: Exit ()
12: else go to step 14.
13: end if

// Now after checking the destination, level of QoS, and availability of spectrum - If all are satisfied, the price is calculated and finally it is sent to user.

// Lines 14-52: Second Stage

14: if f (L_{QoS}) == 1 // the level 1 of QoS
// now to find the path we define S: current nodes,
// Z: the current sum of $Prob_k$
15 Level1 [] = $Prob_k$ // because it is level one so the constraints is saved for
// level one in this array
15: for i=1 to W // W is the number of entries in profile table
16: Z (Li) = 0
17: Z (As) = 1
18: end for
19: for i_1=1 to ∞
20: for i_2=1 to W

```
21:             if Z (i_2) ==0                          // if unknown
22:                 temp = [temp Level1 (A_s, i_2)]
23:                     else
24:                         temp = [temp ∞]
25:             end if
26:             end for
27:     [A, B] = min (temp)                         // to store the minimum delay
28:     L = [L A]                                   // to store node for path
29:     temp = []
30:      A_s = B
31:     Z (A_s) = 1
32:     L = [L A_s]
33:     if A_s == SU_d
34:     break
35:     end if
36:     end for                                 // for line 19
```

// after finding the path, the path will be sent to each function to do the calculation; the functions are Intermediate cost and price function.

```
37:     BaseStationCost (L)                         // as per equation 4.1
38:     InterCost (L)                               // as per equation 4.4
39:     Cost_1 (L)                                  // as per equation 4.3
40:     Profit = Cost_1- BaseStationCost – InterCost // as per equation 4.2

41:     else if  f (LQoS) = = 2                     // the level 2 of QoS

                    // the values of level 1 and level 2 are obtained from profile table.
                    // Min ∑ (Prob_PU / Prob_k) is calculated through steps from 15 to 36

42:     BaseStationCost (L)                         // as per equation 4.1
43:     InterCost (L)                               // as per equation 4.4
44:     Cost_2 (L)                                  // as per equation 4.3
45:     Profit = Cost_2 – BaseStationCost – InterCost // as per equation 4.2

46:     else if f (L_QoS) = = 3                     // the level 3 of QoS

                // the values of level 1, level 2 and level 3 are obtained from profile table
                // Min ∑ ((Prob_PU * ETX) / (Prob_k) is calculated through steps from 15 to 36

47:     BaseStationCost (L)                         // as per equation 4.1
48:     InterCost (L)                               // as per equation 4.4
49:     Cost_3 (L)                                  // as per equation 4.3
50:     Profit = Cost_3 – BaseStationCost – InterCost // as per equation 4.2
51:     end if
52: end                                             // end for begin
```

The following algorithm shows how SU deals with the price received from different PUs. The SU sends ACK to the PU of which the price is accepted. After that PU sends the response profile which contains the path nodes id.

Route Management Algorithm (SU-Side)

Parameters:

// SU receives prices from different PUs. SU compares these prices and decides the one to be accepted.

// Line 1-24: Third Stage

$Q \in N$: is the sub-set of available PUs

P_{total}: the total price that is offered to SU

Min: the temporary variable

I: a variable to check if SU receives P_{total} from available PUs

I_2: a value indicates the number of elements that belongs to Q

ID: the PU who has offered the smallest price.

Functions:

Send (C, B), a function to send the acknowledgment to accept the price or not

// Lines 1-19: To find the smallest price.

```
 1: Begin
 2:      for each PU_I ∈ N
 3:        Receive (P_total)
 4:        Min = 0                          // initiate the temporary variable
 5:      end for
 6       for I =0 to N
 6:                if I >I_2
 7:        Exit ()
 8:                else if I = = 0
 9:                Min = P_total
10:                 ID = PU_id
11:                I = I + 1
12:                else if P_total < Min
13:                Min = Ptotal
14:                I = I + 1
15:                else
16:                Min = Min
17:                I = I + 1
18                      end if
```

```
                end if
    endif

  Send (ACK, ID)                      // SU sends its ACK to ID

end
```

4.4 Example: Profile Management and Path Selection

In this section, a simple example is studied to understand how the calculation and management are going on. Hence, there is a network, with two primary users and five secondary users, is assumed in Figure 4.9:

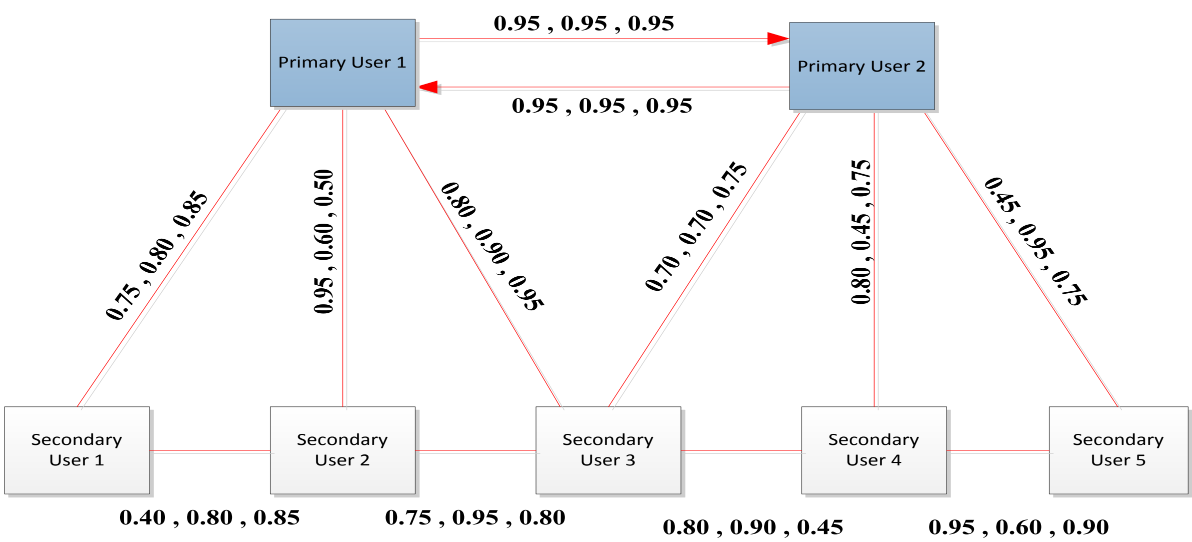

Figure 4.9: Scenario consists of 2 PUs and 5 SUs

The stages are as follows:

- Preliminary stage: It consists of two phases: In the first stage each SU sends its profile to the sensed PU, and in the second stage PUs exchange among each other the received profiles, as shown in Figure 4.10 and Figure 4.11, respectively.

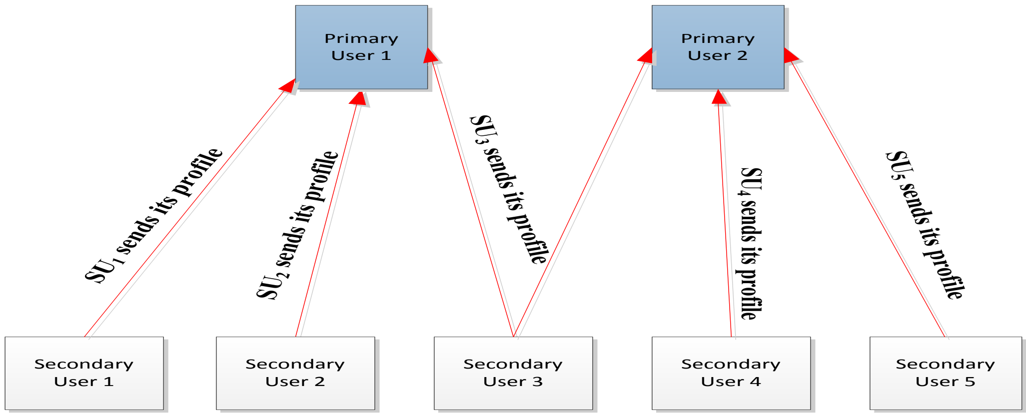

Figure 4.10: Profile Exchange

- In this stage, each PU will create its table as in Table 4.2 and 4.3

Profile$_{id}$	**SU$_{id}$**	**k$_{id}$**	**PU$_{id}$**	**neigbor$_{count}$**	**neigbor$_{id}$**	**Prob$_k$**	**Prob$_{PUk}$**	**Prob$_{link}$**	**Bandwidth (BW)**
SU_1^1	SU_1	k_{PU1}	PU_1	1	SU_2	0.40	0.80	0.85	100 KHz
SU_2^1	SU_2	k_{PU1}	PU_1	2	SU_1 , SU_3	0.40,0.75	0.80,0.95	0.85,0.80	150 KHz
SU_3^1	SU_3	k_{PU1}	PU_1	1	SU_2	0.75	0.95	0.80	200 KHz
SU_3^2	SU_3	k_{PU2}	PU_2	1	SU_4	0.80	0.90	0.45	300 KHz

Table 4.2: Profile lists in PU_1

Profile$_{id}$	**SU$_{id}$**	**k$_{id}$**	**PU$_{id}$**	**neigbor$_{count}$**	**neigbor$_{id}$**	**Prob$_k$**	**Prob$_{PUk}$**	**Prob$_{link}$**	**Bandwidth (BW)**
SU_3^2	SU_3	k_{PU2}	PU_2	1	SU_4	0.80	0.90	0.45	300 KHz
SU_3^1	SU_3	k_{PU1}	PU_1	1	SU_2	0.75	0.95	0.80	200 KHz
SU_4^1	SU_4	k_{PU2}	PU_2	2	SU_3,SU_5	0.80,0.95	0.90,0.60	0.45,0.90	300 KHz
SU_5^2	SU_5	k_{PU2}	PU_2	1	SU_4	0.95	0.60	0.90	300 KHz

Table 4.3: Profile lists in PU_2

- Now after the SUs finish sending their profile, PUs start exchange what they have between each other as in Figure 4.11.

Figure 4.11: Profile Exchange among PUs

If PU receives a duplicate profile, PU will discard it otherwise the update will be done. If any SU request for any connection to specific destination, the search will be processed. So the total table for both PU_1 and PU_2 becomes as follows (Table 4.4):

$Profile_{id}$	**SU_{id}**	**k_{id}**	**PU_{id}**	**$neigbor_{count}$**	**$neigbor_{id}$**	**$Prob_k$**	**$Prob_{PUk}$**	**$Prob_{link}$**	**Bandwidth (BW)**
SU_1^1	SU_1	k_{PU1}	PU_1	1	SU_2	0.40	0.80	0.85	100 KHz
SU_2^1	SU_2	k_{PU1}	PU_1	2	SU_1 , SU_3	0.40,0.75	0.80,0.95	0.85,0.80	150 KHz
SU_3^1	SU_3	k_{PU1}	PU_1	1	SU_2	0.75	0.95	0.80	200 KHz
SU_3^2	SU_3	k_{PU2}	PU_2	1	SU_4	0.80	0.90	0.45	300 KHz
SU_4^1	SU_4	k_{PU2}	PU_2	2	SU_3,SU_5	0.80,0.95	0.90,0.60	0.45,0.90	300 KHz
SU_5^2	SU_5	k_{PU2}	PU_2	1	SU_4	0.95	0.60	0.90	300 KHz

Table 4.4: Total profiles in the network for both PUs

Now if SU_1 wants to connect or send packets to SU_5, in our example (Figure 4.9) some possible ways are:

A) $Path_1$

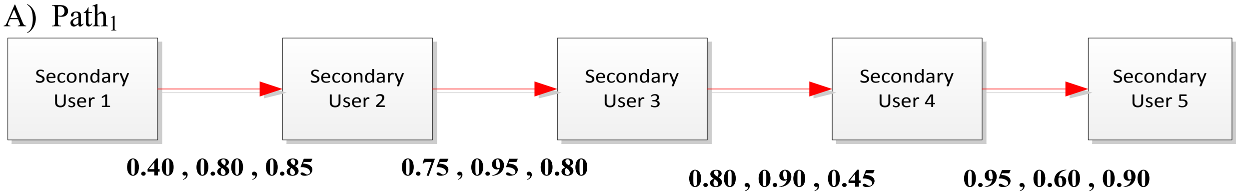

Figure 4.12: $Path_1$ from SU_1 to SU_5

For the path in Figure 4.12, the equations 3.4, 3.5, 3.6, and 3.7 in Chapter3 are used to get the following values: $Prob_k = (0.40 + 0.75 + 0.80 + 0.95) / 4 = 0.73$, $Prob_{PU} = (0.8 + 0.95 + 0.90 + 0.60) / 4 = 0.81$, $ETX = \sum (1 / P_{link}) = (1 / 0.85) + (1/0.80) + (1/0.45) + (1/0.90) = 5.7$

B) $Path_2$ as in Figure 4.13

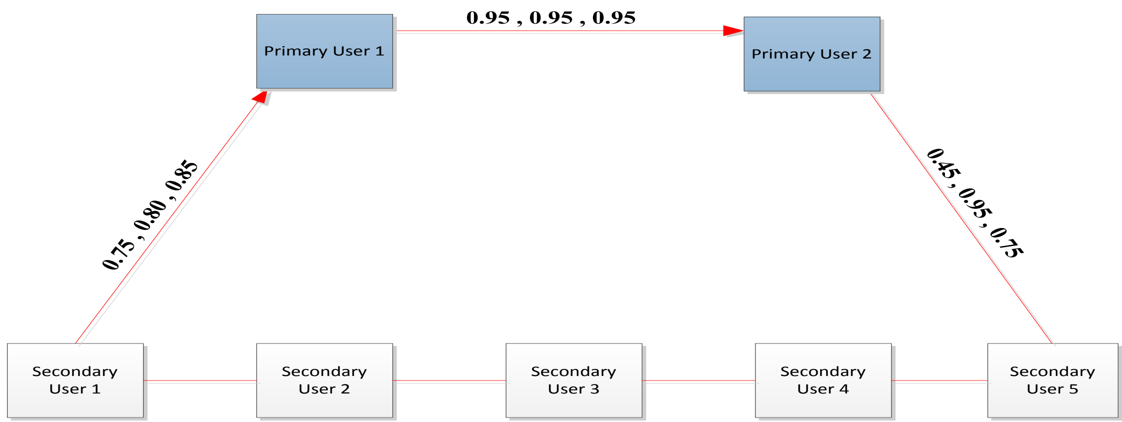

Figure 4.13: $Path_2$ from SU_1 to SU_5

$Prob_k = (0.75 + 0.95 + 0.45) / 3 = 0.72$, $Prob_{PU} = (0.80 + 0.95 + 0.75) / 3 = 0.83$

$ETX = \sum (1 / Plink) = (1/ 0.85) + (1/0.95) + (1/0.75) = 3.56$

C) $Path_3$ as in Figure 4.14

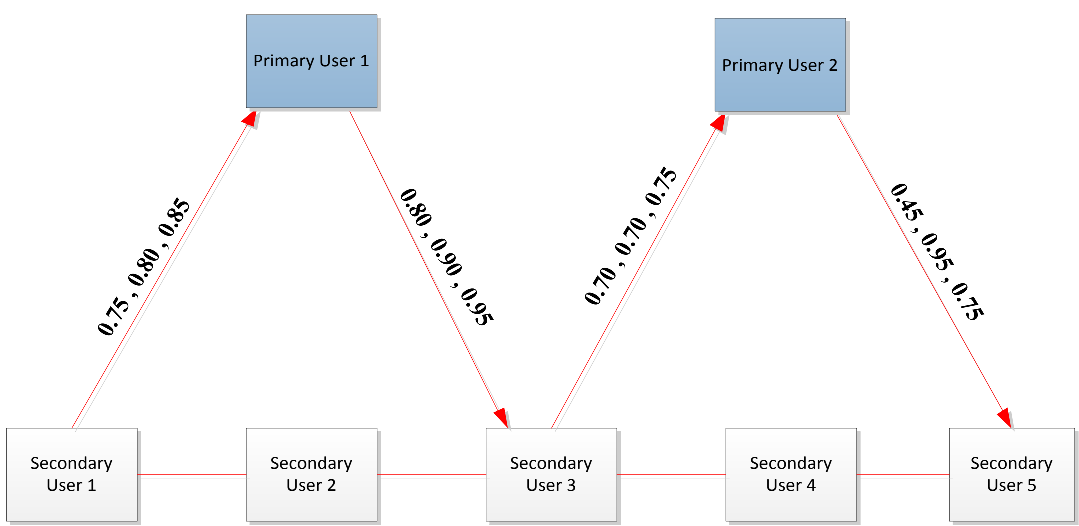

Figure 4.14: $Path_3$ from SU_1 to SU_5

$Prob_k = (0.75 + 0.80 + 0.70 + 0.45) / 4 = 0.68$, $Prop_{PU} = (0.80 + 0.90 + 0.70 + 0.95) / 4 = 0.84$

$ETX = \sum (1 / Plink) = 4.90$

D) $Path_4$ as in Figure 4.15

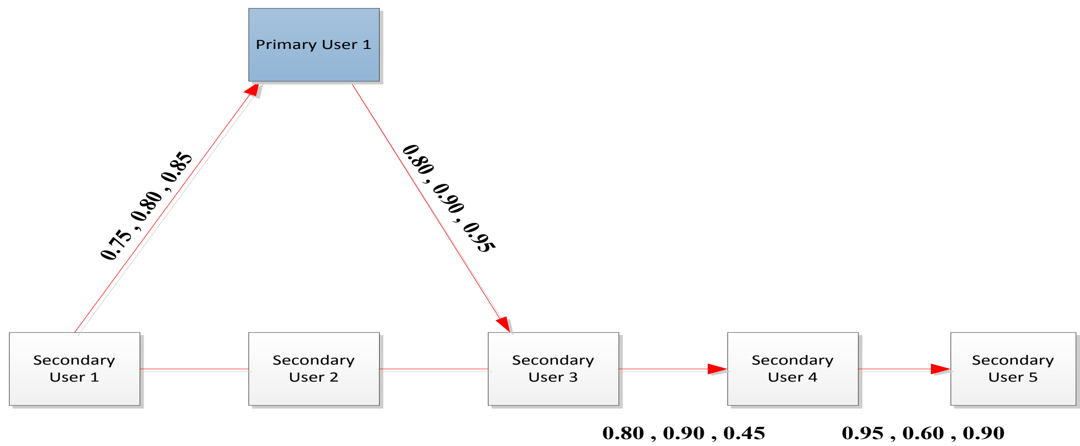

Figure 4.15: $Path_4$ from SU_1 to SU_5

Probk = (0.75 + 0.80 + 0.8 + 0.95) / 4 = 0.83, ProbPU = (0.8 + 0.9 + 0.9 + 0.6) / 4 = 0.8

ETX = 5.56

E) $Path_5$ as in Figure 4.16

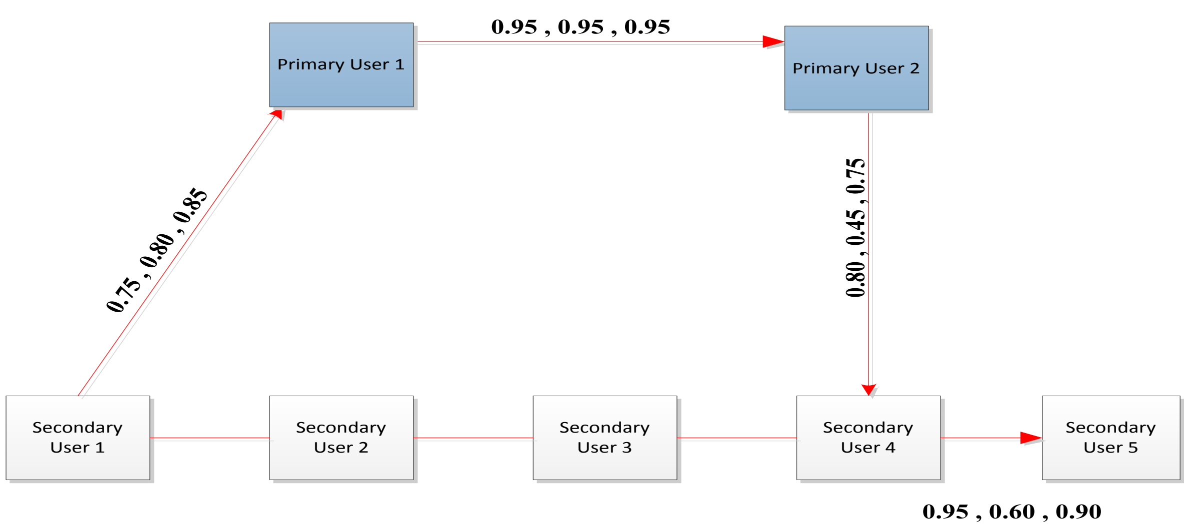

Figure 4.16: $Path_5$ from SU_1 to SU_5

$Prob_k$ = (0.75 + 0.95 + 0.80 + 0.95) / 4 = 0.86, $Prob_{PU}$ = (0.80 + 0.95 + 0.45 + 0.60) / 4 = 0.70

ETX = 4.67

F) $Path_6$ as in Figure 4.17

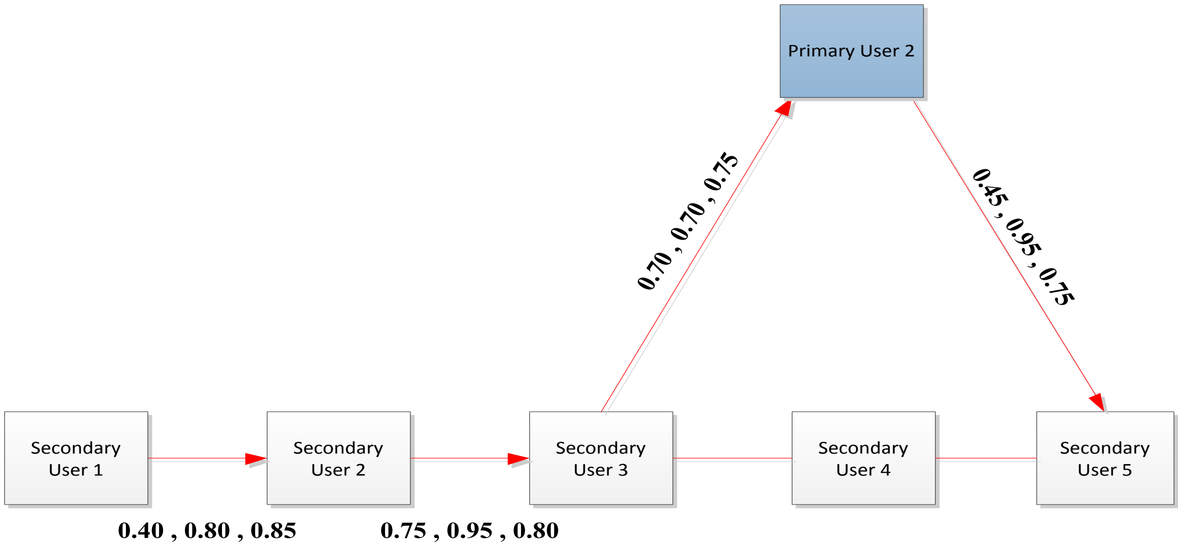

Figure 4.17: $Path_6$ from SU_1 to SU_5

$Prob_k = (0.40 + 0.75 + 0.70 + 0.45) / 4 = 0.58$, $Prob_{PU} = (0.8 + 0.95 + 0.7 + 0.95) / 4 = 0.85$

ETX = 5.09

The previous such possible ways are described in Table 4.5 as follows:

$Path_{id}$	**$Prob_k$**	**$Prob_{PU}$**	**ETX**
$Path_1$	0.73	0.81	5.70
$Path_2$	0.72	0.83	3.56
$Path_3$	0.68	0.84	4.90
$Path_4$	0.83	0.80	5.56
$Path_5$	0.86	0.70	4.67
$Path_6$	0.58	0.85	5.09

Table 4.5: The paths with Values of QoS Levels

Table 4.5 shows the probabilities for delay and the presence of PU, the last column shows the routing metric ETX which is the expected transmission count. The path will be selected based on secondary user requirements that are represented by the QoS levels. In our model, the price factor, which controls the process, is considered. To satisfy the first level of QoS the second column is referred where this column shows different values of $Prob_k$, which represents the delay and this value affects the price. In the second column, the best choice is $path_5$ because this value represents the probability of idle periods, which means there is not much delay when compared with other values but the worst one is $Path_6$. For second level of QoS, the second column and the third column are considered. The best choice in terms of probability of PU presence is $Path_5$ and the worst choice is $Path_6$. In response to third level of QoS, the best choice is $Path_1$ and the worst choice is $Path_2$. When more levels are combined, it is a kind of contradiction to make the choice. Following expressions are formulated to help to select the path:

- Path based on level 1 = Min $Prob_k$
- Path based on level 2 = Min $\sum (Prob_{PU} / Prob_k)$ among all paths
- Path based on level 3 = Min $\sum ((Prob_{PU} * ETX) / Prob_k)$ among all paths

A new table is created, Table 4.6, for all paths based on the above

$Path_{id}$	**$Prob_k$**	**$(Prob_k / Prob_{PU})$**	**$(Prob_k / (Prob_{PU} * ETX)$**
$Path_1$	0.73	0.87	0.24
$Path_2$	0.72	0.90	0.16
$Path_3$	0.68	0.81	0.17
$Path_4$	0.83	1.04	0.19
$Path_5$	**0.86**	**1.23**	**0.26**
$Path_6$	0.58	0.68	0.13
Best choice for level 1	**$Path_5$**		
Best choice for level 2		**$Path_5$**	
Best choice for level 3			**$Path_5$**

Table 4.6: The best path among possible paths

4.5 Game Theory Framework for System Model

Recently, game theory has been used in communication. It has been used to model and to analyze resource allocation problems in a competitive area. Game theory is a useful tool that can be used for spectrum management in a cognitive radio network [4-5]. Some existing works related to spectrum trading or leasing use one stage of dynamic game structure as in [27], the stage was between primary user and secondary user. Other existing works use two stages; one stage between primary user and secondary user and the other stage among PUs as in [16, 28, and 11]. Some other existing works use two stages; one stage between the primary user and secondary user whereas the other stage is among the secondary users as in [25 and 47], instead of PUs. In this section, the model with game theory concept is introduced. As mentioned above, the existing research works consider one stage or two stages. In this work, three stages are introduced. The first stage is among the primary users where the Bertrand game is formulated. The second stage is between primary user and secondary user where the Stackelberg game is formulated, and the third stage is among the secondary users where the Evolutionary game is formulated. Three stages are illustrated in the following Figure 4.18 and the game theory approaches is connected to layers as in Figure 4.19.

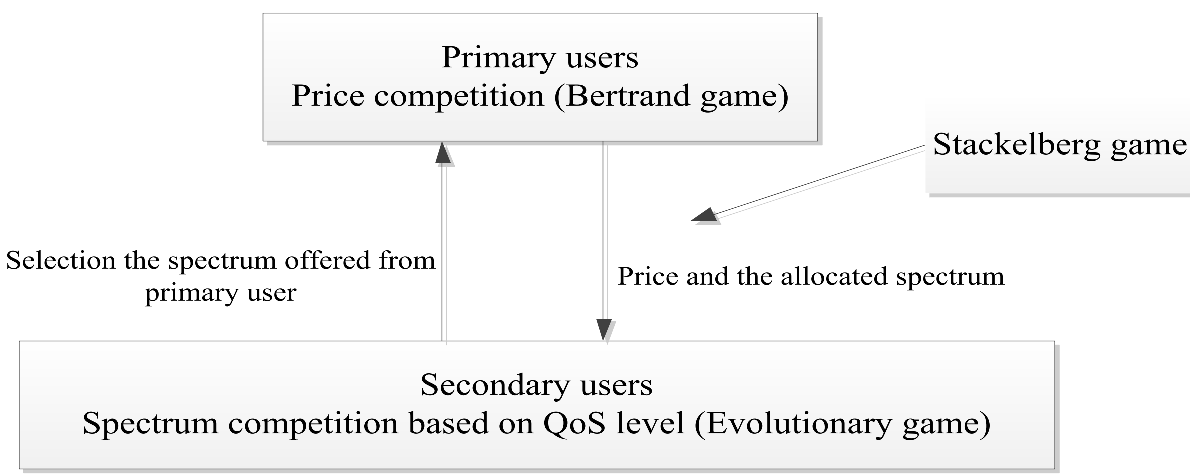

Figure 4.18: Three Stages of Game Theory

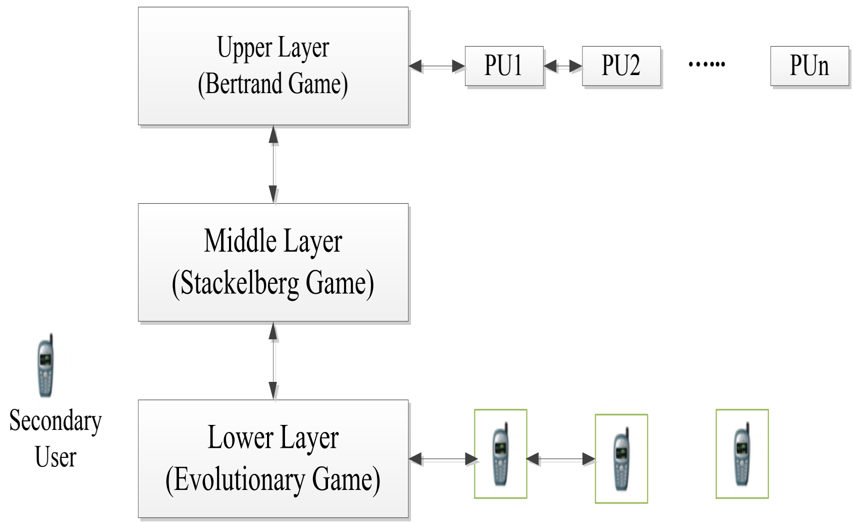

Figure 4.19: Hierarchy of our Game Theoretic Approach

In the following sub-sections, the three stages are described that are the Stackelberg game, the Bertrand game, and the Evolutionary game. In addition, the utility function is described for each user (PU or SU).

4.5.1 Spectrum Trading using Stackelberg Game (Middle Layer)

In Stackelberg competition [4], it is assumed that at least one of the firms in the market is able to pre-commit itself to a particular level of supply before other firms have fixed their level of supply. Other firms observe the leader's supply and then respond with their output decision. The firms that are able to initially pre-commit their level of output are called the market leaders and the other firms are called the followers. The previous concept was applied into our model specifically between the primary user and the secondary user. Hence, the primary user is the leader and the secondary user is the follower. For leader (PU), Q_L and I_L is defined where Q_L is the strategy set and I_L is the information set. For the follower (SU), it has Q_F where Q_F is the strategy set. According to Stackelberg game model, $I_L = Q_F$. For any strategy q_{Lo} which belongs to Q_L chosen by the leader, the follower will choose the reaction strategy q_F which belongs to Q_F to maximize its own payoff U_F.

$$q^*_F = \max U_F (q_F; q_L) \quad (4.10)$$

$$q^*_L = \max U_L (q_L; q_F) \quad (4.11)$$

In equation 4.10, $q_L = q_{Lo}$. After knowing the reaction strategy q^*_F of the follower, the L will announce a strategy q^*_L which belongs to Q_L whereas Leader maximizes its payoff U_L. In equation 4.11, $q_F = q^*_F$.

In our model, the primary user strategy set Q_L is defined as $Q_L = \{P^b_i, I = 0, 1, 2,\ldots\ldots, N\}$ where P^b_i is the total price as in equation 4.6a) and 4.6b) for the allocation of spectrum b. The secondary user strategy set Q_F is defined as $Q_F = \{S^j_{QoS}, j = 1, 2, 3 \ldots M \text{ and } QoS = 1, 2, \text{ or } 3\}$, where S^j_{QoS} is the offered spectrum with level of QoS. The primary user is to choose the price P_i for the spectrum b while the secondary user would like to select the best size of spectrum with requested level of QoS which optimizes its own utility function U_F. In this game the PU first calculates the most probable response S^r_{QoS} (r = 1, 2, 3,……m) from the secondary user given any of its policies P^b_n (n = 0, 1, 2… N).

$$U_L (P^*; S^*QoS) \geq U_L (P^b_r; S^r_{QoS}) \quad (4.12)$$

Equation 4.12 shows that the reaction price is always greater than the initial price, as well as the reaction spectrum size with QoS, which is greater than the response spectrum size with QoS.

4.5.2 Spectrum Competition using Bertrand Game (Upper Layer)

In Bertrand's game [4], a firm changes its behavior if it can increase its profit by changing its price, on the assumption that the other firms' prices will remain the same and their outputs will adjust to clear the market. When the unit cost of production is a constant c, the same for both firms (e.g. competitive PUs), and the demand is linear, Bertrand's game has a unique Nash equilibrium, in which each firm's price is equal to c. The previous concept was applied to model the competition among primary users. In this competition, k channels are offered by n primary users wherein each PU_i can offer k_i at a cost P_{total} (k_i). In our model, the primary users set different prices that allow secondary user to select the lowest price among the offered prices. Each primary user sets the price based on alpha value as shown in equations 4.8 and 4.9. Each PU is looking to maximize its utility (profit) by getting more customers (secondary users).

4.5.3 Selection strategies using Evolutionary Game (Lower Layer)

The dynamic competition of spectrum selection among secondary users is modeled as an evolutionary game [4]. This is the lower layer in our hierarchical model. This evolutionary game was initially developed to describe the behavior of biological agents [78]. It was also used to model the behavior of human beings in the society [79] and entities in a market environment [80]. The strategy adaption of this game is subject to control from the primary users in terms of the size of the spectrum leased to provide spectrum for the secondary users. In addition, the primary users observe the spectrum selection of secondary users and decide the spectrum size to be leased to SUs dynamically. The secondary user can select the spectrum dynamically according to the perceived utility, which depends on the spectrum, the price, and the QoS level. A secondary user can access the spectrum from only one PU at a time. The strategy of each SU is the selection of the primary user with lower price and better QoS. The utility function of each SU is a function of the spectrum, b_i, and the price, P_i as discussed in the following section. When the utility function is formed for SU, the following concerns are considered; (i) a secondary user chooses the primary user that will provide the best spectrum in terms of price and level of QoS and (ii) a secondary user observes the behaviors of other users and changes the decision on spectrum selection.

4.5.4 Utility Function of Primary User and Secondary User

In [81], the authors have considered the utility function of the primary user as a combination of revenues from both data transmission and spectrum trading. This work considers the following; the primary user's utility function consists of five parts: (i) satisfaction of its own transmission, (ii) revenue from selling spectrum to the secondary BS, (iii) gain more demands, (iv) the corresponding payment due to the intermediate secondary users, and (v) the performance loss due to the shared spectrum with the secondary users.

$$U_L = W * \log(b) + P * b - f(L_{QoS}) \quad (4.13)$$

where W is the data transmission rate, b is the spectrum traded, P is the price unit, and $f(L_{QoS})$ is the QoS function. Replacing $f(L_{QoS})$ from equation 4.3 gives the following:

$$U_L = W * \log(b) + P * b - QoS_{level} * \ln(b) \quad (4.14)$$

QoS_{level} is the level of QoS. Secondary user's utility function consists of the spectrum size and the QoS_{level}. For SU, the utility function is the following:

$$U_F = W * QoS_{level} * \log(b) - (QoS_{level})^2 * \ln(b) * P^2 * b \quad (4.15)$$

The derivation of SU's utility provides the best value of spectrum size in term of QoS. Let $(dU_F / dQoS_{level} = 0)$, you have:

$$QoS_{level} = (W / (2 * b * P^2)) \quad (4.16)$$

which means given strategy P chosen by PU, the SU's best response is to set the QoS level QoS_{level} as in equation 4.15. Substituting the value of QoS_{level} from equation 4.16 in equation 4.14 for the utility function of PU, you get:

$$U_L = W * \log(b) + P * b - (W / 2 * b * P^2) * \ln(b) \quad (4.17)$$

The derivation of PU's utility gives the best price to SU. The derivation of SU's utility is substituted in the PU's utility. Now let (dU_L / db = 0), you get the following equation in terms of P:

$$2*P^3 *b^2 + P^2*W*b + W (\ln (b) - 1) = 0 \quad (4.18)$$

4.5.5 Simulation Result

In this subsection, the proposed game theory model is used to examine network dynamics under different levels of QoS. Three levels of QoS are introduced as well. This model consists of three kinds of game; all the games have a solution called Nash equilibrium. The challenge in doing so is that, it is not *a priori* clear whether Nash equilibrium exists, and there is no standard algorithm for finding Nash equilibrium, unlike when each player's strategy set is finite [79].

4.5.5.1 Simulation Parameters

In the simulation, the cognitive nodes are randomly placed in 300x300 m^2 and the transmission range is set to 150 meters. The length of the packet size is 64Kbit. The total number of channels is 15, the transmission rate is 100kpbs, the transmission power is 0.1 watt, the total numbers of SUs are 12 users, and the number of PU is 2 users. PU_1 has 10 channels and PU_2 has the remaining 5 channels. The usage period is fixed for all users, and is 6 hours. The number of SUs that request channel from PU_1 are 7 users and the remaining request channel from PU_2. The competition factor is calculated for each primary user as per equation 4.9 as well as the constant as per equation 4.7 by using the previous parameters. For PU_1, the competition factor $\alpha_1 = 0.517$ and for PU_2, $\alpha_2 = 0.512$. The constant A values are $A_1 = 7 - 1 = 6$ and $A_2 = 5 - 1 = 4$.

4.5.5.2 Game Solutions

In this subsection, the Nash equilibrium is obtained for each game in this work. Figure 4.20 shows the price unit response functions and the Nash equilibrium of the competitive pricing of two primary users with fixed spectrum. The figure shows the existence and uniqueness of the Nash equilibrium. Moreover, Figure 4.20 shows that the slope of the Price unit strategy of primary user PU_1 is always greater than one. On the other hand, the slope of the Price unit strategy of primary user PU_2 is always less than one.

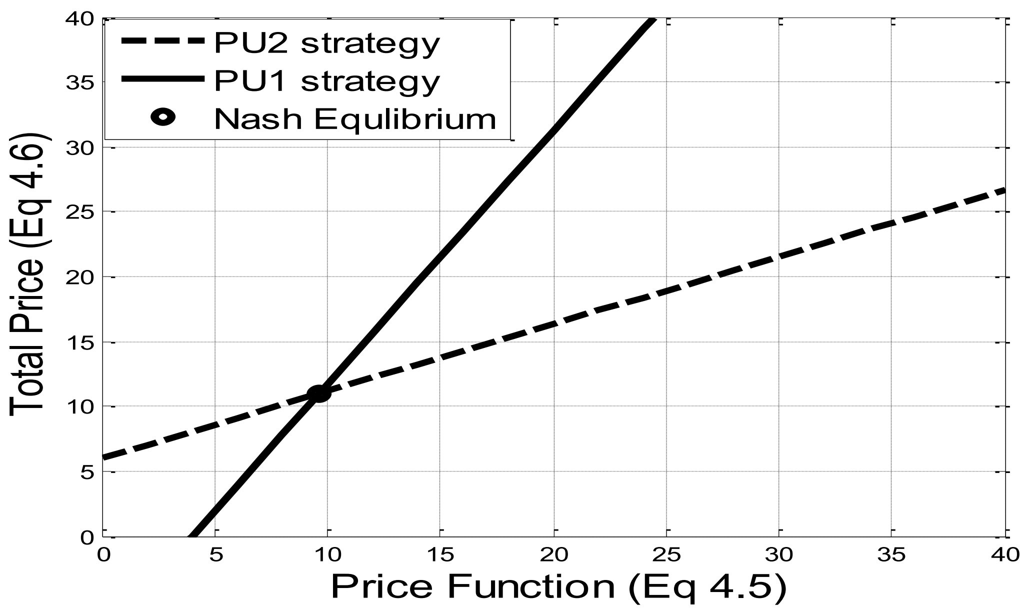

Figure 4.20: Existence of Nash Equilibrium

As a result, there is only one point of intersection, which is called Nash equilibrium. Here, the offered price for PU_1 is $P_1^* = 9.61873$ and for PU_2 is $P_2^* = 10.97288$. Basically, when one primary user changes its strategy, for example the offered spectrum and price unit, the equilibrium point to achieve the highest net payoff of the other primary user changes. The best response of both primary users in terms of spectrum size is shown in Figure 4.21; the size of the offered spectrum in each level is changeable, while the price unit is fixed. If primary user 1 increases the size of offered spectrum, the demand will be increased by customers (SUs).

However, the secondary user observes the other offered spectrum by primary user 2 in order to select the best one in terms of QoS and in terms of price. Basically, if the spectrum size is increased, that means the total price will be increased, which means the profit will be increased. As shown in Figure 4.21, the Nash equilibrium is the intersection between each PU strategy with other PU in each level. In Figure 4.21, you have three Nash equilibrium points wherein each level has one point. For the sake of simplicity, the only size of the offered spectrum is shown in Figure 4.22 and the only spectrum price unit strategies are shown in Figure 4.20.

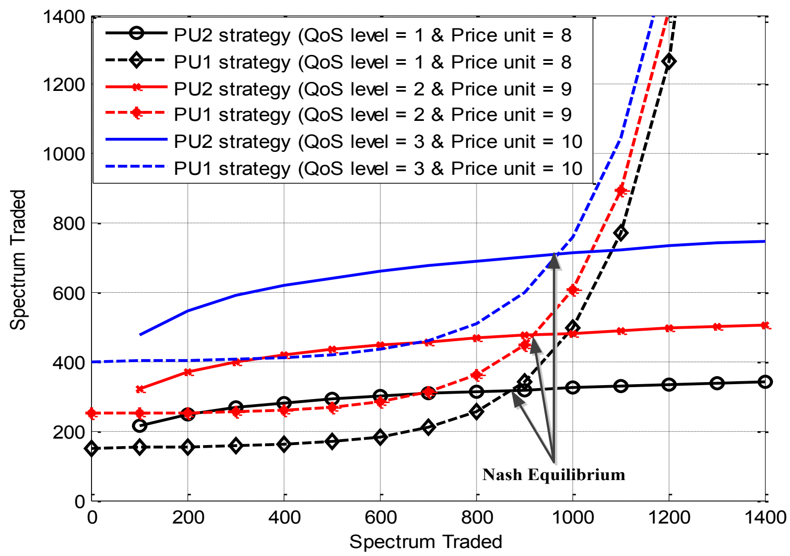

Figure 4.21: PU_1 and PU_2 Strategies in different QoS level and the Nash Equilibrium for Each

The payoff (utility) function of each player in QoS level 1, 2, and 3 is illustrated in Figures 4.22, 4.23 and 4.24 respectively. It shows that the utility function of PU increases, while channel price is increasing. Meanwhile, the strategy of the SU, which is the spectrum size with the QoS level to be used, is increasing, and its utility increases as well.

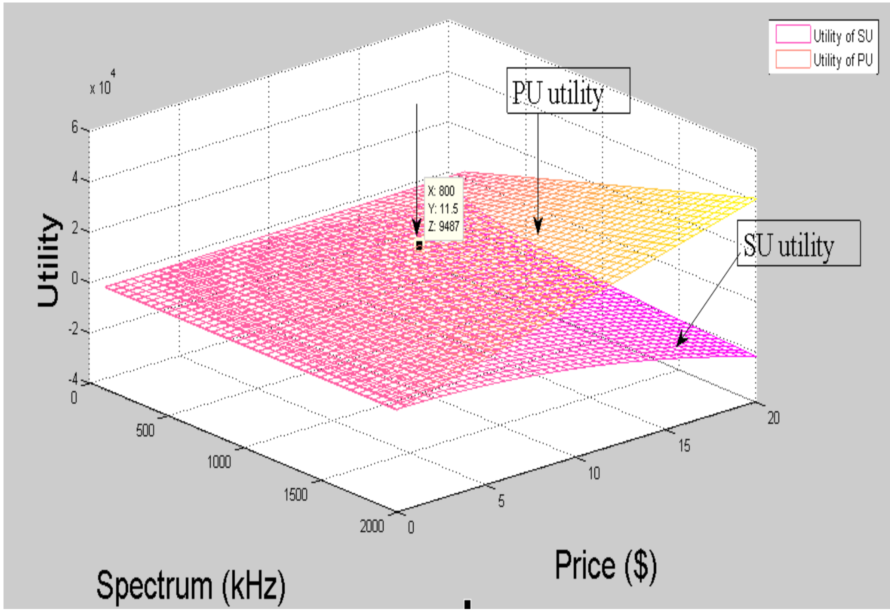

Figure 4.22: PU and SU Utility in QoS Level 1

According to the two-dimensional plane indexed by two decision variables, price and spectrum size, the PU calculates the equilibrium contract (q_L*; q_F*) according to equations (4.15), (4.16), and (4.17) respectively. Then it waits until the SU announces its policy q_F as q_F*.

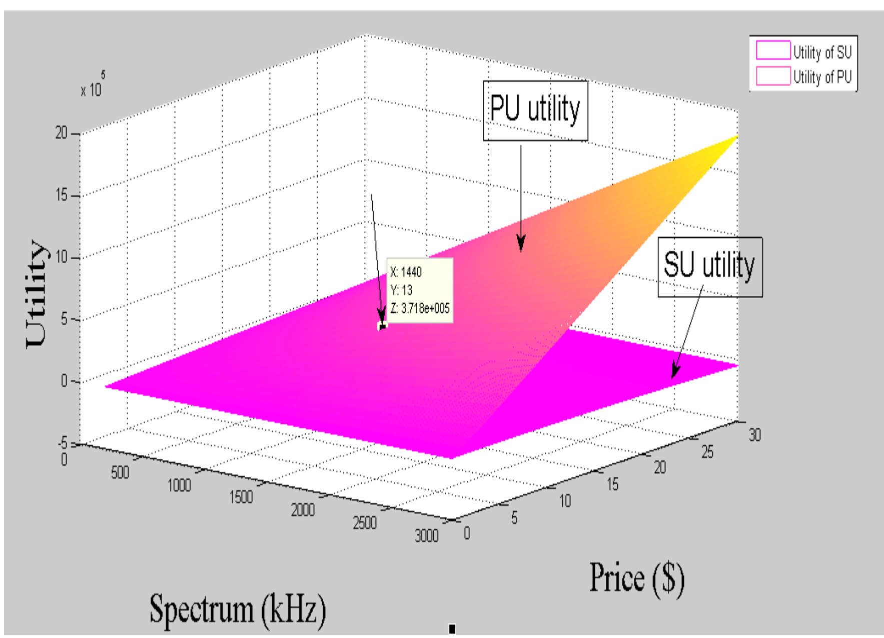

Figure 4.23: PU and SU Utility in QoS Level 2

In our simulation, (q_L*; q_F*) = (11.5; 800) is calculated for first level of QoS, (q_L*; q_F*) = (13; 1440) for the second level of QoS, and (q_L*; q_F*) = (16; 1880) for the third level of QoS. The first value represents the best price unit for the PU and the second value represents the best spectrum size with QoS level. Note that the utility function of the PU does not achieve maximum when price unit = 11.5 in QoS level 1 or price unit = 13 in QoS level 2 or price unit = 16 in QoS level 3. However, this point called the Nash equilibrium considers the best response for both users, either PU or SU. This point (Nash equilibrium) gives satisfaction to primary user to serve maximum customers while its profit is still acceptable.

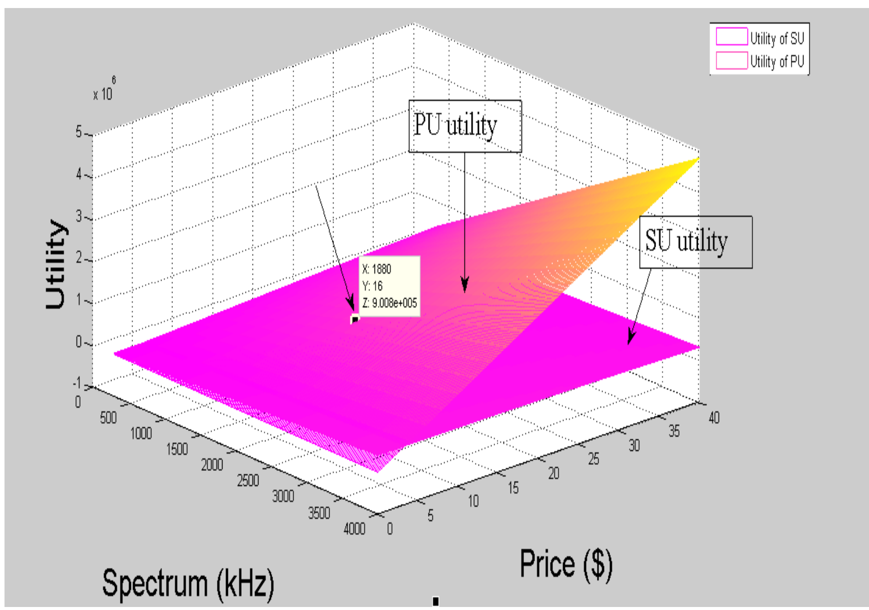

Figure 4.24: PU and SU Utility in QoS Level 3

4.6 Summary

In this chapter, the system overview was introduced; the system model without game theory was described as well as the system model with game theory. The routing algorithm was presented. Finally, the chapter concluded with a demonstration and discussion by studying a case study that showed how the system model worked. In the next chapter, the performance evaluation is presented.

Chapter 5: Performance Evaluation

In this chapter, the revenue equations are analyzed, algorithms for all equations are presented, and the network performance is studied. Finally, the chapter is concluded by comparing the proposed algorithms with traditional as well as the recent routing algorithms.

5.1 Revenue Equations Performance Evaluation

In this section, the flow chart, algorithm, and simulation results for each equation are introduced.

5.1.1 Base Station Cost (C_{BS})

In this subsection, the parameters that affect the base station cost are studied and simulation experiments conducted to study their effects. The flow chart of this cost is presented in Figure 5.1. The parameters that are used to simulate all the model equations are described in Table 5.1.

Parameter	Value
Bandwidth	5000 bytes/sec
Available Channel	5
Price unit	9
Available Path	6
Usage period	55 mins
Number of secondary users	24

Table 5.1: Simulation Parameters for the model's equations

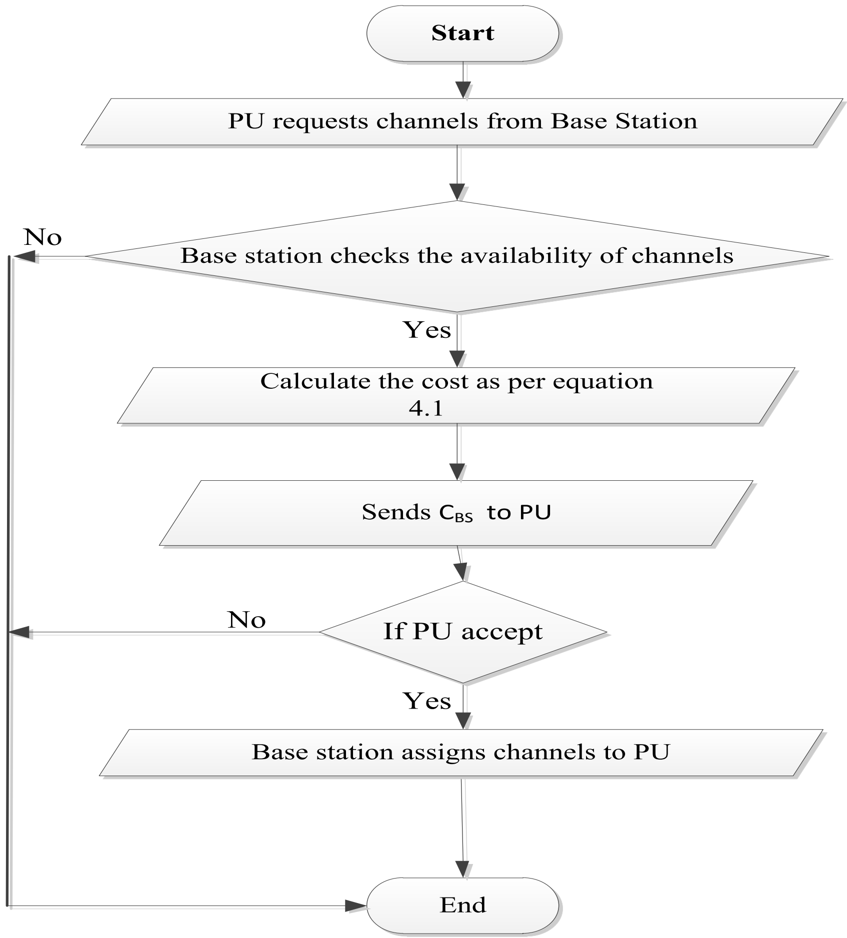

Figure 5.1: Flow Chart of Base Station Cost

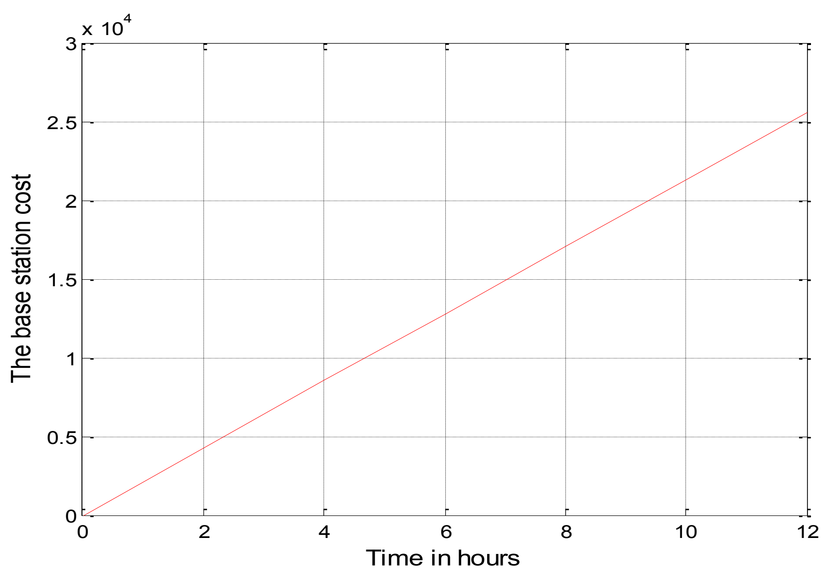

Figure 5.2: The Relation between the Base Station Cost and the Time.

Figure 5.2 shows that the base station cost increases when the time usage increases, which comply with equation 4.1mentioned in Chapter 4.

5.1.2 Competition Factor (α)

A new factor, called competition factor is defined to control the behaviors among PUs. The flow chart and the simulation results for the equation 4.8 are described.

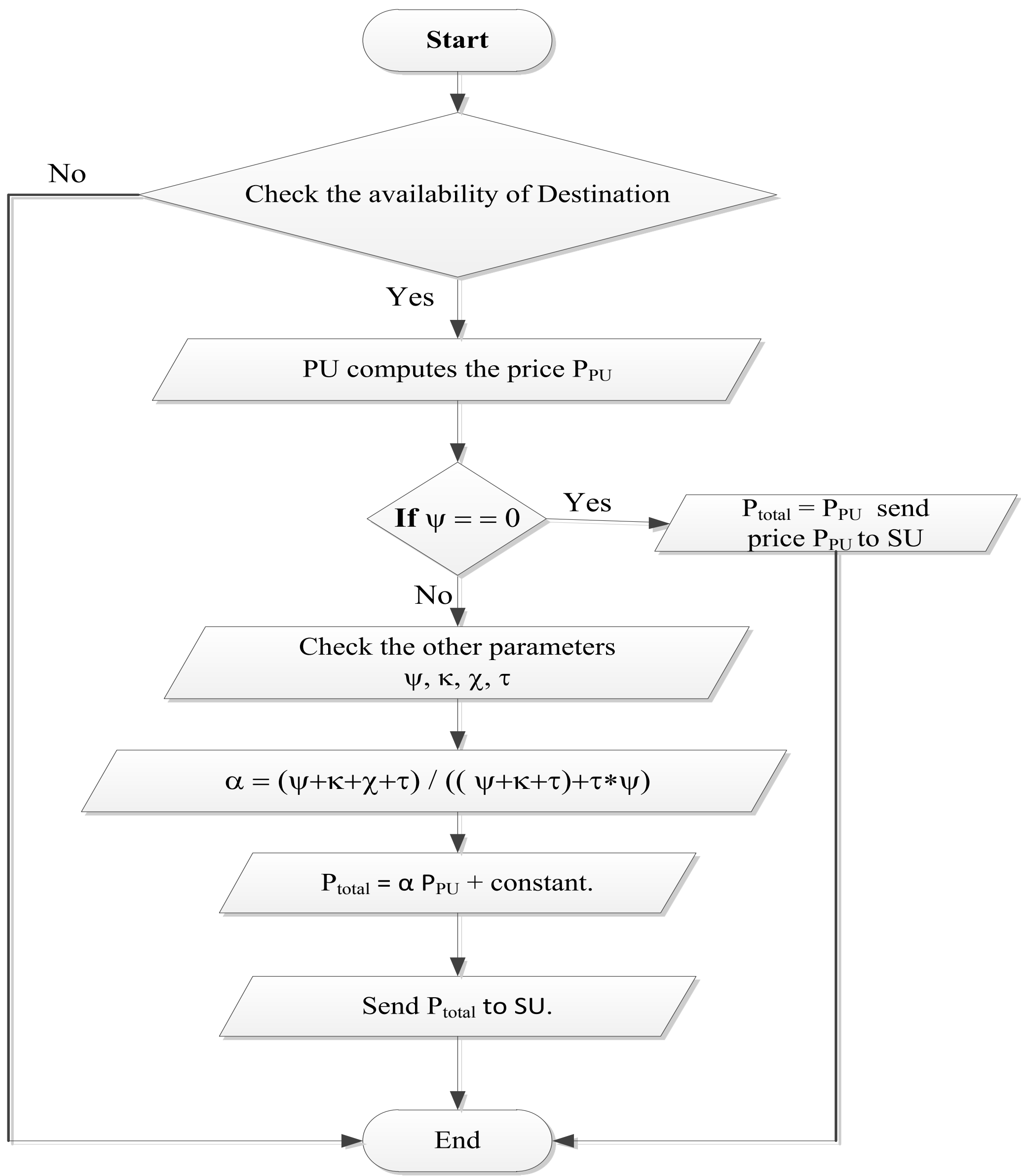

Figure 5.3: Flow Chart of Competition Factor Calculation

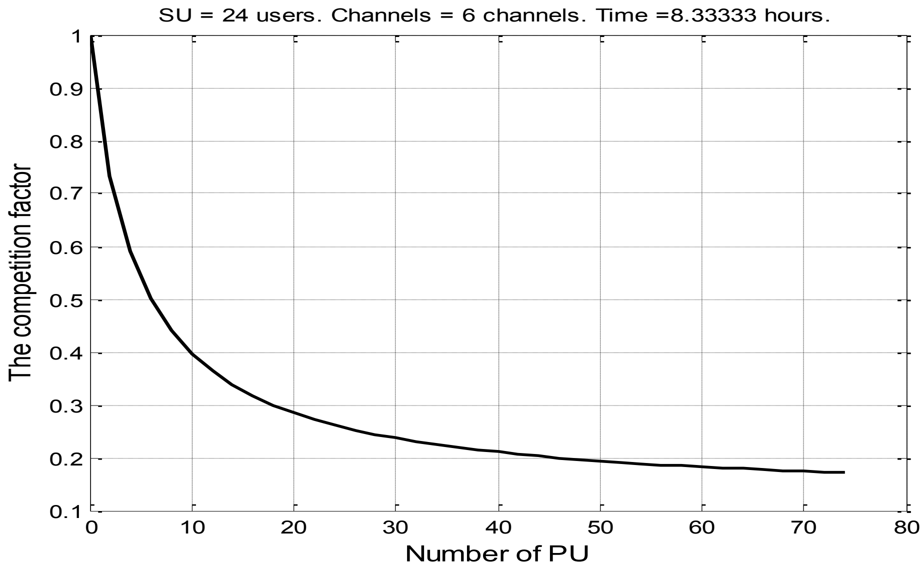

Figure 5.4: Relation between Competition Factor and Number of PUs

Figure 5.4 shows the inverse relationship between the competition factor and the number of PUs i.e. if the number of PUs increases the value of α decreases. When the number of PUs becomes very large, the difference between the values of α is small. The reason behind that is the cost for level 2 and level 3 in terms of price is more expensive compared to the cost of level 1.

5.1.3 Intermediate Cost (C_{SU})

Intermediate cost is the cost paid by PU to each intermediate node for providing a channel with the level of QoS requested. It is defined in equation 4.4.

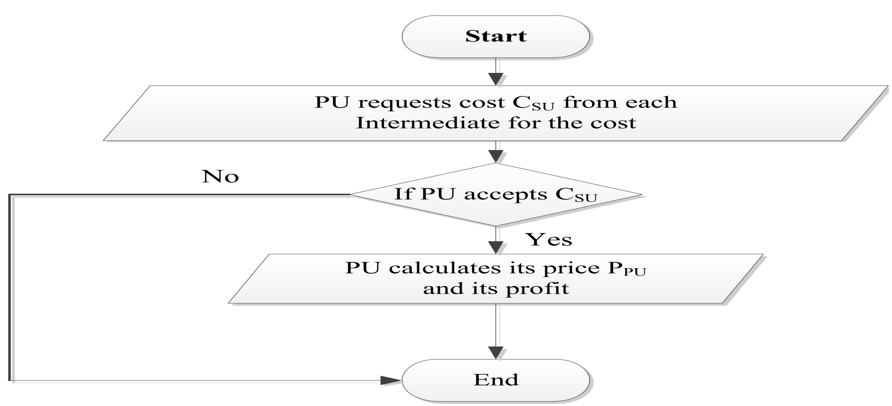

Figure 5.5: Flow Chart of Intermediate Cost Process

In the initial phase, each SU shares its profile with the corresponding PUs as mentioned earlier. The profile contains the available SU channels with their level of QoS. PU updates the directory based on profiles. In our model, there is no negotiation between PU and intermediate nodes.

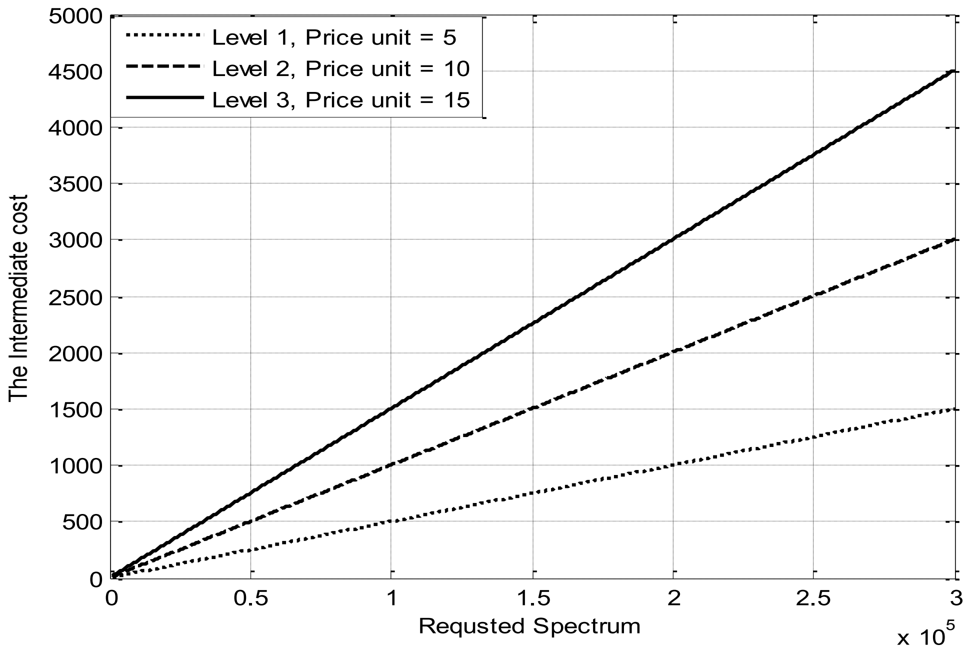

Figure 5.6: Relation between the Intermediate Node Cost and the Spectrum Offered

Figure 5.6 shows the relation between the intermediate node cost and the requested spectrum. The cost as shown is proportional with the requested spectrum and the level of QoS, where the highest level of QoS is level 3 with price unit as 15, the intermediate is level 2 with price unit as 10, and the lowest is level 1 with price unit as 5.

5.1.4 Price Function

This function is defined in equation 4.5). In this subsection, flow chart, and the simulation results are described. Figure 5.7 shows the steps starting from a SU request until the price is sent to the SU. It also shows the steps for calculating the total price. Figure 5.8 shows the relation between the price and the level of QoS as in equation 4.5). The parameters for previous equations are used.

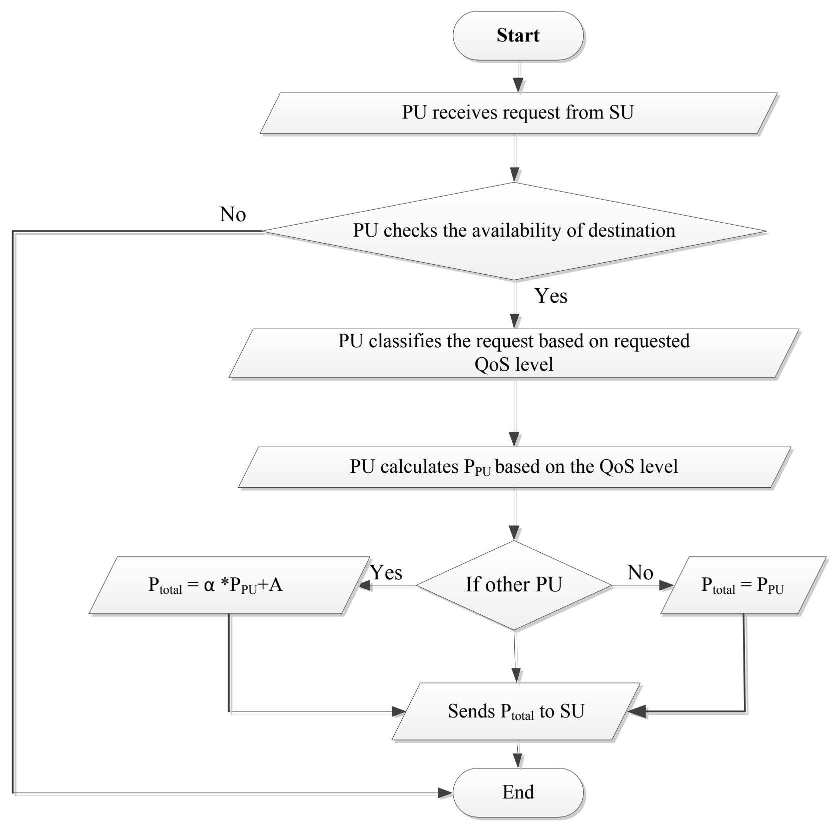

Figure 5.7: The Flow Chart of Price Equation

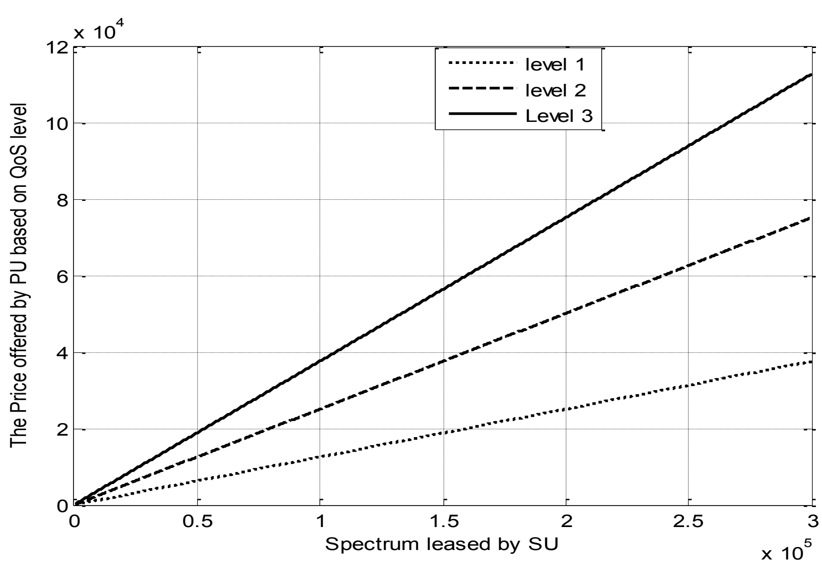

Figure 5.8: The Relation between PU Prices with Spectrum Trading for different QoS Levels

5.1.5 Profit function:

This function is defined in equation 4.2). A PU tries to maximize its revenue by getting more customers (SUs). However, a PU takes into account many factors such as the other competing PUs, the number of SUs, the level of QoS, and the time usage of that spectrum or channel. In the previous subsection the parts of profit equation are described. Figure 5.9 describes how to calculate the profit at PU. Next, the profit equation is simulated based on the parameters of previous equation.

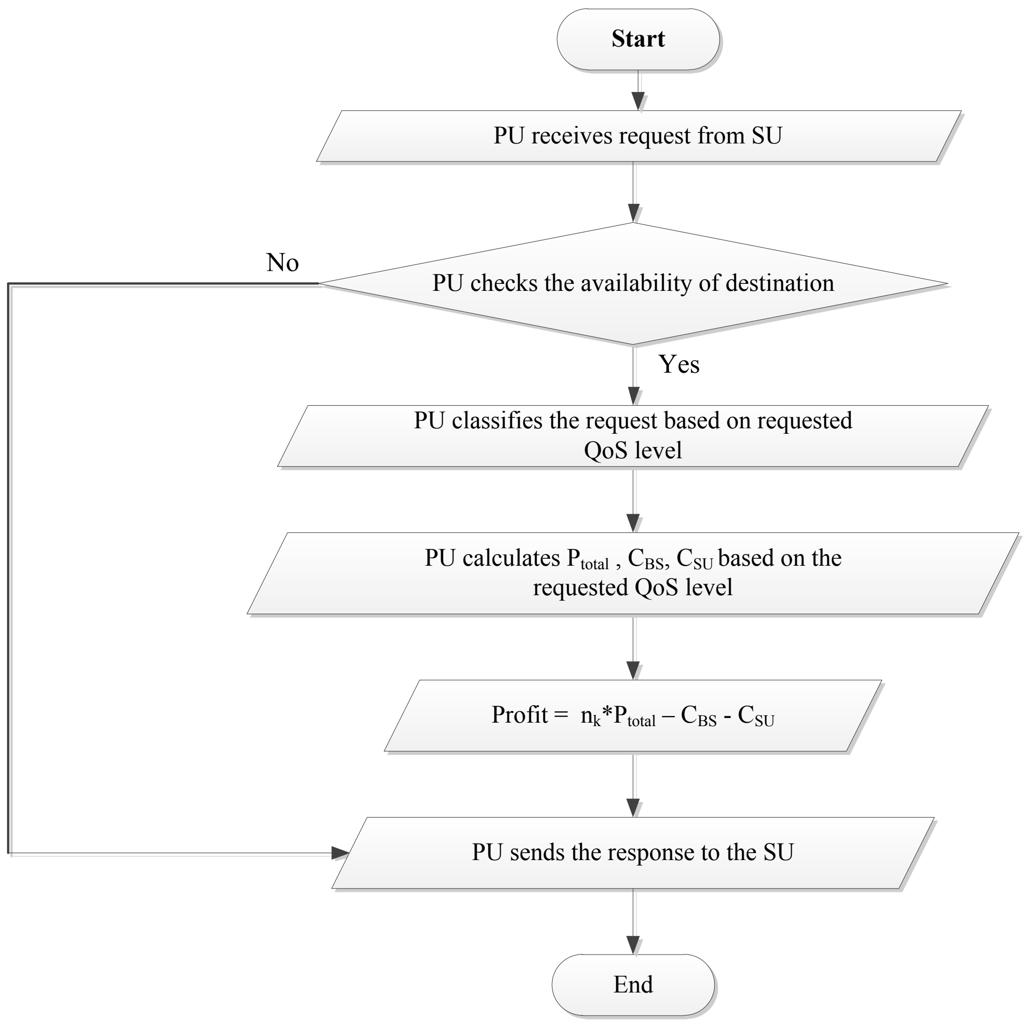

Figure 5.9: The Flow Chart of the Profit Flow

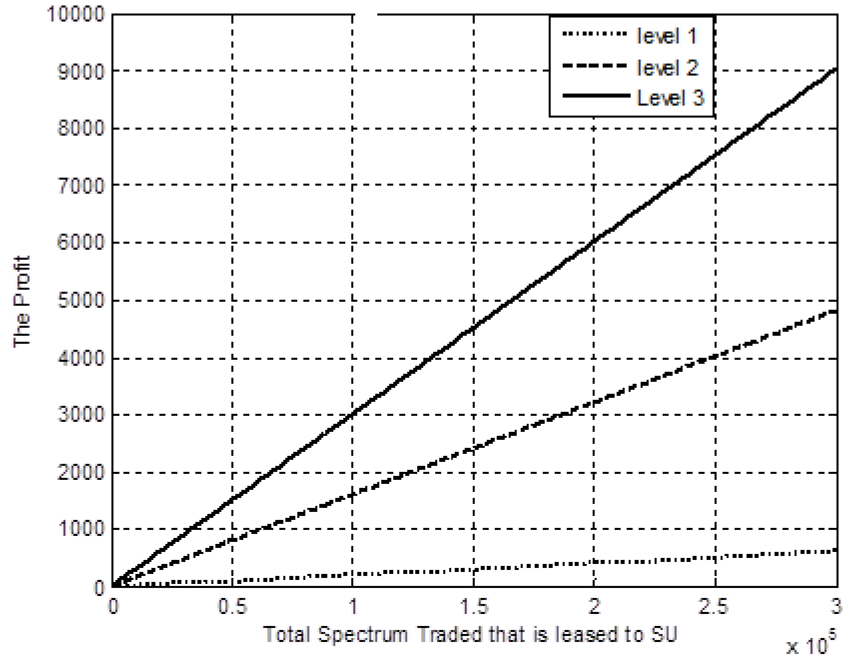

Figure 5.10: Relation between PU's Profit and Spectrum Traded

Figure 5.10 shows how the profit increases when the level of QoS becomes higher. In addition, it is clearly shown, if the primary user maximizes its profit, PU must get more demand from SU especially requesting the third level of QoS. Figure 5.10 shows the differences between the profits for three levels. The difference between level 1 and level 2 is greater than the difference between level 2 and 3. The reason behind that is the price for level 1 is not much cost rather than the price for level 2 and level 3. Basically, when you have the path, all the intermediate nodes must agree on the level of QoS. Also, the users could be malicious users but this part is considered as future work by applying punishment cost for malicious user if any. In addition, the billing system is part of future work.

The section 5.1.1 to section 5.1.5 address all the equations related to this work in terms of flow chart, and simulation results. Many constraints to guarantee a reliable and stable service with three levels of QoS are proposed. The most researched papers especially for routing in cognitive radio network try to apply traditional algorithms in cognitive radio network, which is not efficient at all. However, in this work, it has been attempted to manage the users' profile, which relates to the spectrum aspects in cognitive radio network, to play an important role in improving, enhancing, and developing the path provided. In addition, levels of QoS are incorporated into this work in order to provide a flexible and dynamic model. Moreover, the price model is introduced as well, which plays a vital role in preventing the malicious behavior in the network. In the next subsection, the proposed algorithm is compared with traditional algorithms (AODV and shortest hop) and recent algorithms (RACON and DORP) in terms of delay and throughput. The relation between the profit, the price, and the spectrum size for three levels (level 1, level 2, and level 3) of QoS and the profit is maximized as the QoS level becomes higher. Here again, the cognitive nodes are randomly placed in 300x300 m^2 and the transmission range is 150 meters.

Parameter	Value
Bandwidth	1200 bytes/sec
Transmission Rate	1000 bps
Base station price unit for level 1, 2, and 3	5, 8, and 11
The primary user price unit for level 1, 2, and 3	7, 10, and 13
Total Channel	15
Requested channels	5
Number of primary user	15
Number of PUs	5
Transmission Power	0.1 watt

Table 5.2: Simulation Parameters for Figure 5.11

Figure 5.11 shows the relation between averages of spectrum traded and average profit within the three proposed QoS levels in our model. The figure clearly shows that the profit increases when the requested QoS level is higher, where level 3 > level 2 > level 1 in terms of better service.

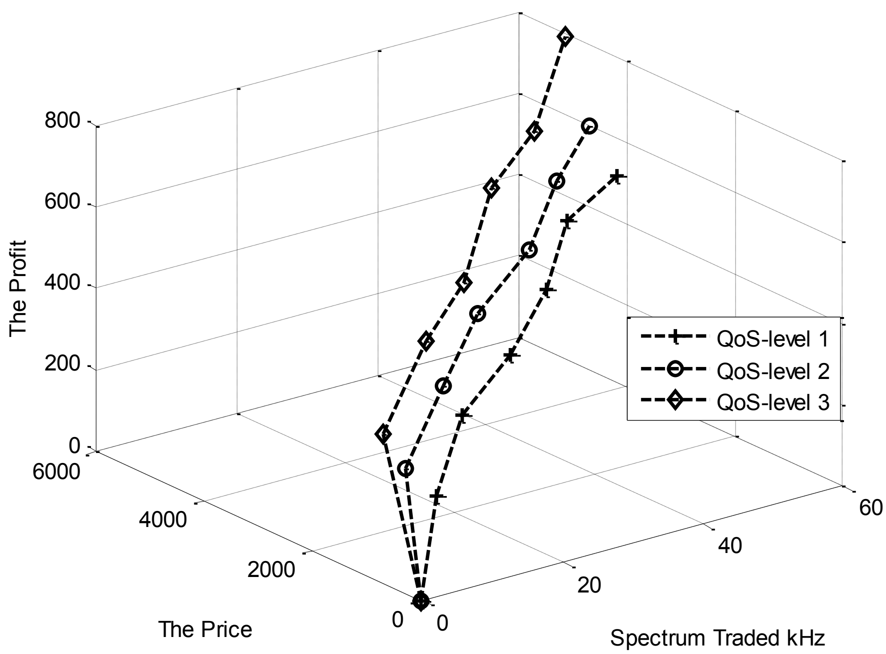

Figure 5.11: PU Profit based on the Level of QoS

5.2 Comparisons between the Proposed QoS Routing Algorithm with Traditional Algorithms and Recent Algorithms

In this subsection, the performance of the proposed QoS routing algorithm is evaluated. The goal of this simulation is to concentrate on the effects of aggregate delay and the throughput in comparison with the traditional routing algorithm as well as some of the recent algorithms. Basically, routing protocol for mobile cognitive radio networks [44] (RACON) and joint on-demand routing with spectrum assignment [42] (DORP) are considered as recent algorithms for comparison purposes. In the simulation, cognitive nodes are randomly placed in 300x300 m^2 and the transmission range is 150 meters. In addition, the number of cognitive nodes in CRN is 25, whereas the number of PUs is 10 and the number of SUs is 15. Randomly, 5 nodes are selected as source nodes, and 5 nodes as destination nodes. The length of the packet size is 64Kbit. In addition, the profile's parameters are the same for any algorithm in the simulation area. The simulation results were checked in case of random failures in the path and the results were better than the recent algorithms and the traditional algorithms.

5.2.1 Delay Factor

The simulation result is shown in Figure 5.12. Regardless of the QoS level used in our algorithm, Figure 5.12 shows that the transmission delay of our proposed algorithm is always smaller than the traditional routing algorithms as well as the recent algorithms (DORP and RACON). This is due to the fact that the traditional algorithms look for minimum hops without considering other parameters (e.g. PU presence, node's mobility, and different characteristics of each channel). These parameters affect the delay because the primary user's presence causes link failure which requires more time to find alternative link, the ratio of idle slots to busy slots cause more buffering time.

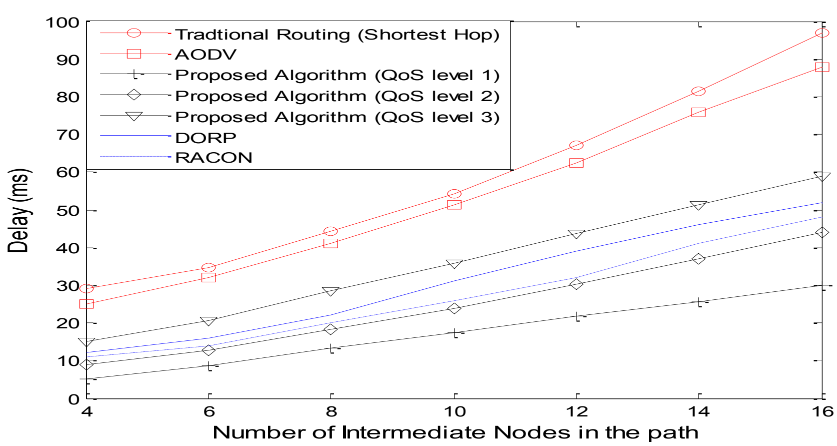

Figure 5.12: Transmission Delay for Different Number of Nodes

We also apply AODV algorithm on cognitive radio network as shown in Figure 5.12 wherein the AODV is an on-demand routing protocol. In AODV routing protocol, the secondary node must broadcast RREQ packet to all its available neighbor nodes on all available channels. The switching delay and the backoff delay is therefore longer than the routing algorithm proposed in this work. As shown in Figure 5.12, the recent algorithms give better performance than level 3 in the proposed algorithm because the third level in the proposed algorithm considers the link robustness and ETX besides the delay. In Figure 5.13, the number of available channels is changed. Again, the proposed algorithm is always better than the traditional routing algorithms and recent algorithms in terms of delay.

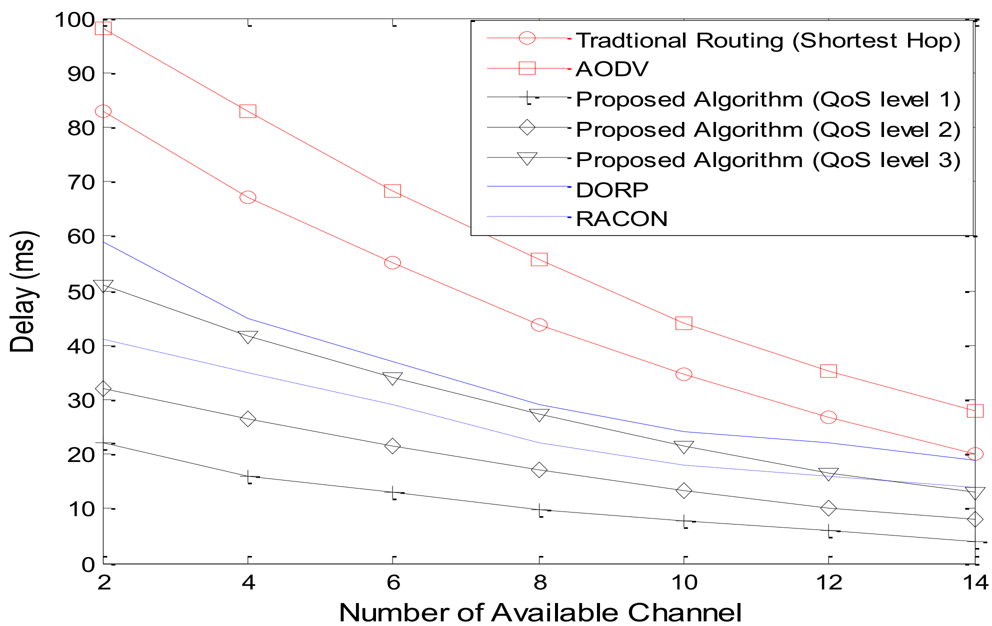

Figure 5.13: Transmission Delay for Different Number of Available Channels

Clearly, as seen in Figure 5.13, the proposed algorithm is more efficient in terms of delay because (i) when the number of available channels is increased, the switching delay and backoff will also increase (ii) There is no overhead in the proposed algorithm for link replacement, and (iii) the proposed algorithm considers the most important factors that affect the network. From

Figure 5.12 and Figure 5.13, it is clearly seen that the proposed algorithm performs better than the traditional algorithms and recent algorithms in term of transmission delay.

5.2.2 Network Efficiency

In Figure 5.14 and Figure 5.15, the proposed algorithm is compared with the recent algorithms (DORP and RACON) in terms of throughput and efficiency. The traditional algorithms are not compared with the proposed algorithm because the traditional algorithms only consider the delay factor in choosing the paths. The throughput referred in Figure 5.14 is obtained in terms of the number of total packets received by destination.

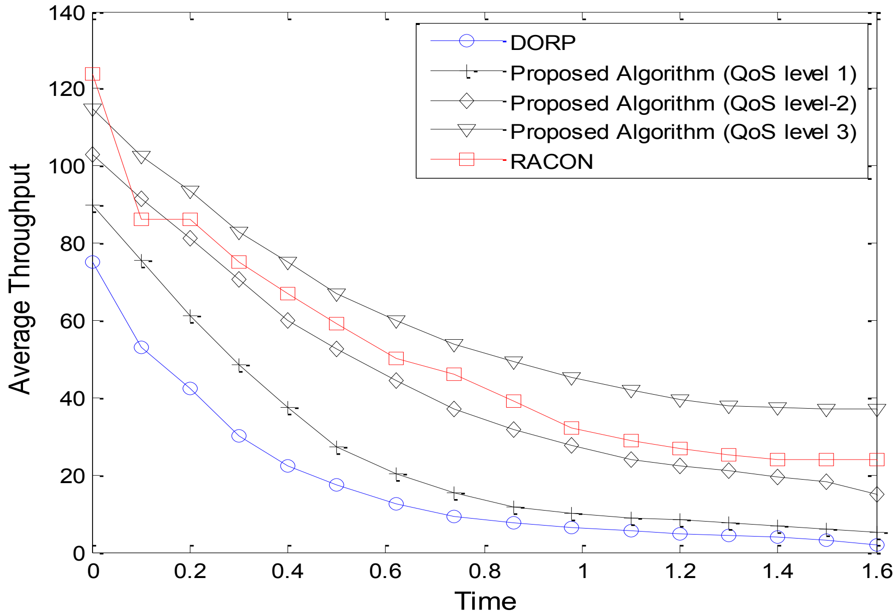

Figure 5.14: The Throughput Comparisons between Our Algorithm and Recent Algorithms (RACON and DORP)

The average throughput in relation to time, for the proposed algorithm as well as the recent algorithms (RACON and DORP) is plotted in Figure 5.14. This figure depicts the average throughput for DORP as decreasing with the presence of PUs as time goes by. Although DORP has higher initial throughputs, its average throughput drops very rapidly due to poor management because it does not consider the presence of PU. However, the proposed algorithm is better than DORP in all cases, either QoS level 1 or 2 or 3, and the proposed algorithm (level 3) is better than RACON in terms of throughput for the following reason; the third level in the proposed algorithm considers the ETX and probability of the PU presence, which gives a higher throughput. RACON is slightly better than the proposed algorithm (level 2) because of RACON's feature of finding the alternate link in the case of a link failure.

Figure 5.15 illustrates the degradation of network performance when the probability of a primary user's presence is increased, which is not considered either in DORP or RACON. Hence, in our model, by managing all the profiles, channels, and services according to the proposed three levels of QoS, the efficiency of the network is improved by our algorithm, as shown in Figure 5.16.

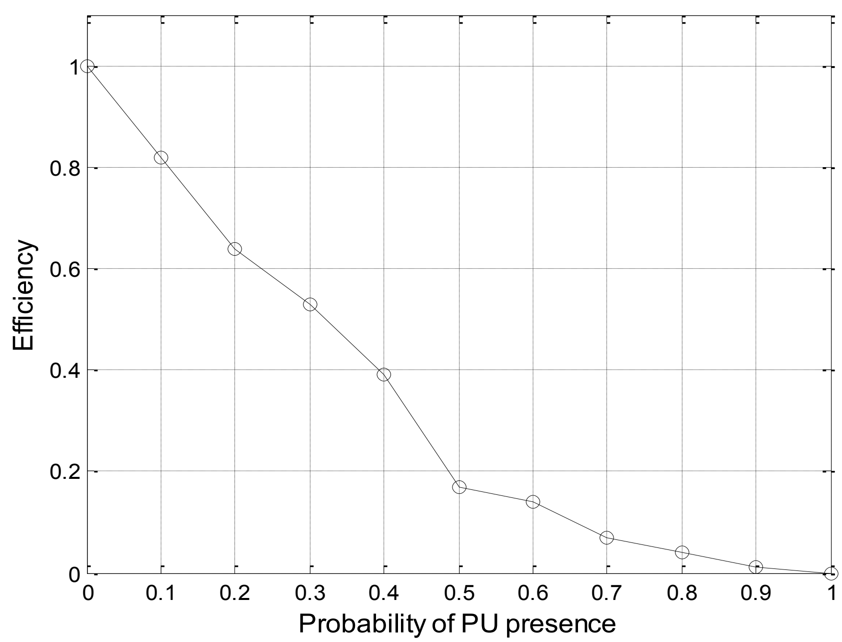

Figure 5.15: The Impact of Primary User Presence on the Network Performance

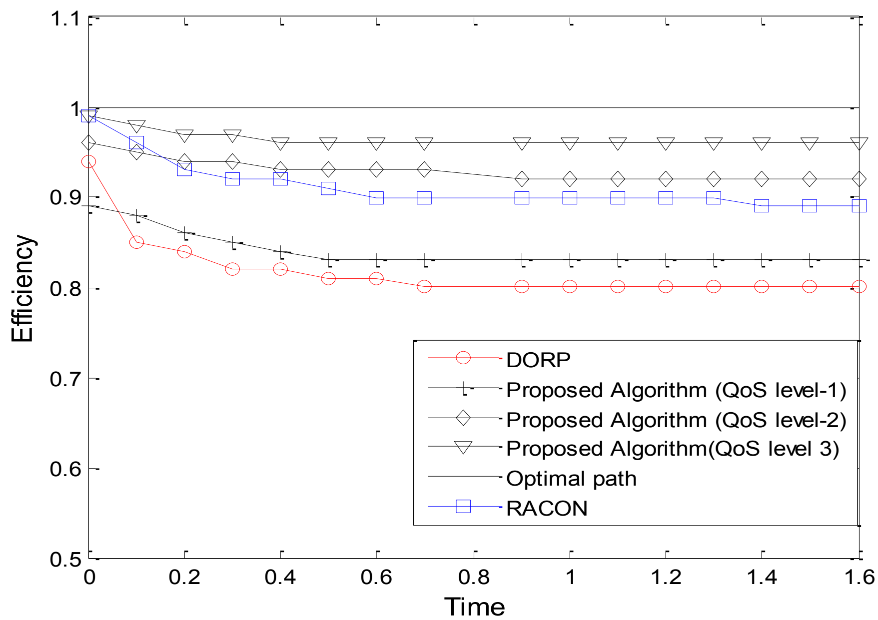

Figure 5.16: The Comparison of Traditional Algorithm and the Proposed Algorithm in terms of Efficiency.

5.2.3 The Role of Spectrum Management in the Network Performance

In this subsection, the following scenario is to study the effect of spectrum management on the network performance. The previous parameters mentioned in Table 5.1, section 5.1.2, and sections 5.1.3 are considered for the network shown in Figure 5.17 for simulation.

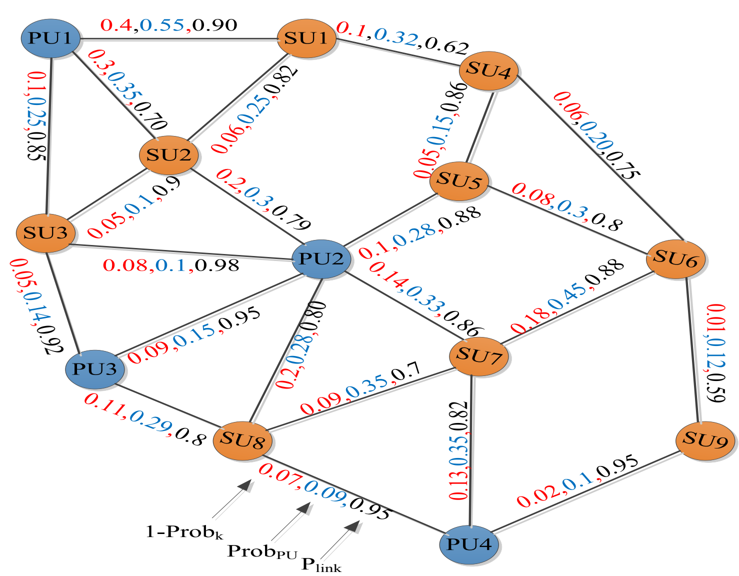

Figure 5.17: A Network Consisting of 4 PUs and 9 SUs

Figure 5.18 and Figure 5.19 show the role of spectrum management on the network performance in terms of throughput and delay. It is clearly shown that the spectrum management gives better results. The spectrum management, which consists of spectrum trading and spectrum competition, manages the channels (spectrums) according to the profile received from all participating secondary users that ensures higher throughput and lower delay. However, the conventional method, as shown in Figure 5.18 and Figure 5.19, has unstable values, in that there are more link failures that require the replacement of the channel or spectrum. The main reason behind this is that the conventional method does not manage the spectrum, which means that it does not consider the PUs' presence.

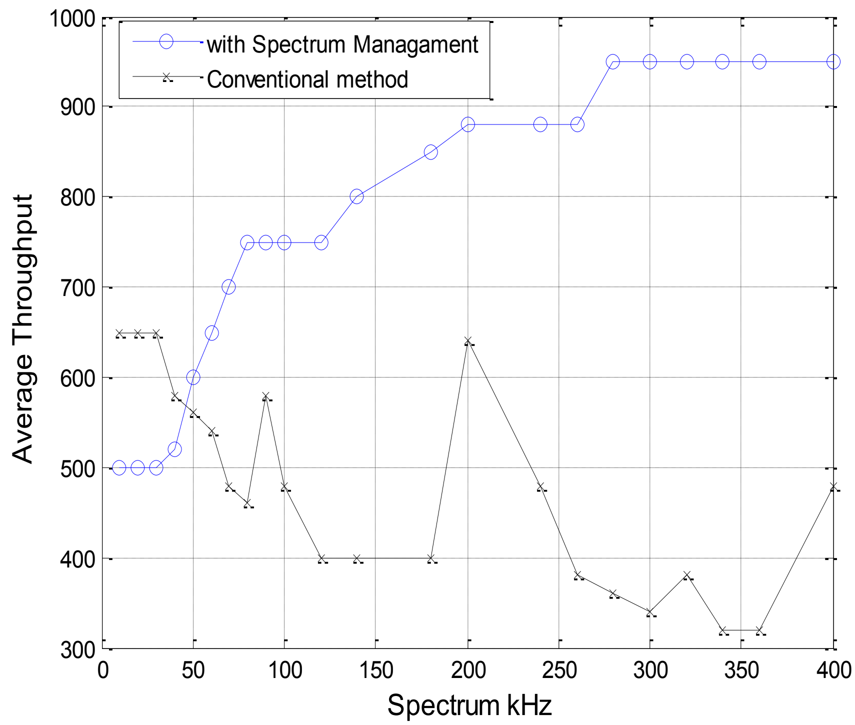

Figure 5.18: The Role of Spectrum Management on the Network Throughput

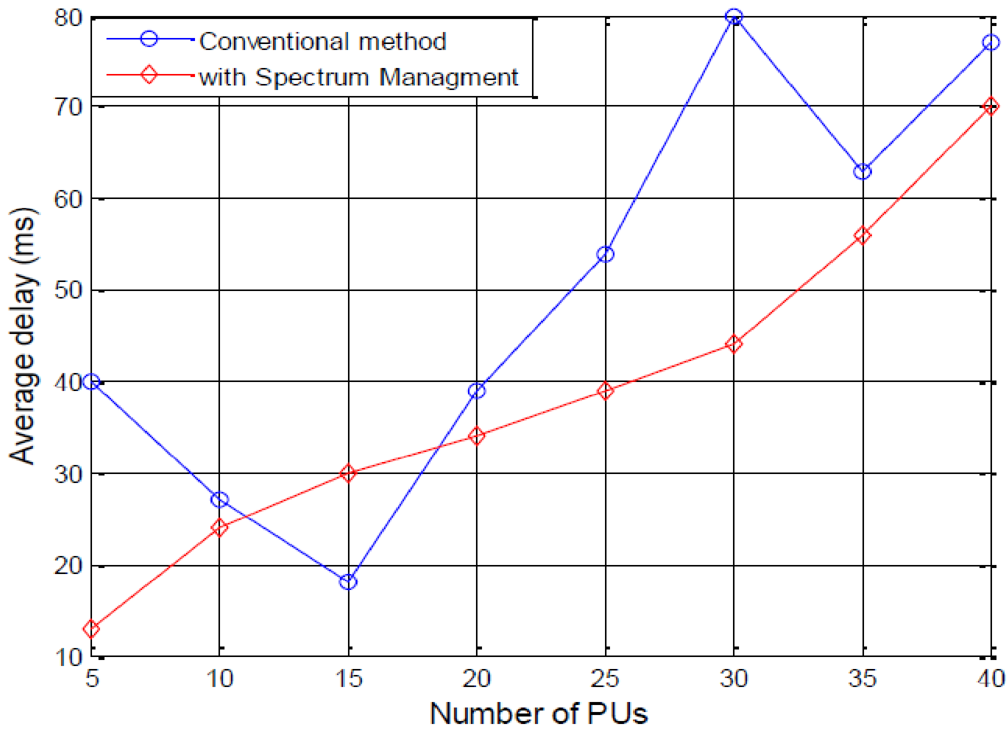

Figure 5.19: The Role of Spectrum Management on the Delay

5.3 The Comparison between the Spectrum Management with/without Game Theory in terms of Network Performance

In this subsection, the comparison between the proposed models in terms of throughput and delay is studied. Figure 5.20 and figure 5.21 show the average throughput as well as the average delay, respectively. The spectrum management with and without game theory are applied into the proposed routing algorithm to analysis the network performance. The network performance is better in case of using the spectrum management without game theory because the path will be selected as per SUs' requirement. However, the spectrum management with game theory is more efficient and dynamic in long term because the path will be selected based on the game, which means every specific period the game will update the choice based on the inputs to the game.

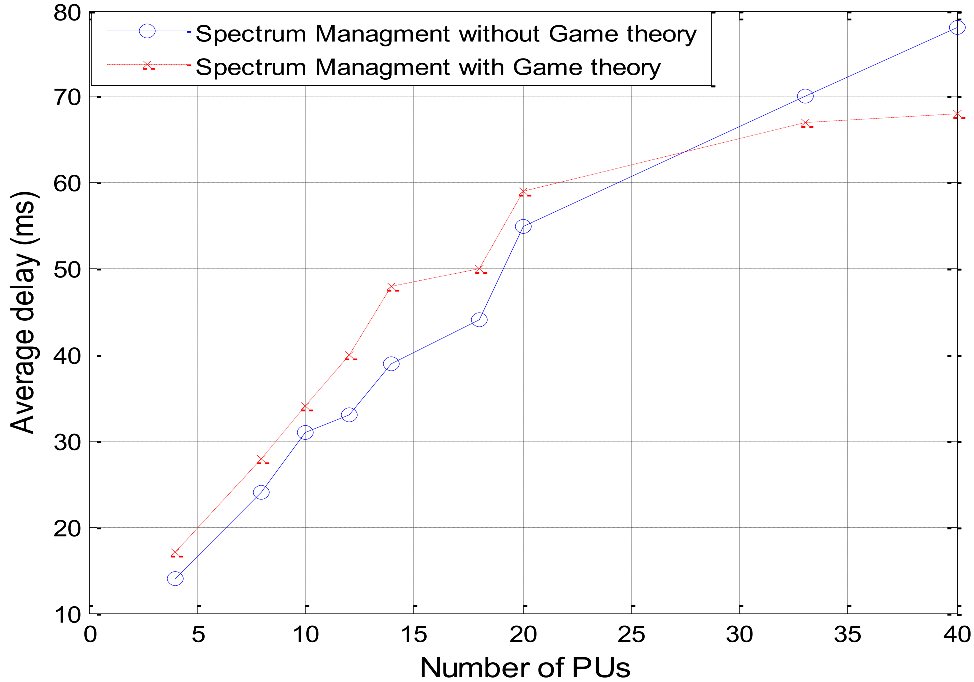

Figure 5.20: The comparison between the spectrum management with and without game theory in terms of delay

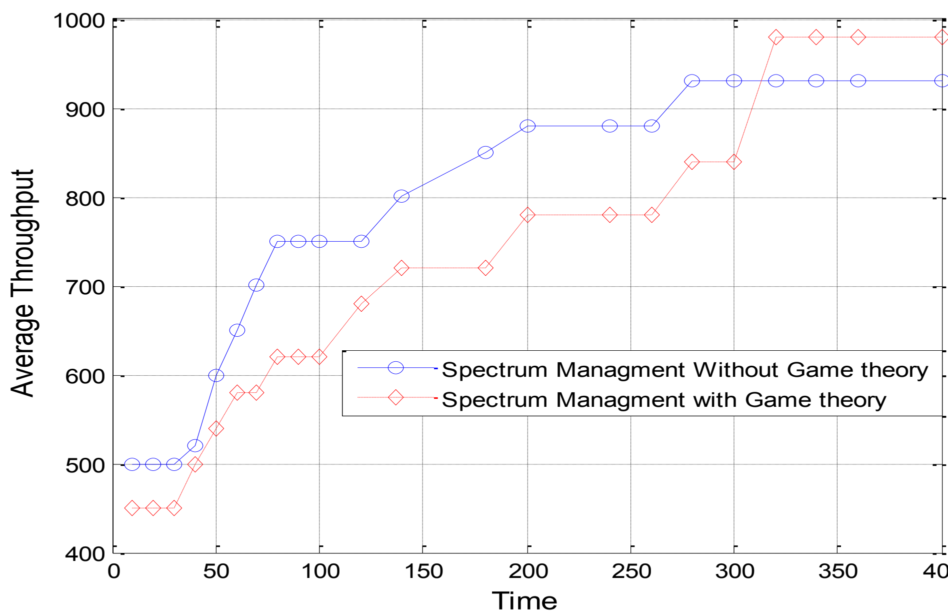

Figure 5.21: The comparison between the spectrum management with and without game theory in terms of throughput

5.4 Summary

The performance evaluation was studied in this chapter. The proposed algorithm was compared with the traditional routing algorithms and the recent routing algorithms. The results showed that the proposed algorithm improved the overall network performance and provided better performance in terms of delay and throughput.

Chapter 6: Conclusion and Future Work

6.1 Conclusion

The problem of developing an efficient QoS algorithm based on spectrum management in a cognitive radio network with game theory application is studied in this thesis. More specifically, this research is focused on designing a QoS routing algorithm by trading the spectrum and considering the competition among PUs from one side and among SUs on the other side. Two models for spectrum management are presented; the first system model is without game theory, where the challenge is to find a more dynamic, efficient, and applicable model to express all the relations between PUs and SUs by considering all the network elements that could affect the price or spectrum or QoS. In the second system model, the game theory concept is incorporated, where the challenge is to obtain Nash equilibrium in each game. A Bertrand game is formulated to model the competition among primary users in terms of price unit for the offered spectrum size. A Stackelberg game is formulated to model the relation between the primary user and the secondary user wherein the primary user is the leader and the secondary user is the follower. An Evolutionary game is formulated to model the selection competition among SUs. The proposed models are incorporated into a proposed QoS routing algorithm in order to improve the network performance. The proposed QoS routing algorithm considers the following: (i) different levels of QoS (ii) shared profiles among PUs & SUs, (iii) spectrum trading (iv) spectrum competition and (v) game theory concept.

The simulation results show (i) the dynamicity and efficiency of the proposed equations, (ii) the Nash equilibrium for each game under different system parameters and under different QoS levels, (iii) that when the proposed models are applied into the proposed QoS routing algorithm, it is better than the traditional routing algorithms (AODV and Shortest Hop) and the recent routing algorithms (DORP and RACON). Simply, the aggregate throughput, delay, efficiency, and the stability of the routes determined by the proposed QoS route algorithm are superior to existing wireless routing algorithms.

6.2 Future Work

Given that this research is the first research work that combines the spectrum management, QoS levels, and game theory for routing algorithm in a CRN, there is still more work to be done. This list represents a few open topics and questions.

- Security: The game theory is used to model the users' behaviors. It can also be applied to suppress selfish and malicious behaviors in these networks to greatly enhance system performance.
- Optimization: The Nash equilibrium does not achieve the highest profit for each primary user. The optimal price, which gives the highest profit, could be obtained by applying optimization techniques.
- QoS levels: Three levels are introduced; it can be extended to more levels as well as to classify the users to a group based on the level.
- Complexities: The complexity in terms of location is a nice and attractive topic in CRN. It can be considered as a part of future work.
- Billing System: This work does not consider the payment process, which can be extended to have the billing system for base station, intermediate node, primary user, and secondary user.

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