# SCHEDULING BASED INTRA NETWORK SPECTRUM SHARING IN COGNITIVE RADIO NETWORKS

By

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# ABSTRACT

The rapid advancement in the wireless technology has created scarcity of the spectrum bandwidth. The wireless connectivity is rapidly increasing which also involves the crowding of unlicensed spectra. This scarcity of spectra has pushed the regulatory authorities to device new ways for the efficient utilization of the existing spectrum. According to Federal Communication Commission (FCC) more than 70% of the available spectrum is not utilized optimally. Due to the shortage of available frequencies the bandwidth becomes expensive. For optimal and efficient usage of spectrum one possibility is to scan the whole spectrum to determine the opportunity for transmission. The term Cognitive Radio refers to the intelligent radios that have spectrum scanning and parameter adjustment capability. This thesis presents schemes for intra-network spectrum sharing in centralized cognitive radio networks. In such schemes a centralized spectrum server is responsible for sharing the spectrum among the cognitive radio users. All transmitters are assumed to have fixed transmitting power. The data rate for the links is computed by using the signal-to-interference ratio on those links. The centralized spectrum server is assumed to have the prior knowledge about the link gains based on which it finds an optimal schedule that maximizes the average data rate on all the active links. Three important scheduling schemes Maximum Sum Rate Scheduling, Max-min Fair Scheduling and Proportional Fair scheduling have been implemented in the context of cognitive radio networks. All of these techniques try to maximize different parameters with the sole objective of maximizing the utility of spectra. In the end Dynamic Scheduling is done by using the three above mentioned techniques by taking the maximum data need as input from the CR users. A simulation of these techniques has been developed in MATLAB and a thorough comparison of these techniques has also been performed.

# DEDICATION

I would like to dedicate this thesis to my teachers, my family and my friends.

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*Chapter 1*

# INTRODUCTION

## 1.1 Introduction

The rapid advancement in the wireless technology has created scarcity of the spectrum bandwidth. The wireless connectivity is rapidly increasing which also involves in the crowding of unlicensed spectra. This scarcity of spectra has pushed the regulatory authorities to device new ways for the efficient utilization of the existing spectrum. The Federal Communications Commission (FCC) which is dealing with the communication and spectrum related issues within the United States is currently working on fixed spectrum assignment policy. They issue license to users in particular geographic areas. This traditional fixed spectrum assignment approach to spectrum regulation has ensured that the licensed (primary) users cause least interference to each other. However, it has created a very crowded spectrum with most of allocated frequency bands to different licensees that demands robust mechanism for better utilization of existing spectrum [2].

To deal with the problem of the shortage of unlicensed spectra, the FCC has been in search of new ways for the management of allocated radio spectrum. The basic idea behind the efficient utilization of spectrum is to allow communication parties to use the licensed spectrum for their communication on negotiated or opportunistic basis with the promise to the licensed users that these secondary users will not create any sort of interference for the licensed users. Cognitive radio technology is emerging as a solution to limited spectra problem.

Cognitive Radio is an intelligent radio that has the ability to sense and adjust its operating parameters according to the radio environment in a very smart way. By sensing I mean that the radio can scan the whole radio spectrum and find opportunity for its transmission. After finding the opportunity in the radio spectrum cognitive radio has the ability to modify its parameters like modulation type, power etc by adjusting in the given environment.

If we look in to the past than we came to know that there were fixed radios and these radios were operating on fixed spectrum with fixed parameters latter on Software Defined Radio (SDR) came to play its role in the communication market. A SDR is a radio that provides the facility to alter its operating parameters including the frequency range, modulation type or maximum radiated power through the use of software without modifications in its hardware. SDR remain favorite among communication parties because of its minimal hardware requirements, cost effectiveness and reliability but it will not incorporate the sensing capability. Now the Cognitive Radio (CR) can be thought of as radio that will take hold the responsibility of transmission in the future wireless networks. It is like the SDR from the functionality point of view with the additional capabilities of sensing, decision and sharing of spectrum.

The FCC Spectrum Policy Task Force [12] reported vast temporal and geographic variation in the usage of allocated spectrum with utilization ranging from 15% to 85% in the bands below 3 GHz.

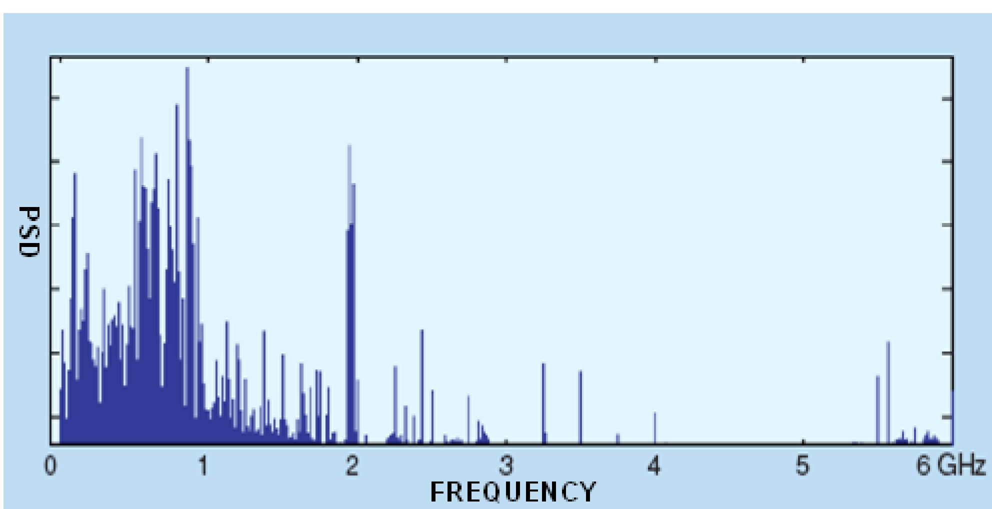


Figure 1.1 Spectrum Utilization Measurements from 0-6 GHz [12]

In the frequency range above 3 GHz the bands are even more poorly utilized as shown by the measurements in Figure 1.1.

The Cognitive radio technology provides the following main functionalities spectrum sensing (find that portion of the allocated spectrum that is not utilized by the primary or licensed use), spectrum management ( analysis and decision of the sensed spectrum based on the requirement of the secondary or unlicensed users) , spectrum sharing ( allocate the spectrum among the secondary users) and spectrum mobility (seamless transition to some other channel whenever the primary user came back on the same channel which is utilizing by the secondary user) [1].

### 1.2 Distinct Features of Cognitive Radios

The main features that distinct the cognitive radios from other type of radios are Cognitive Capability and Reconfigurability [1]. Cognitive radio dynamically sniffs the radio spectrum and finds holes from radio environment in order to perform their communication on the available channel.

#### 1.2.1 Cognitive Capability

This feature allows the Cognitive radio to sense the radio environment and performs real time interaction with it by using the sensed data from the radio environment. The three components of cognitive cycle, Spectrum Sensing, Spectrum Analysis and Spectrum Sharing together explain this feature [1]. The Spectrum Sensing unit performs the holes detection task and delivers its measurements to spectrum analysis block. The spectrum analysis block than analyze the detected spectrum hole and direct its output to spectrum decision block. In the end the spectrum decision block will selects the best channel according to the user requirements.

#### 1.2.2 Reconfigurability

The cognitive radio will have the ability to work on different frequency bands for the transmission of the given data and it can also work on different access technologies with the support of its hardware design [9]. Through this capability, the best spectrum band and the most appropriate operating parameters can be selected and adjusted according to the requirement of the environment. This dynamic reconfiguration is achieved by adjusting all the layers of communication on run time as shown in Figure 1.2.

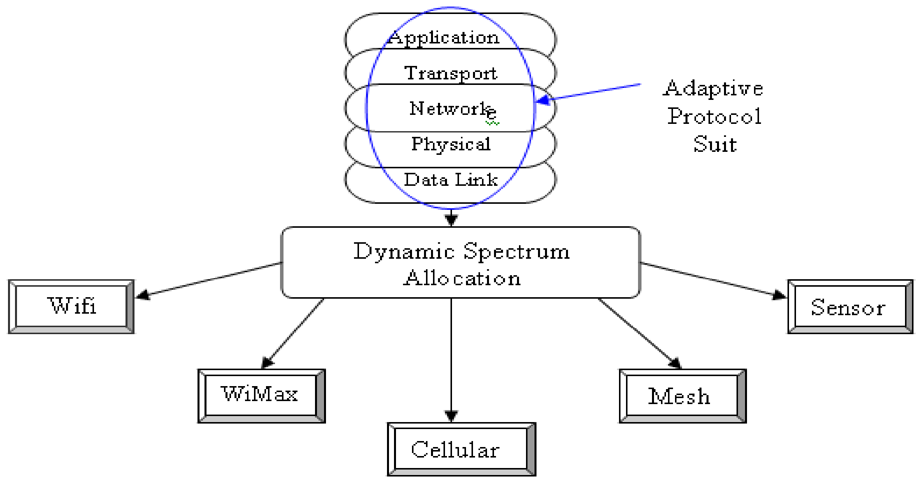


Figure 1.2 Adaptive Protocol Suit [1]

**1.3 The Cognitive Cycle**

The main functionalities of cognitive radio can be best visualized through the cycle given in the figure 1.3.

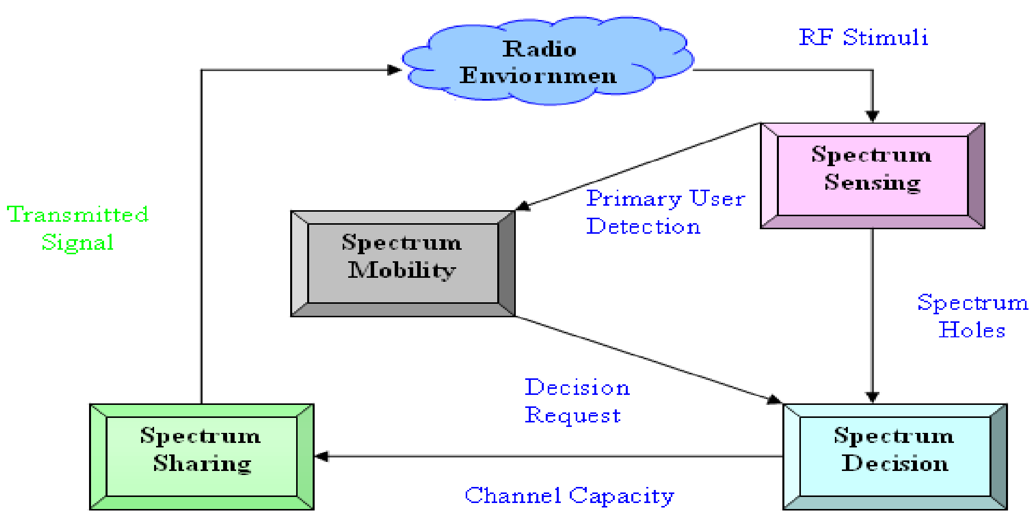


Figure 1.3 Cognitive Cycle [1]

**1.3.1 Spectrum Sensing**

The main objective of the spectrum sensing is to find the portion of the spectrum which is not utilized by the licensed user at any particular time by continuously scanning the radio environment as shown in Figure 1.4. The increasing demand of wireless spectrum creates a challenge of spectrum usage without causing interference to primary user. To alleviate the interference problem the cognitive radio has to shift the spectrum for the primary user in case of arrival of primary user or it can stay on the same spectrum by changing its parameters like modulation type etc.

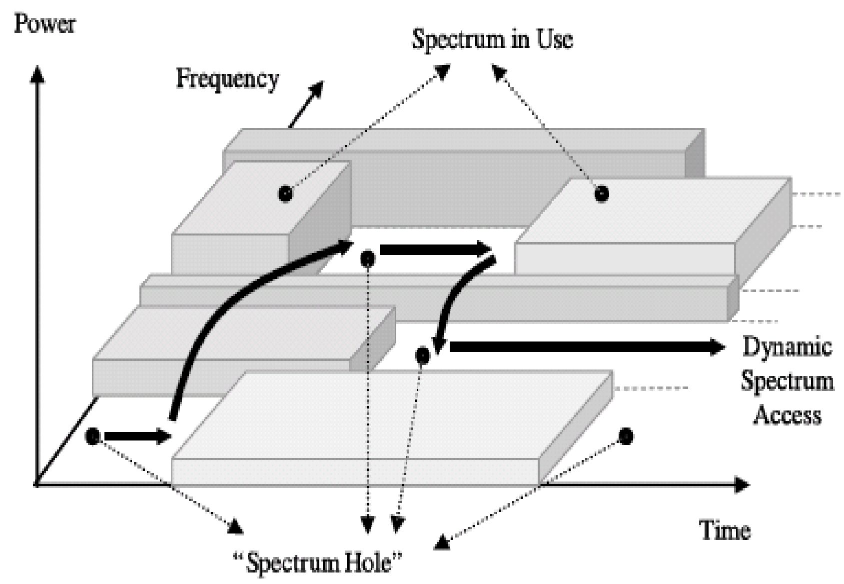


Figure 1.4 Spectrum Hole Concept [1]

### 1.3.2 Spectrum Analysis

The analyses of the detected spectrum holes that are detected through spectrum sensing and their different parameters are estimated during this phase. This step is necessary step towards the selection or rejection of the sensed spectrum.

### 1.3.3 Spectrum Sharing

The Spectrum Sharing coordinates the access to the channel with other users. It is similar to that of multiple accesses technique for the allocation of medium to different users. There are two popular approaches towards the spectrum sharing i.e. underlay and overlay spectrum sharing.

#### *1.3.3.1 Underlay Spectrum Sharing*

The Underlay Spectrum Sharing approach uses the spread spectrum techniques to share the spectrum among the cognitive radio users. In this scheme the cognitive radio users shares the spectrum in the simultaneous and independent fashion. This technique requires very complicated spread spectrum techniques for their implementation but the output of these techniques is optimal in terms of sharing [13].

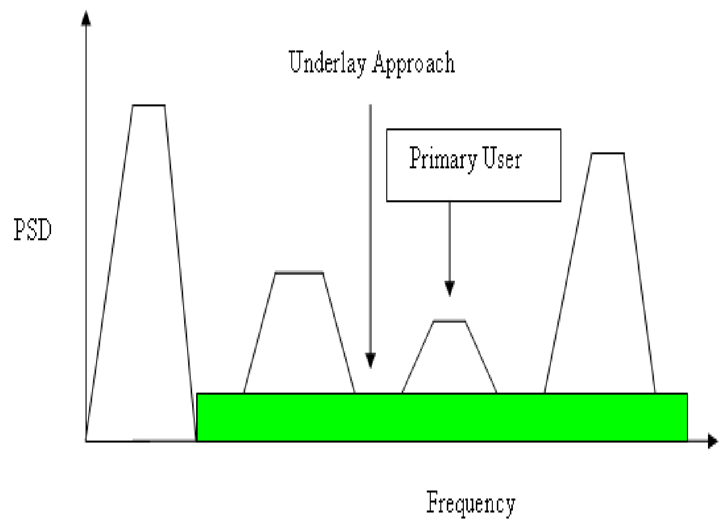


Figure 1.5 Underlay Spectrum Sharing [5]

***1.3.3.2 Overlay Spectrum Sharing***

The Overlay approach shares the available sensed spectrum among the CR users in opportunistic manners [3]. This approach is utilized in cognitive radio networks as shown in figure 1.6.

The spectrum sharing mechanism allows the cognitive radio to communicate on the sensed spectrum in order to maximize the spectrum utilization which is explained in the in the Figure below.

After detecting the spectrum holes through the spectrum sensors the spectrum sharing block allows the usage of detected available spectrum. The main advantage of the sensed spectrum is possible only through the efficient spectrum sharing scheme therefore more attention should be needed towards the sharing schemes.

The overlay approach utilizes the empty spaces in order to maximize the throughput of the Cognitive Radio Networks.

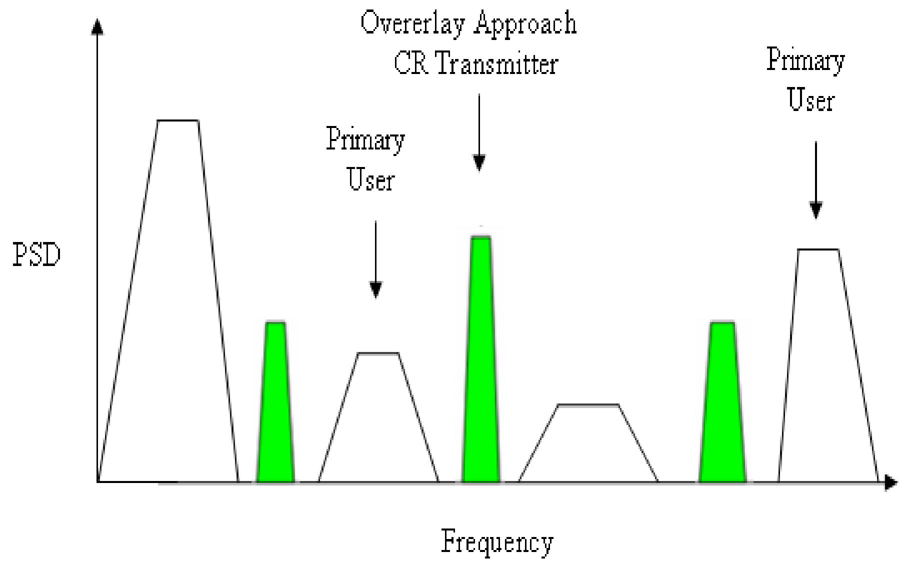


Figure 1.6 Overlay Spectrum Sharing [5]

### 1.3.4 Spectrum Decision

The radio environment is changing continuously so it requires a very intelligent behavior from the cognitive radios. If cognitive radio is using the spectrum of primary user then it must be aware of the changes occurring in the radio environment and if it detects the presence of primary user at any instant of time than it should leave the spectrum or to change its parameter in order to cop with the interference problem with the primary user.

### 1.3.5 Spectrum Mobility

The spectrum mobility ensures the relocation of cognitive radio users to some other available channel whenever the primary user is detected. This functionality is necessary in order to minimize the interference from the primary users.

## 1.4 The Cognitive Radio Architecture

The architecture of cognitive radio seems similar to the existing cellular network architecture. It is not exact because it has its own additional responsibilities that has to be considered during the actual implementation. Moreover, due to dynamic frequency range of the cognitive radios a detailed and well defined explanation of the components of the CR network is essential for the development of communication protocols of these new emerging technologies [1].

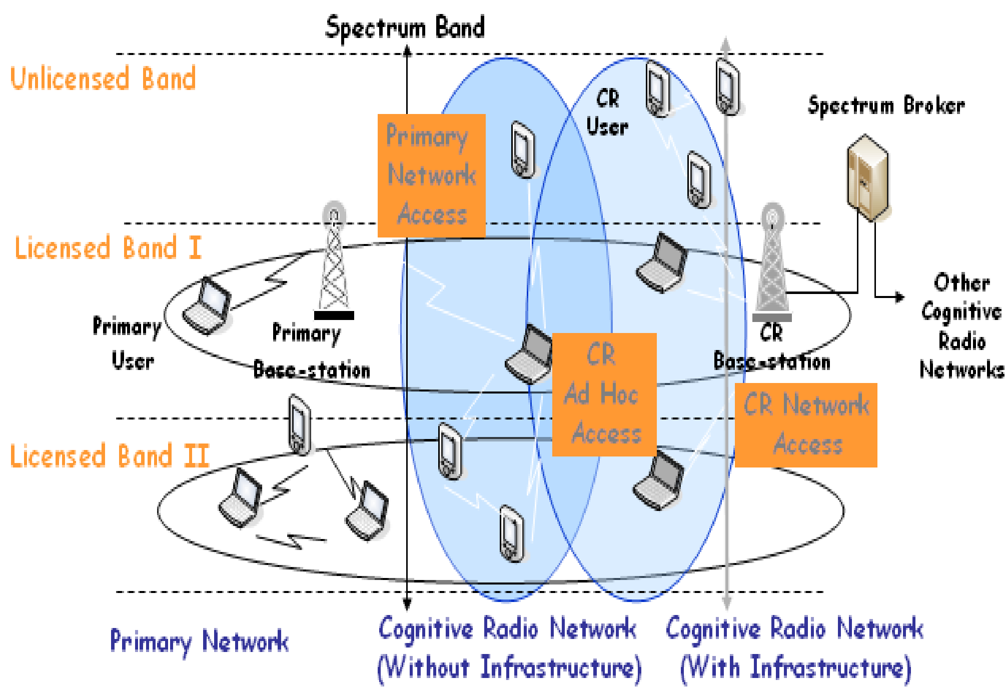


Figure 1.7 Cognitive Radio Network Architecture [1]

The components of the Cognitive Radio network architecture, as shown in figure 1.7, can be classified in two groups such as the primary network and the Cognitive Radio Network.

### 1.4.1 Primary network

A network with rights of the utilization of the radio spectrum band is called primary network, examples include the common cellular network, WiMAX, CDMA and TV broadcast networks. The main components of the primary network are as follows.

#### *1.4.1.1 Primary user*

A primary user has rights to operate in a spectrum band purchased by the primary network holders to carry out its transmission. It has access to the primary network through a central entity called base-station. The base station of primary network is responsible to provide the facility to the user of primary network.

#### *1.4.1.2 Primary base-station*

An entity that controls operations of the user of the primary network is called Primary base-station. Examples are base-station transceiver system (BTS) in a cellular system and BTS in WiMAX etc. Primary base-station needs some modifications if it wants to work with the CR technology because it does not have capability for coexisting with Cognitive Radio Network,

### 1.4.2 Cognitive Radio network

A network that will first find the spectrum holes and then adjusts the parameters according to the environment is called CR network. The CR network can be taken as any sort of network like infrastructure network and an ad hoc network as shown in Figure 1.7. The main components of a CR network are as follows.

#### 1.4.2.1 Cognitive Radio user

Cognitive Radio user or secondary user is a user that doesn't have the licensed band for its operation. It only works on negotiation basis with the existing primary network.

#### 1.4.2.2 Cognitive Radio base-station

Cognitive radio base-station is just like the primary network base-station that has the responsibility to control the operations of CR users with additional features to negotiate with the base station of the primary network.

#### 1.4.2.3 Spectrum broker

Spectrum broker is a central network entity that provides the sharing of spectrum resources among different CR networks. The spectrum broker can work like spectrum server but it has little bit greater responsibility than the spectrum server in the respect that it will take sharing decisions among two or more cognitive radio networks. Hence, spectrum broker can be connected to each network like star topology in Networks and can act as centralized server having all information about spectrum resources to enable coexistence of multiple CR networks.

## 1.5 Applications of Cognitive Radios

Cognitive Radio Networks can be applied to the following cases:

### 1.5.1 Rural Markets and Unlicensed Devices

The rural areas usually have a low density spectrum utilization and since there is very little chance of fading and other types of error many applications can take advantage of that. The unlicensed devices can operate at higher power levels in these areas without causing harmful interference to authorized services [15].

### 1.5.2 Dynamically Coordinated Spectrum Sharing

The ad hoc spectrum sharing techniques can be useful for those types of applications whose spectrum usage pattern is not sure. The coordination information necessary for spectrum sharing can be gathered more effectively through dynamic coordination between sharing entity and the cognitive radio users.

### 1.5.3 Interoperability between Communication Systems

The interoperability is the main requirement in certain type of application like disasters involving multiple jurisdictions, In such application CR network technology seems to be helpful [4].

### 1.5.4 Leased network

The CR network can also negotiate the primary network to utilize their band on leasing basis. The CR can utilized the band available and then pay according to the terms and conditions agreed upon during the negotiation.

### 1.5.5 Cognitive mesh network

The one of the main objective of mesh networks is to meet the high throughput demand of certain applications. Since CR network has the facility of broader spectrum range so it can be thought as the future technology that can fulfills the requirement of mesh networking.

### 1.5.6 Emergency network

Cognitive Radio Networks can also be used in safety as emergency networks [17]. If natural disaster occurs and primary networks are unable to work than their spectrum band can be utilized by using the CR network. CR networks can communicate on available spectrum band in ad hoc mode without the need for an infrastructure.

### 1.5.7 Military Purpose Network

The CR network can also be implemented for the use of military use in remote and any other area where the military radios can choose arbitrary intermediate frequency bandwidth, modulation schemes and coding schemes, according to the radio environment...

### 1.6 Problem Statement

The main purpose of this thesis is to study and design a scheduling based spectrum sharing algorithms for the cognitive radio network. The scheduling among CR users is done against three types of scheduling algorithms i.e. Maximum Sum Rate scheduling, Max-Min Fair scheduling and Proportional Fair scheduling .The results are analyzed and compared among three implemented techniques.

### 1.7 Objectives

The primary objective of this thesis is to study the scheduling based spectrum sharing techniques and implement them through a software to compare their results. The secondary objective is to include identify areas for improvement of results and resolution of the identified deficiencies.

### 1.8 Thesis Organization

The rest of the research is organized as follows. Chapter 2 gives the picture of literature review of the techniques that have been used for spectrum sharing. Chapter 3 gives the formal definition and provides a framework for the solution of the problem in hand. It also lists the assumptions and conditions that define the scope of the work. Chapter 4 illustrates the detailed design of different spectrum sharing techniques. It also further explains how these modules are finally integrated to form a complete test program. Chapter 5 gives a depth analysis of the results obtained during the experimentation and comparison of spectrum sharing techniques. The final chapter concludes the research and highlights of future work, which can be done to carry forward this effort.

### 1.9 Summary

This Chapter covers the broader aspects of the research topic. It presents the motivation behind the selection of this subject as final thesis. It has highlighted the basic aspects of

Cognitive Radio Networks. The problem statement is given to clarify the scope of the project. In the end an organization of the remaining document is provided.

*Chapter 2*

# LITERATURE REVIEW

## 2.1 Introduction

This chapter includes the summary of various spectrum sharing techniques used for the effective utilization of sensed spectrum in CR networks. The chapter encompasses the background work on spectrum sharing techniques for cognitive radio networks.

## 2.2 The Radio Spectrum Regulations

The efficient and reliable spectrum usage demands the regulation authority to provide effective means of transmission of data. In fact the regulators decide about the rights of user and provide an idea how to maximize the usage of available spectrum. There are three possible ways for the spectrum utilization [6].

- Licensed Spectrum
- Unlicensed Spectrum
- Open Spectrum

### 2.2.1 Licensed Spectrum

The licensed spectrum is that portion of the spectrum which is allocated to different parties on certain term and conditions. These portions are assigned to the particular parties with license of operation. The owners pay certain amount for this facility and promise to not create any sort of problem for other license holders.

The static assignment of the spectrum is not the optimal choice for the spectrum utilization due to inflexible behavior it will create problem of spectrum under utilization.

In fact if the spectrum holder commit the action like underutilization its band must be taken back and redistributed for the other technology in order to cop the under utilization problem [6].

### 2.2.2 Unlicensed Spectrum

The unlicensed spectrum is available to all technologies. There is no need to purchase band here. Anyone who is interested in communication can use this spectrum but under the obligation of certain ethical rules to avoid the interference with the other communication parties. Since different technologies can use the same radio spectrum so there may be a chance that it will create starvation problem during certain time.

### 2.2.3 Open Spectrum

The open spectrum allows access in any spectrum portion without the need of a license but under the constraint that it must obey certain rules of spectrum sharing [6]. The target is the liberalization of the radio communication with the aim to overcome the block in accessing the spectrum.

## 2.3 Spectrum Sharing

The main objective after the detection of spectrum holes from the radio environment is to maximize the throughput by optimal spectrum sharing among the cognitive radio users. Many factors will influence the deliverable throughput that needs consideration during the design of spectrum sharing techniques.

### 2.3.1 Similarities with the Medium Access Control (MAC) mechanism

The spectrum sharing in cognitive radio networks looks similar to the MAC access mechanism in wireless LAN (WLAN). In both of these scenarios the multiple transmitters try to capture the shared channel resource for their transmission. The channel access must be coordinated in order to prevent collision among the users of the spectrum.

### 2.3.2 Unique Features

The spectrum sharing in cognitive radio networks differ from the MAC channel access mechanism because of its wide range of spectrum availability and the coexistence issue of cognitive radio users with the primary or licensed users.

## 2.4 Main functions in Spectrum Sharing

The spectrum sharing comprises of the following five main steps namely spectrum sensing, spectrum allocation, spectrum access, and transmitter-receiver hand shake and spectrum mobility [1].

### 2.4.1 Spectrum Sensing

A cognitive radio user can only use a portion of the spectrum if that portion is not used by a licensed user. Before the actual usage of the spectrum the cognitive radio needs to first sniff spectrum to find an opportunity to carry on its transmission.

### 2.4.2 Spectrum Allocation

If the cognitive radio finds some free portion in the spectrum it will forward the measurements to some central entity that will allocate a channel. This allocation procedure not only depends on the availability of spectrum, but also depends on the exchange policies. Hence, the design of a spectrum allocation policy to improve the performance of a node is an important research topic.

### 2.4.3 Spectrum Access

The spectrum access step in spectrum sharing will play a major role in solving the problem of collision when multiple cognitive radio users are trying to access the available spectrum. The access to the spectrum is organized in a way that the throughput should be maximum with minimal numbers of collisions.

### 2.4.4 Transmitter-Receiver Handshake

After the selection of appropriate channel for communication there is a need for the indication of selected spectrum to the receiver. Hence, a transmitter-receiver handshake protocol is essential for efficient communication in cognitive radio networks. The central party may also involve a handshake procedure in the cognitive radio networks. The handshake procedure is he necessary step to exchange control information for the proper communication between the CR users.

### 2.4.5 Spectrum Mobility

This spectrum mobility is a tool to avoid interference of the primary or licensed user in the cognitive radio network. If the cognitive radio user is using a portion of spectrum and during transmission it finds that the primary user needs the spectrum than it must leave the spectrum in order to avoid interference.

These main functions must be under consideration during the design of any sharing technique in cognitive radio networks. The efficiency of the spectrum sharing techniques is directly related to above mentioned five steps.

## 2.5 Classification of Spectrum Sharing Techniques

Figure 2.1 shows the classification of spectrum sharing. The spectrum sharing can be classified as centralized or distributed spectrum on the basis of network architecture [11].

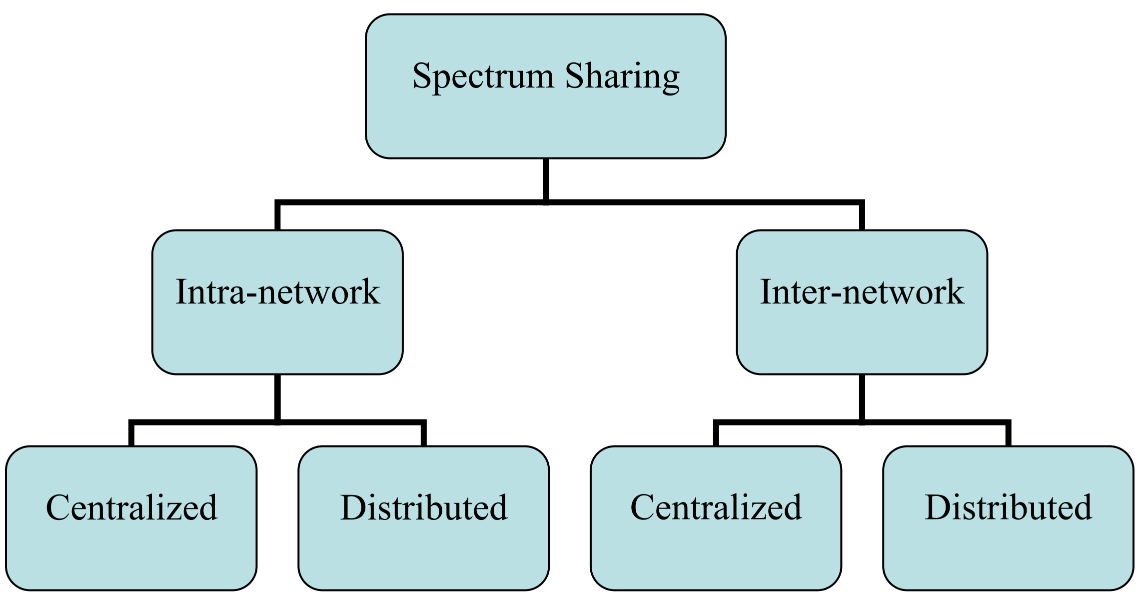


Figure 2.1 Classification of Spectrum Sharing

Depending on how the sharing information is held by the devices, the sharing scheme is called centralized spectrum sharing or distributed spectrum sharing [11]. In centralized spectrum sharing (infrastructure mode) a central entity called spectrum server or cognitive radio base station (CRBS), is responsible to share the available spectrum among the cognitive radio users. On the other hand in distributed spectrum sharing(ad-hoc mode), all the cognitive radio users mutually responsible to share the spectrum efficiently in order to maximize the spectrum usage. The spectrum sharing can be further classified as intra-network spectrum sharing and inter-network spectrum sharing [8]. In intra network spectrum sharing the idea is to shares the spectrums between the same networks entities while in case of inter network spectrum sharing the sharing is done between the entities of different networks. In the past, the problems of centralized spectrum sharing were considered similar to those in Medium Access Control (MAC) mechanism. However, there are many challenges that are unique to centralized spectrum sharing approach that has need to be address in depth for the better implementation of scheduling at the spectrum server. The Coexistence with primary user and wide range of spectrum availability are the two most important problems.

### 2.5.1 Intra-Network Spectrum Sharing

The Intra-network Spectrum Sharing deals with the sharing of sensed spectrum among the cognitive radio users within the CR network. The main focus is the spectrum allocation between the CR users. It also coordinates multiple accesses among CR users in order to prevent their collision in overlapping portions of the spectrum [19].

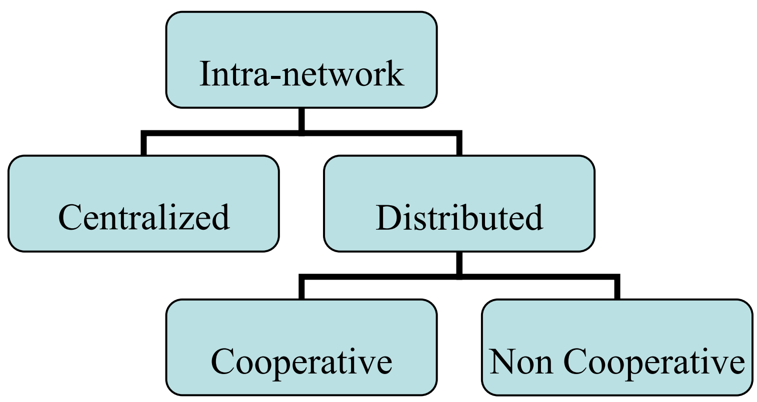


Figure 2.2 Intra-Network Spectrum Sharing

The Intra-network spectrum sharing can be further classified as centralized or distributed as shown in Figure 2.2.

#### *2.5.1.1 Centralized Intra-network Spectrum Sharing*

In centralized intra-network spectrum sharing also called as infrastructure based spectrum sharing a central entity called spectrum server is responsible for the sharing of the spectrum among the CR users. Depending upon the quality of the link and availability of the spectrum the spectrum server forms the allocation map to maintain the records of the link.

In simple language we can say it works like the traffic controller which allocates the certain time to the traffic of particular side keeping in mind the load on that side.

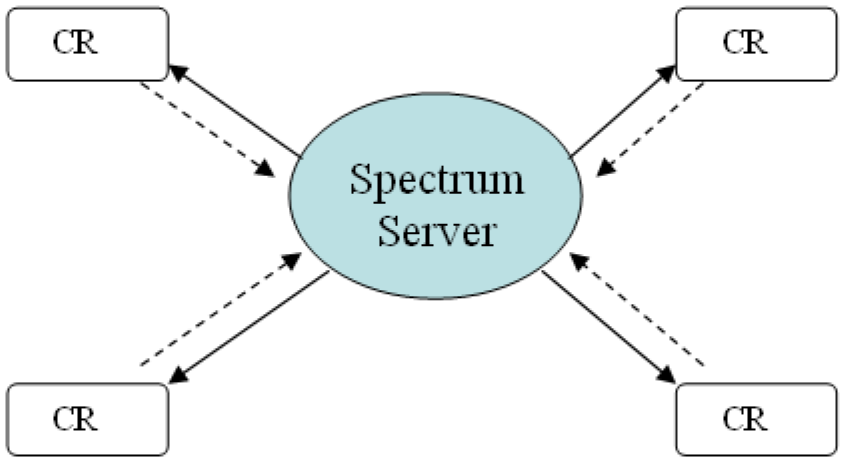


Figure 2.3 Intra-Network Centralized Spectrum Sharing [19]

Figure 2.3 explains the working principle in the centralized mode. All the CR users forward their measurements to the spectrum server through the channel indicated by the dashed lines. The spectrum server analyzes the data forwarded to it and finds the optimum schedule in order to maximize the throughput on the available spectrum. The spectrum server forwards its decision on the channel indicated by the bold line in the above figure.

***2.5.1.2 Distributed Intra-network Spectrum Sharing***

In Distributed Intra-network Spectrum Sharing also called ad-hoc based spectrum sharing each CR user takes part in the sharing of the spectrum among them. The distributed spectrum sharing is further divided into two types cooperative and non cooperative depending upon their sharing behavior.

***2.5.1.2.1 Distributed Cooperative Intra-Network Spectrum Sharing***

In Distributive Cooperative Intra-network spectrum sharing each CR user pass its sensed information to other CR users to make aware of the information it got from the environment as indicated in the figure below by the dashed line.

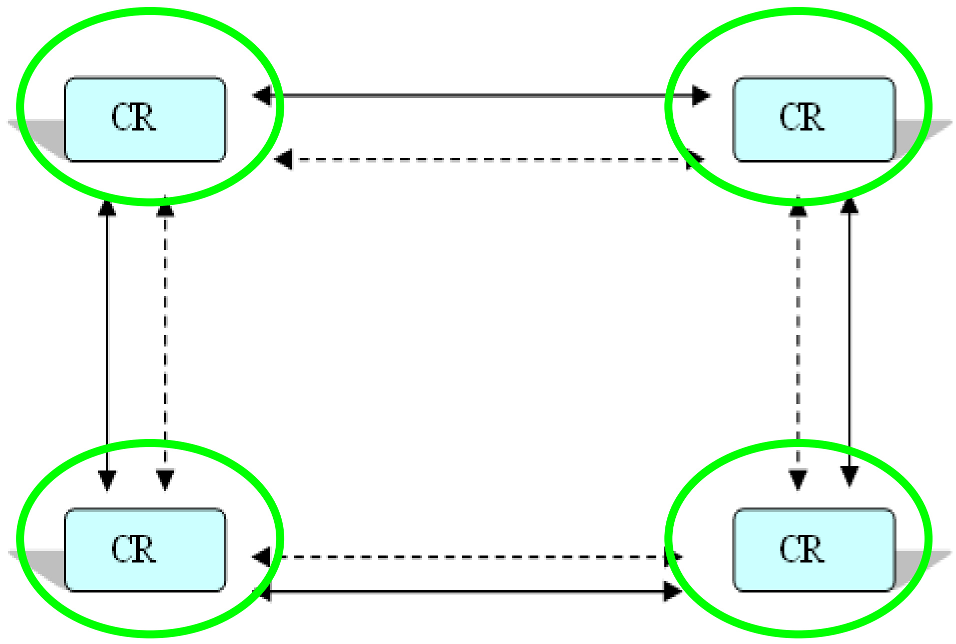

Figure 2.4 Distributed Cooperative Intra-Network Spectrum Sharing

Each CR user then collectively decides about the sharing of available spectrum among them and passes their sharing information to the other CR users as indicated by the bold lines between the CR users in the figure 2.4. By the collective decision of the spectrum sharing the selfish behavior is alleviated and high degree of fairness can be achieved.

***2.5.1.2.2 Distributed Non Cooperative Intra-network Spectrum Sharing***

In Distributive Non-Cooperative Intra-network Spectrum Sharing each CR user is acting independent of each other. CR users do not exchange any information between each other. They only work to maximize their own interests. Some times this behavior is called selfish because these users do not take care of other users interests. The CR users scan the whole spectrum and whenever they find opportunity of transmission they start their transmission on the available spectrum. The selfish behavior causes some CR user to remain in the stall state. In some situations, CR user has to wait long for its transmission on the available band.  This selfish behavior can be minimized by exchanging the control information among CR users to form cooperative behavior.

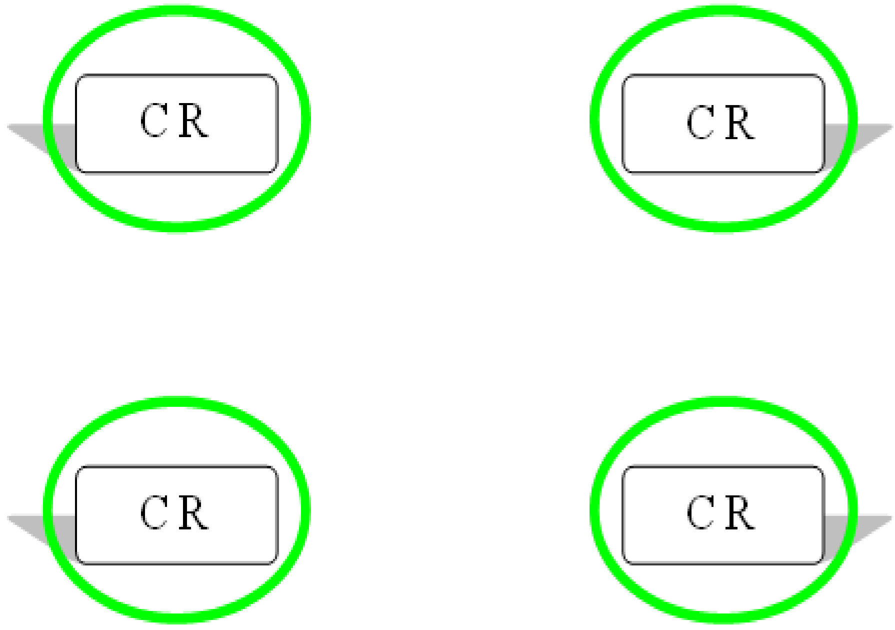


Figure 2.5 Distributed Non Cooperated Intra-Network Spectrum Sharing

### 2.5.2 Inter-Network Spectrum Sharing

The Inter-network Spectrum Sharing deals with the sharing of the spectrum among two or more than two systems that has overlapping locations and spectrum bands. There are further two approaches in this technique distributive and centralized as shown in the Figure 2.1.

#### *2.5.2.1 Centralized Inter-Network Spectrum Sharing*

In Centralized Inter-network Spectrum Sharing a central entity called spectrum broker is responsible for the sharing of the spectrum among the different CR networks. Depending upon the availability of the spectrum, the spectrum broker allocates the spectrum to different CR networks. The spectrum server is also responsible for the coordination and passing of information between different CR networks. The centralized approach is simple to implement but it rely on single entity.

The term System Broker is used in the centralized inter-network spectrum sharing at the place of the spectrum server but the basic idea is same from the functionality point of view.

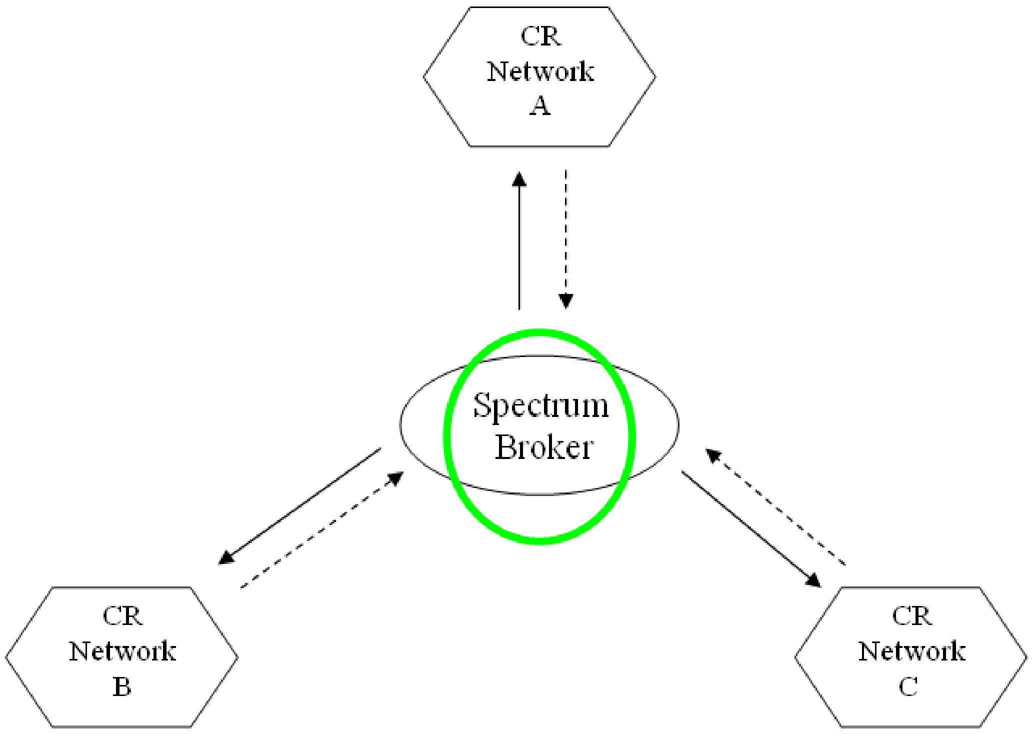


Figure 2.6 Centralized Inter-Network Spectrum Sharing [19]

The Figure 2.6 explains the working of the spectrum broker in the environment where it is responsible to coordinate the sharing of spectrum among three different types of networks A, B, C. Each network forwards its request to the spectrum broker on certain channel indicated by the dotted lines. The spectrum broker analyzes the request and entertains according to the available spectrum and passed the sharing information on the channel indicated by the bold lines.

***2.5.2.2 Distributed Inter-Network Spectrum Sharing***

In Distributive Inter-network Spectrum Sharing each base station at each CR network is acting as manager to share the spectrum among the CR users in its range. It allocates the spectrum to the CR users according to the QoS requirement and availability of the spectrum. The Coordination among different networks is maintained through the information passed on the reserved channel for control information as indicated by the lines between different networks.

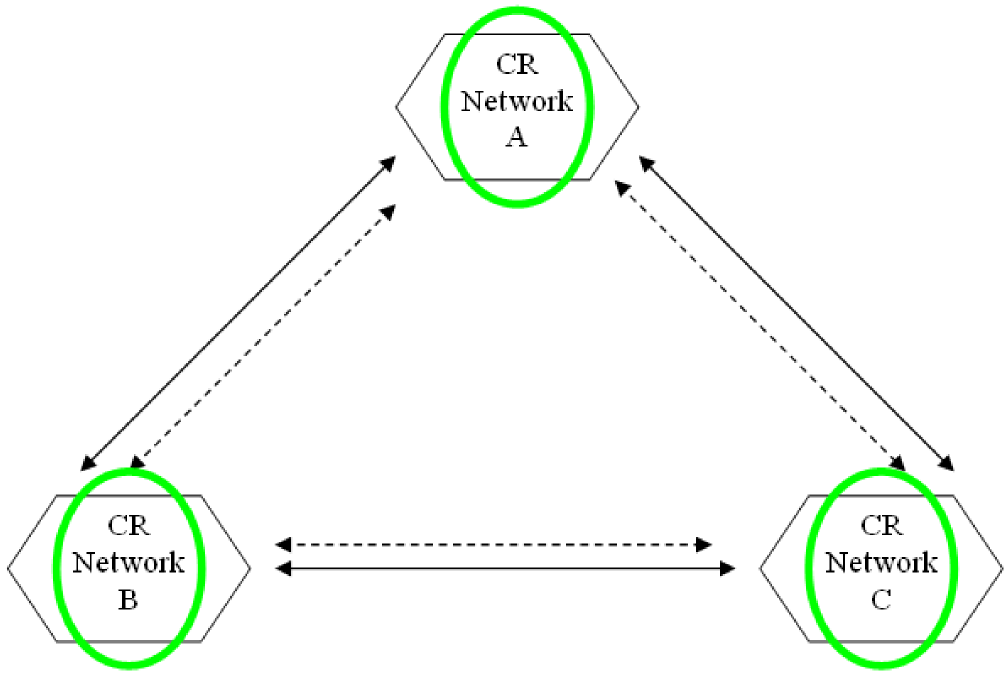


Figure 2.7 Distributive Inter-Network Spectrum Sharing [19]

The classification schemes depicted in the last section create a baseline towards the development of the protocols in the respective architecture.

In the next section the network which is presented in the literature for the implementation of the scheduling scheme is depicted to move towards the implementation approach.

**2.6 Network Model**

The network model that was considered in the literature fort the implementation of spectrum sharing techniques consists of "U" number of users that wants to communicate between each other. There will be maximum possibility of U/2 transmitters and U/2 receivers so they will maximally form "C=U/2" logical links to share the available spectrum. The “C" number of logical links forms "t" number of transmission modes T ={0,1,2,3,4,5 ----------------2C-1}. The pattern vector “$P_S$” is a binary vector that indicates the information about the activation and deactivation of certain link under transmission mode "t” as shown in Figure 2.8 which indicates the network under consideration and figure 3.2 shows a network scenario under certain transmission mode [3].

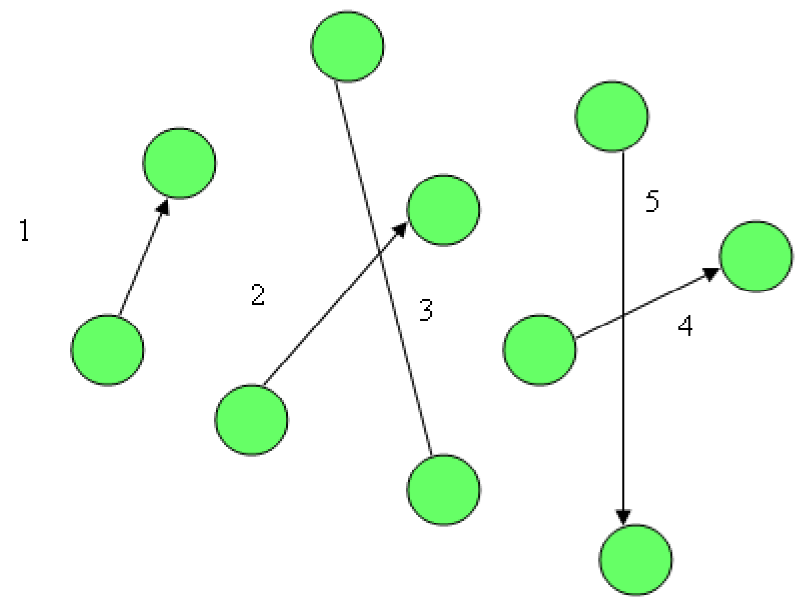


Figure 2.8 Network Showing Nodes and Links

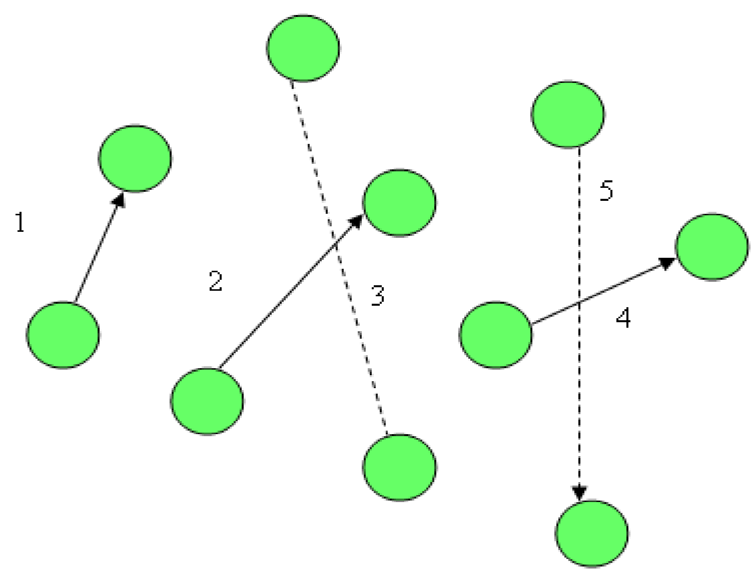


Figure 2.9 Network under Certain Transmission Mode

In the figure 2.8 there are "U"=10 CR users that will take part in the communication so there will be maximum U=10/2 =5 transmitters and U=10/2 =5 receivers at particular time and there will be C=5 logical links and that will results in to "t= $2^{C=5}$=32" transmission modes as shown in the Table 2.1. In particular transmission mode "31" which is in binary "11111" all links are in on state and all the transmitters are active under this transmission mode.

Table 2.1 Transmission Modes for the Five Links

| **Link1** | **Link 2** | **Link 3** | **Link 4** | **Link 5** |
|---|---|---|---|---|
| 0 | 0 | 0 | 0 | 0 |
| 0 | 0 | 0 | 0 | 1 |
| 0 | 0 | 0 | 1 | 0 |
| 0 | 0 | 0 | 1 | 1 |
| 0 | 0 | 1 | 0 | 0 |
| 0 | 0 | 1 | 0 | 1 |
| 0 | 0 | 1 | 1 | 0 |
| 0 | 0 | 1 | 1 | 1 |
| 0 | 1 | 0 | 0 | 0 |
| 0 | 1 | 0 | 0 | 1 |
| 0 | 1 | 0 | 1 | 0 |
| 0 | 1 | 0 | 1 | 1 |
| 0 | 1 | 1 | 0 | 0 |
| 0 | 1 | 1 | 0 | 1 |
| 0 | 1 | 1 | 1 | 0 |
| 0 | 1 | 1 | 1 | 1 |
| 1 | 0 | 0 | 0 | 0 |
| 1 | 0 | 0 | 0 | 1 |
| 1 | 0 | 0 | 1 | 0 |
| 1 | 0 | 0 | 1 | 1 |
| 1 | 0 | 1 | 0 | 0 |
| 1 | 0 | 1 | 0 | 1 |
| 1 | 0 | 1 | 1 | 0 |
| 1 | 0 | 1 | 1 | 1 |
| 1 | 1 | 0 | 0 | 0 |
| 1 | 1 | 0 | 0 | 1 |
| 1 | 1 | 0 | 1 | 0 |
| 1 | 1 | 0 | 1 | 1 |
| 1 | 1 | 1 | 0 | 0 |
| 1 | 1 | 1 | 0 | 1 |
| 1 | 1 | 1 | 1 | 0 |
| 1 | 1 | 1 | 1 | 1 |

If we consider "t=16" which is in binary "01000" indicates the only the link 2 is active and rest of links remains in off state**.** The transmitter of link 2 is only transmitting the data toward the receiver of link 2.

### 2.6.1 Signal to Interference Ratio (SIR)

The quality of each link is determined through the signal to the interference ratio on that particular link. Since there are different patterns of activation of links exist on the basis of transmission modes so there is strong need to calculate the SIR ratio of each link under all possible transmission modes. If we consider the same network which is depicted in the Figure 2.8 than we have to calculate SIR of each links under 32 possible modes so in this case the size of the SIR matrix is 5*32 where five indicates the number of active links and 32 indicates the number of transmission modes. Let assumes that all the transmitters are transmitting data with the same power "Ps" and $K_{Cj}$ is the link gain from the transmitter of link j to the receiver of link C and $\eta_C$ is the noise power at the receiver of link "C", the SIR $\lambda_{Ct}$ at the receiver of link "C" Under transmission mode "t" can be calculated by the relationship [3]

$$\lambda_{Ct} = \frac{Bct * Gcc * Ps}{\sum_{K \in EandK \neq c} Bkt * Gck * Pk + \eta c2}$$

Where $G_{Ck}$ is the link gain from the transmitter of link k to receiver of link C. Ps is the power of link l and $\eta c^2$ is the noise power of link C and Bct is the binary number indicates whether the link c is active under transmission mode t.

### 2.6.2 Data Rate

The data rate of each link under each possible transmission mode "t" is calculated in order to get the qualitative indication about each link under all possible transmission modes. The data rate "Dct" of link c under transmission mode t can be calculated as follow.

$$\text{Dct}=\log(1+\lambda ct)$$

### 2.6.3 Average Data Rate

The average data rate of each link "Ac" c is calculated after getting the scheduling time from the scheduling algorithm. Let "St" is the scheduling time of each link" C" under transmission mode "t" then the average data rate " Ac" can be calculated as [3].

$$\text{Ac}=\sum_t D_{ct} * S_t$$

The real interest lies in findings the "t " number of variables of scheduling time $S_{t.}$ The main objective is to find optimal values of St that will satisfy the CR users requirements.

**2.7 Scheduling Based Spectrum Sharing Techniques**

There are three basic scheduling based spectrum sharing techniques for the sharing of the spectrum among the cognitive radio users that are presented in the literature i.e. Maximum Sum Rate Scheduling, Max-Min Fair Scheduling and Proportional Fair Scheduling as shown in Figure [3].

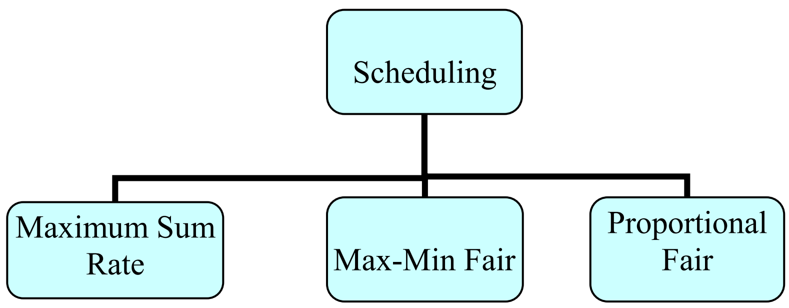


Figure 2.10 Classification of Scheduling Techniques

**2.7.1 Maximum Sum Rate Scheduling**

The Maximum Sum Rate scheduling focuses its attention to maximize the sum of the average data rates over all available links provided that it will satisfy all the constraints. It will take the minimum data rate requirement of each link and then after satisfying the minimum data need of each link it directs its attention towards the best quality links in order to optimal utilization of the available resources. There are two further cases exists in this algorithm minimum rate constraint and non zero minimum rate constraint as shown in Figure

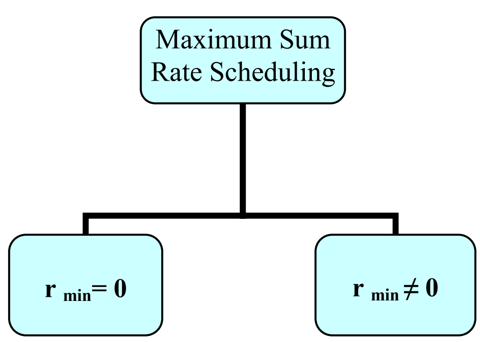


Figure 2.11 Two Cases in Maximum Sum Rate Scheduling

In the first case the maximum sun rate scheduling scheme selects the best of best links for the transmission may be only one link among the “C” possible links. So this will cause starvation for the rest of links.

In the second case this algorithm must have restriction to satisfy the minimum requirement of each link provided that it doesn’t conflict with the available data rate on link.

By maximizing the average data rate it will attain the high value of throughput but it totally ignores the fairness criteria. It is modeled in the form of the linear program.

The objective function of the maximum sum rate scheduling scheme is $1^T A = \sum_t A_t$ is to maximize the sum of average data rates of the all the available links. The constraint $\mathbf{A} \geq \mathbf{A}min$ represent the minimum data rate constraint of each link. The constraint $1^T S = \sum_t S_t$ is the constraint on the scheduling time assign to different links.

$$\begin{aligned} \text{max} \quad & \mathbf{1}^T\mathbf{DS} \\ \text{subject to} \quad & \mathbf{DS} \geq \mathbf{A}\text{min} \\ & \mathbf{1}^T\mathbf{S} \leq 1 \\ & S \geq 0 \end{aligned}$$

***2.7.1.1 No Minimum rate constraints***

We now consider the special case when the minimum data rate requirement from all the links $\mathbf{A}min.\mathbf{1} = \mathbf{0}$. In such case the maximum sum rate algorithm will entertain and focus only the best quality links and use them for transmission and neglects the rest of poor quality links and thus causes unfairness to poor quality links. Thus it will shows preference to certain transmission modes from the possible transmission mode 'TM'. For example there are three links available and link 1 and link 2 have relatively low quality as compared to link three in this particular case the transmission mode 1 is active for the whole period of one second and rest of links 1 and 2 remains un entertained.

### 2.7.2 Max- Min Fair Scheduling

The maximum sum rate scheduling is biased towards links that have the best quality (i.e., least interference) and is unfair to the other links that have poor quality. In order to resolve these issues there are other scheduling techniques that will concentrate on fairness criteria known as max-min fair, proportional fair. The max-min fair[3] scheduling schemes allocates the time to all active links in such a way that at the end each link gets the same data rate. The poor quality links requires more time to reach the equal average data rate point. The LP which maximizes the minimum common rate among the links is[

$$\begin{aligned} \max \quad & A\text{min} \\ \text{subject to} \quad & \mathbf{A} = \mathbf{DS} \\ & \mathbf{A} \geq A\text{min}\mathbf{1} \\ & \mathbf{1}^T S = 1 \\ & \mathbf{S} \geq \mathbf{0}. \end{aligned}$$

### 2.7.3 Proportional Fair Scheduling

The max-min fair schedule discussed in the previous section leads to global fairness. In order to provide the fairness on individual link basis another technique is popular called proportional fairness technique. This technique schedules the links according to their link quality. The idea is simple it will assign the same scheduling time to each link and in the results the links that has the poor quality gets lower average data rate. It is also modeled as the linear program in the literature [3].

$$\max \sum_t \log At$$

$$\text{subject to } A=DS$$

$$1^T S=1$$

$$S \geq 0$$

The three existing scheduling based spectrum sharing schemes device a way for the new scheme efficient utilization of available spectrum.

### 2.8 Summary

This chapter explained the core ideas extracted through the literature review regarding the sharing and the scheduling techniques.

*Chapter 3*

# MODELING PHILOSOPHY

## 3.1 Introduction

The main purpose of this thesis is to develop an efficient spectrum sharing scheme within the infrastructure cognitive radio network. Extensive research has been carried out to arrive at the final results which shall be presented later in this report.

## 3.2 Scope

In the present system the cognitive radios pass their sensed information which contains the data (spectrum availability, data rate, modulation type) to the centralized spectrum server located at the cognitive radio base station. The spectrum server is assumed to be aware of the link gains and the power of each transmitter. The spectrum server forms the allocation map by scheduling the resource among the cognitive radio users in order to maximize the spectrum utilization. The scheduling algorithm used in the system not only maximize the resource utilization but also allows the fairness among the competitors of the spectrum in the infrastructure mode of operation.

## 3.3 Block Diagram

The block diagram of the system under consideration is depicted in the figure 3.1. The spectrum server takes the sensing information as input from the CR users. On the basis of link gains and power of transmitters it will calculate the data rate for each of the link. The server has the choice to schedules the time for each of the link by selecting any of the three schemes mentioned in the diagram.

The average data rate can be calculated by multiplying the data rate with the scheduling time assign to each link. The average data rate depends on the scheduling time assigns to individual links that will indicates the link activation pattern. In certain case all the links are active under certain transmission mode.

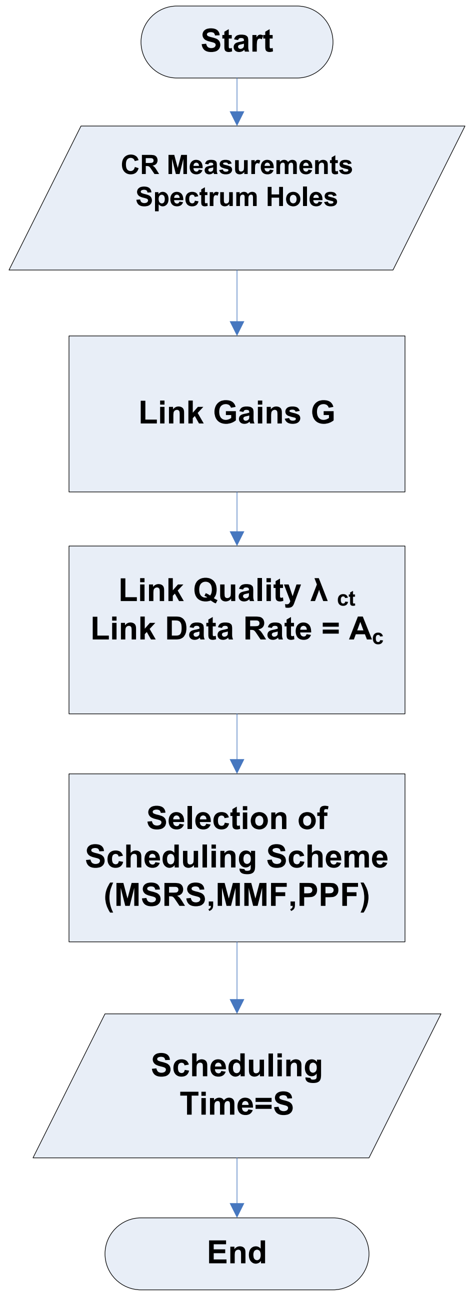


Figure 3.1 Block Diagram of System

### 3.3.1 Cognitive Radio Measurements

The Cognitive radio forwards its measurements towards the spectrum server for the purpose of sharing of the sensed spectrum. The main measurement is the sensed spectrum information etc.

### 3.3.2 Spectrum Server

The Spectrum Server which has the link gain information performs some necessary tasks in order to calculate the quality of each link.

### 3.3.3 Data Rate Calculation

On the basis of link gains and the quality of links, the spectrum server calculates the data rate on each individual link.

### 3.3.4 Scheduling

The spectrum server has a choice of three different techniques for the scheduling purpose. It can select any scheme and perform the necessary steps to provide the scheduling results.

### 3.3.5 Average Data Rate

The average data rate is calculated by multiplication and averaging of the data rate and the scheduling time.

All steps which are described above are necessary in order to perform the resultant scheduling.

## 3.4 The Modeling Procedure

In order to understand the true behavior of the algorithms of three basic scheduling schemes, there is a need to break it into different steps to provide modular approach of understanding.

### 3.4.1 Modeling Steps of Maximum Sum Rate

The linear program of maximum sum rate scheme can be modeled in the following way. The D matrix is C*t matrix and S is the vector of length C. The resultant matrix is obtained by the multiplication of both matrices.

$$D*S=\begin{bmatrix} D_{11} & D_{12} & D_{13} & \dots\dots\dots & D_{ct} \\ D_{21} & D_{21} & D_{23} & \dots\dots\dots & D_{Ct} \\ D_{31} & D_{31} & D_{33} & \dots\dots\dots & D_{Ct}. \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ D_{c1} & D_{c2} & D_{c3} & \dots\dots\dots & D_{Ct} \end{bmatrix}\begin{bmatrix} S_1 \\ S_2 \\ S_3 \\ \dots\dots \\ S_t \end{bmatrix}$$

Where D is the data rate and S is the scheduling time of individual transmission modes.

**Formation of Objective function:**

$$\mathbf{F=1}^{\mathbf{T}}\begin{bmatrix} D_{11}.S_1 & D_{12}.S_2+ & D_{13}.S_3+ & \dots\dots\dots & +D_{1t}.S_t \\ D_{21}.S_1+ & D_{22}.S_2 & D_{23}.S_3+ & \dots\dots\dots & +D_{2t}.S_t \\ D_{31}.S_1+ & D_{32}.S_2+ & D_{33}.S_3+ & \dots\dots\dots & +D_{3t}.S_t \\ \vdots & \vdots & \vdots & \dots\dots\dots & \vdots \\ D_{C1}.S_1+ & D_{C1}.S_1+ & D_{C1}.S_1+ & \dots\dots\dots. & +D_{Ct}.S_t \end{bmatrix}$$

**Formation of Greater than Constraint:**

$$\text{CX} \geq \mathbf{r}\text{min}=\begin{bmatrix} D_{11} & D_{12} & D_{13} & \dots\dots\dots & D_{ct} \\ D_{21} & D_{21} & D_{23} & \dots\dots\dots & D_{Ct} \\ D_{31} & D_{31} & D_{33} & \dots\dots\dots & D_{Ct}. \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ Dc_1 & Dc_2 & Dc_3 & \dots\dots\dots. & D_{Ct} \end{bmatrix}\begin{bmatrix} S_1 \\ S_2 \\ S_3 \\ \dots.. \\ Sc \end{bmatrix} \geq \begin{bmatrix} A_{\min 1} \\ A_{\min 2} \\ A_{\min 3} \\ \vdots \\ A_{\min c} \end{bmatrix}$$

**Formation of Less than Equal to Constraint:**

$$\left[S_1 + S_2 + S_3 + S_4 + S_5 \dots\dots\dots\dots\dots\dots\dots. S_t\right] \leq 1$$

**Formation of Lower Bound:**

$$\left[S_{1,} S_{2,} S_{3,} S_{4,} S_5 \dots\dots\dots\dots\dots\dots\dots S_t\right] \geq 0$$

### 3.4.2 The Modeling Steps of Max-Min Fair Scheme

The linear program of Max-Min Fair scheduling scheme presented in the chapter 2 can be modeled in the following way. The D matrix is C*t matrix and S vector is of length C.

$$\text{D*S}=\begin{bmatrix} D_{11} & D_{12} & D_{13} & \dots\dots\dots & D_{ct} \\ D_{21} & D_{21} & D_{23} & \dots\dots\dots & D_{Ct} \\ D_{31} & D_{31} & D_{33} & \dots\dots\dots & D_{Ct}. \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ Dc_1 & Dc_2 & Dc_3 & \dots\dots\dots. & D_{Ct} \end{bmatrix}\begin{bmatrix} S_1 \\ S_2 \\ S_3 \\ \dots.. \\ Sc \end{bmatrix}$$

**Formation of Objective function:**

F= [0, 0, 0, 0 ,0, 0, 0…………t , -1]

**Formation of Equal to Constraint:**

$$\begin{bmatrix} A_1 \\ A_2 \\ A_3 \\ \vdots \\ Ac \end{bmatrix} = \begin{bmatrix} D_{11} & D_{12} & D_{13} & \dots\dots\dots & D_{ct} \\ D_{21} & D_{21} & D_{23} & \dots\dots\dots & D_{Ct} \\ D_{31} & D_{31} & D_{33} & \dots\dots\dots & D_{Ct}. \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ Dc_1 & Dc_2 & Dc_3 & \dots\dots\dots & D_{Ct} \end{bmatrix} \begin{bmatrix} S_1 \\ S_2 \\ S_3 \\ \dots\dots \\ Sc \end{bmatrix}$$

**Formation of Greater than Equal to Constraint:**

$$\begin{bmatrix} A_1 \\ A_2 \\ A_3 \\ \vdots \\ Ac \end{bmatrix} \geq A_{min.} \begin{bmatrix} 1 \\ 1 \\ 1 \\ \vdots \\ 1 \end{bmatrix}$$

**Formation of Equal to Constraint:**

$$[S_1 + S_2 + S_3 + S_4 + S_5 \dots\dots\dots\dots\dots\dots S_t] = 1$$

**Formation of Lower Bound:**

$$[S_1, S_2, S_3, S_4, S_5 \dots\dots\dots\dots\dots\dots S_t] \geq 0$$

**3.4.3 The Modeling Steps of Proportional Fair Scheme**

The linear program of Proportional Fair scheduling scheme presented in the chapter 2 Can be modeled in the following way. The D matrix is C*t matrix and S vector is of length C.

$$D*S= \begin{bmatrix} D_{11} & D_{12} & D_{13} & \dots\dots\dots & D_{ct} \\ D_{21} & D_{21} & D_{23} & \dots\dots\dots & D_{Ct} \\ D_{31} & D_{31} & D_{33} & \dots\dots\dots & D_{Ct}. \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ Dc_1 & Dc_2 & Dc_3 & \dots\dots\dots & D_{Ct} \end{bmatrix} \begin{bmatrix} S_1 \\ S_2 \\ S_3 \\ \dots\dots \\ S_t \end{bmatrix}$$

**Formation of Objective function:**

F=[0, 0, 0, 0 ,0, 0, 0…………t , +log($A_1$)+ log($A_2$)+ log($A_3$)+ ……… +log($A_L$)]

**Formation of Equal to Constraint:**

$$\begin{bmatrix} A_1 \\ A_2 \\ A_3 \\ \vdots \\ Ac \end{bmatrix} = \begin{bmatrix} D_{11} & D_{12} & D_{13} & .......... & D_{ct} \\ D_{21} & D_{21} & D_{23} & .......... & D_{Ct} \\ D_{31} & D_{31} & D_{33} & .......... & D_{Ct} \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ Dc_1 & Dc_2 & Dc_3 & .......... & D_{Ct} \end{bmatrix} . \begin{bmatrix} S_1 \\ S_2 \\ S_3 \\ ..... \\ St \end{bmatrix}$$

**Formation of Equal to Constraint:**

$$\left[ S_1 + S_2 + S_3 + S_4 + S_5 .................... S_t \right] = 1$$

**Formation of Lower Bound:**

$$\left[ S_{1,} S_{2,} S_{3,} S_{4,} S_5 ................... S_t \right] \geq 0$$

**3.5 Dynamic Spectrum Sharing Scheme**

The three basic scheduling scheme presented above is scheduling data among the CR users in one second and assuming the network conditions to remain same. As we know that the radio environment is changing continuously so there is strong need to cop this behavior within the scheduling or sharing scheme. Secondly, the mobility behavior is also an important factor for the cognitive radio networks because if the primary user comes back to the same band that is in use of CR user, then CR user must have to leave the band immediately in order to avoid the interference from the primary users. Thirdly, the throughput is also an important consideration for any sort of network. All these three factors demand the robustness of sharing scheme for the cognitive radio network in order to be dynamic and have ability to support mobility and the throughput.

The Dynamic scheme proposed in this section will take the user data requirement in bits/sec and fulfill the user's requirement by utilizing the scheduling schemes presented in the last sections. It will accept the request of users according to the available links and then schedule in a way to fulfill the user requirement in the least possible time. Usually there is a situation in which there more users than the available channel so there is need to maintain the waiting queue. This Scheme will take consideration of both the throughput and the mobility factors by allowing the users to switch between different available channels. The throughput is maximized in such a way that if some link or channel has better quality and it fulfils the users request early than it will bring the data of some other user to maximizes the utilization of available links.

In short the Dynamic scheme has the following capabilities

- Consideration of Changes in the Radio Environment
- Maximizes the Throughput
- Support Mobility
- Segmentation

### 3.5.1 Consideration of Radio Environment

In order to take consideration of changes in the radio environment the link conditions are computed after each second so after each second the SIR ratio of each link is changed and the next time before scheduling of links the updated data is placed in to the scheduler to force it schedule according to the changes in the radio environment.

### 3.5.2 Maximizing Throughput

The Dynamic Scheduler maximizes the throughput by allowing the data of multiple users to be sent on the same link if the quality of link is able to support it.

### 3.5.2 Mobility Support

As we know that for the proper operation of the cognitive radios it must have to support the mobility. The Dynamic scheme also exhibit this behavior..

### 3.5.2 Segmentation

This Dynamic scheme also has the ability to segment the data in to different chunks through the process of segmentation. The data of users is segmented and sent them on different channels by taking into it the consideration of the changes in the radio environment.

By taking all the factors mentioned above the Dynamic Scheduling scheme can utilize the above mentioned technique for scheduling and the demand of users is fulfilled in the least possible time by maximizing the throughput.

### 3.6 Summary

Chapter 3 sets up the basis of this research. It narrows down the vastness of the topic to the conditions and assumptions under which this work has been done. The chapter breaks down the process into modules and briefly explains the functioning of each individual module. In the end the proposed scheme is presented with all the factors that it will take into account.

*Chapter 4*

# IMPLEMENTATION, RESULTS AND DISCUSSION

## 4.1 Introduction

This chapter concentrates on the implementation of spectrum sharing techniques to obtain results for all designed scheduling algorithms and subsequent analysis. First, overall program structure has been discussed followed by the algorithms. Lastly, composition of the different experiments designed and conducted during the research has been discussed.

## 4.2 Basic Network Model

First of all we need to model the centralized intra-network cognitive radio network on which we can apply different spectrum sharing techniques. The model consists of "U" numbers of cognitive radio users that results in to"C" numbers of links. The "C" links forms the possibility of "$2^C$ "Transmition modes.

**Step 1:** The system parameters are set in this part. The parameters are: (i) the power, '$p_s$'; (ii) the noise , 'sigma'; (iii) link gain, 'G'; (iv)number of cognitive radio users, 'U'; (v) number of links , 'C'; (vi) transmission modes, 't'; (vii)signal to interference ratio of each link, 'Si'; (viii) data rate of each link, 'Dc'.

**Step 2:** The number of links can be calculated by simply dividing the number of nodes by 2.

**Step 3:** The transmission mode can be formed by the formula $2^c$ and conversion from decimal to binary.

**Step 4:** The power and link gains are set in order to calculate the quality of each link through the quantity signal to interference ratio.

**Step 5:** The signal to interference ratio and data rate is calculated by utilizing the calculations at step 2, 3 and step 4.

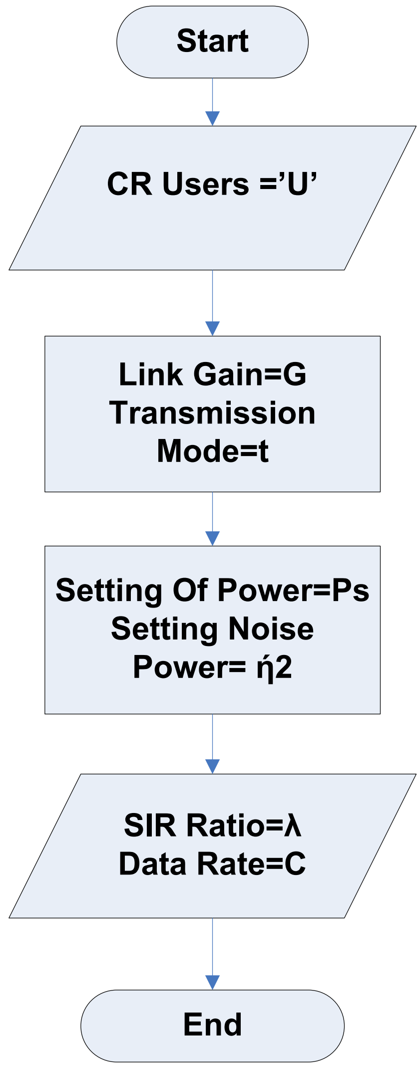


Figure 4.1 Flow Chart for Implementation of Basic Network

The MATLAB script 'BasicNetwork.m', presented on Annex1 simulates the basic network assumed for simulation of Spectrum Sharing in Cognitive Radio Networks. The code is self-expletory.

**4.3 Maximum Sum Rate Scheduling**

The simplest scheduling technique for spectrum sharing is the maximum sum rate scheduling. As discussed in Chapter 3 the maximum sum rate scheduling algorithm is interested in maximizing the sum of the average of data rates. It takes the minimum data rate requirement from each link and maximizes the average data rate over the all possible links. In maximum sum rate scheduling algorithm the links that has the better quality will get the more chance of transmission and it shows little interest towards the poor quality links.

### 4.3.1 Maximum Sum Rate scheduling with Amin ≠ 0

The Maximum Sum Rate scheduling algorithm takes the minimum average data rate requirement from the each R user and makes the schedule on the basis o f the requirement of each CR user. It fulfills the minimum requirement for each CR user and then tries to maximize the sum rate by allowing the CR users that have the better quality link.

### 4.3.2 Maximum Sum Rate scheduling with Amin = 0

There is a special situation in case of the Maximum Sum Rate scheduling algorithm when all the links requires minimum data rate equals to zero. In such scenario the algorithm select the best links among the available and give them to total time to maximize the average data rate on all links. In such case it seems that the Maximum Sum Rate scheduling algorithms favors to some best quality links.

The procedure of the Maximum Sum Rate Scheduling is as follows.

**Step 1:** First call the BasicNetwork.m to get the data rate matrix C by using

Basic Network (U).

**Step 2:** Find the objective function $1^{T}DS$ by using the matrix multiplication and addition to get the objective function f.

**Step 3:** Convert the minimization to maximization optimization problem by equating the

f=-f;

**Step 4:** Set the greater than equal to constraint as follow

A=-c;

b=-Amin .

For less than equal to constraint use matrix multiplication and addition to find 1T S <1.

**Step 5:** Set the lower bound by the following equation

lb=zeros(32,1);

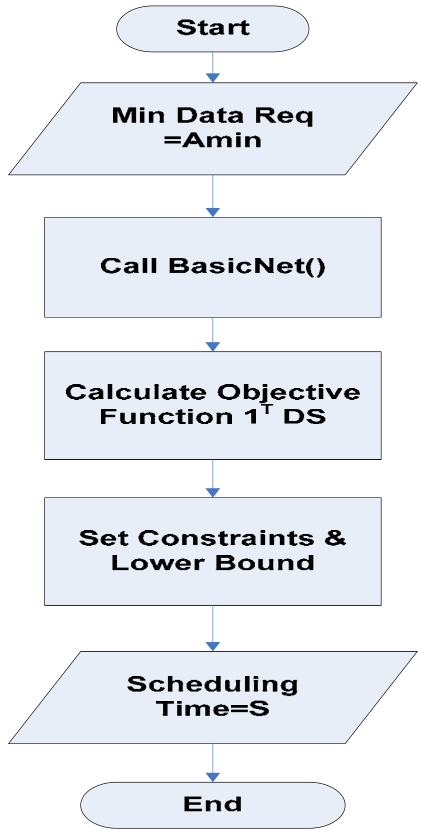


Figure 4.2 Flow Chart for Implementation of Maximum Sum Rate Scheduling

Flow chart for the implementation of Maximum Sum Rate Scheduling is shown in Figure 4.2. The MATLAB script 'MaxSumRate .m', presented in Annex I, Maximum Sum Rate Scheduling for Spectrum Sharing in Cognitive Radio Networks. The code is self explanatory.

### 4.3.3 The Sum Rate

The sum rate is obtained by adding the average data rates on individuals' links. The sum rate is the indication of the quality of each link.

Figure 4.3 shows the average data rates of individual links and sum rate against different values of $A_{min}$, the minimum average data rate requirement of each link. At $A_{min}$=0 the link 1 and link 4 are active only and they maximize the sum rate to optimal value but it will causes unfairness to other links. As the minimum data rate requirement of each link increases the sum rate decreases due to the poor quality of some links and all links try to contribute towards the sum rate and opportunity moves towards fairness. At certain value of $A_{min}$ links will get equal data rate and are said to be in max-min fair mode. This point is in the plot where the data rates from all links meet to a point.

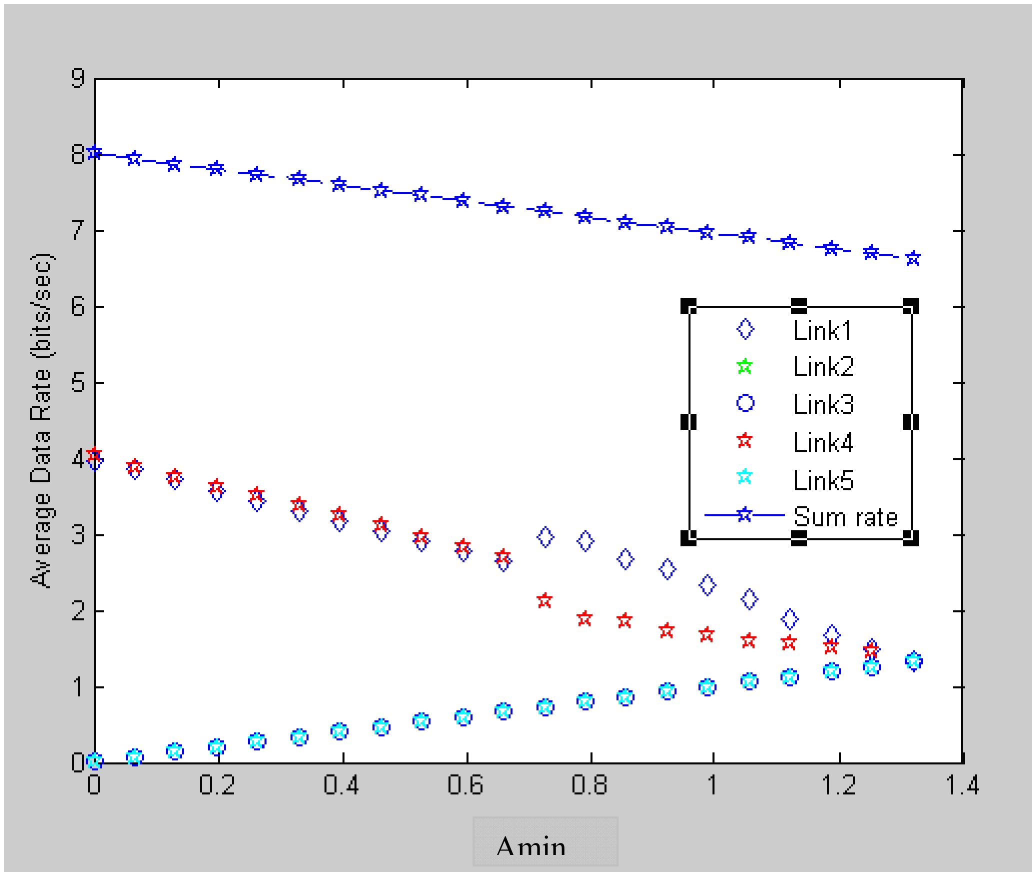


Figure 4.3 Maximum Sum Rate Scheduling at Different Values of $A_{min}$

Figure 4.4 shows the output of Maximum Sum Rate scheduling algorithm in terms of the scheduling time against particular value of $A_{min}$=0. In this case the link 1 & 4 are active and the scheduling allocates the time given to the active links only. The link 2,3,5 are not entertained under these conditions due to their poor quality so all the time is given to the link number 1& 4.

Figure 4.5 shows the output of Maximum Sum Rate scheduling algorithm in terms of the average data rate against particular value of $A_{min}$=0. As on the link 1 & 4 gets the scheduling time so these links contributes their data rate and rest of links remains inactive with zero data rate.

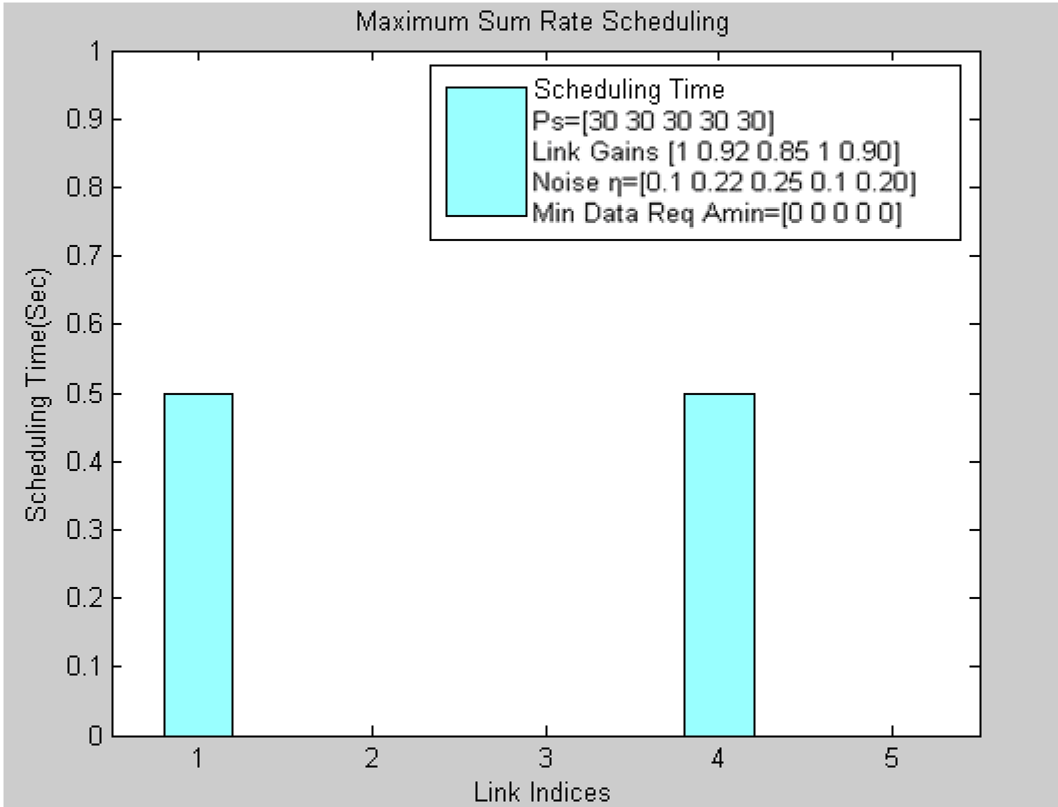


Figure 4.4 Scheduling Time in Maximum Sum Rate Scheduling at Amin=0

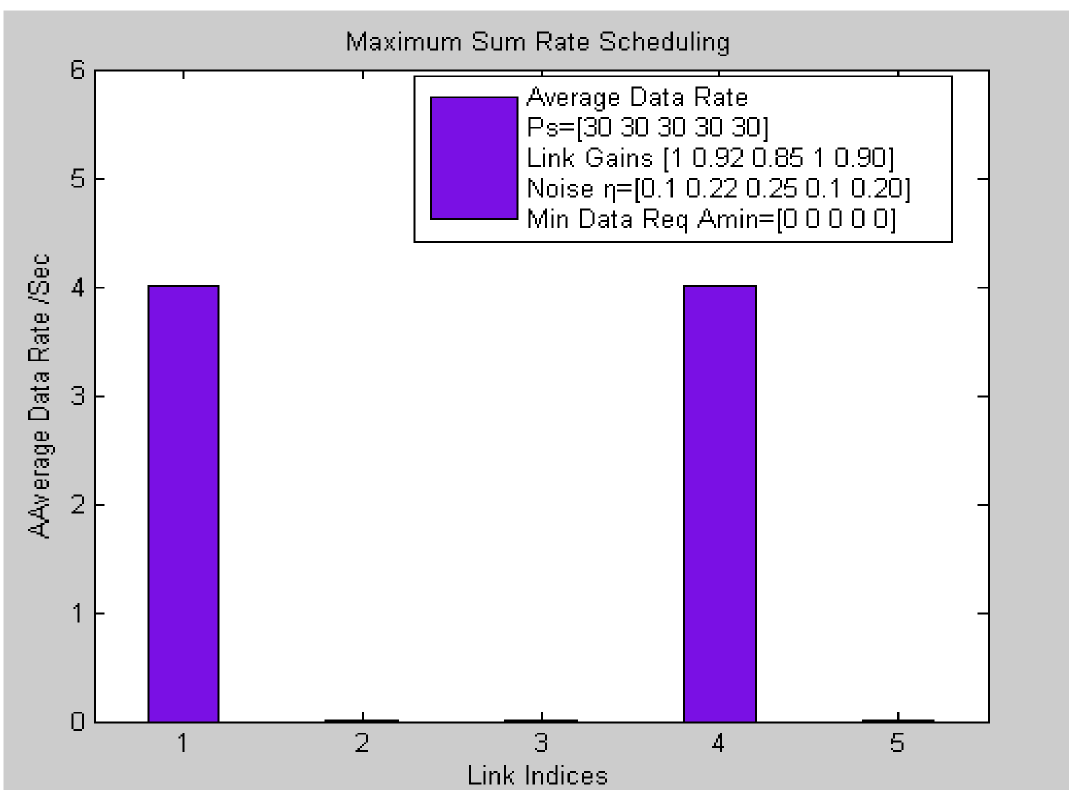


Figure 4.5 Average Data Rate in Maximum Sum Rate Scheduling at Amin=0

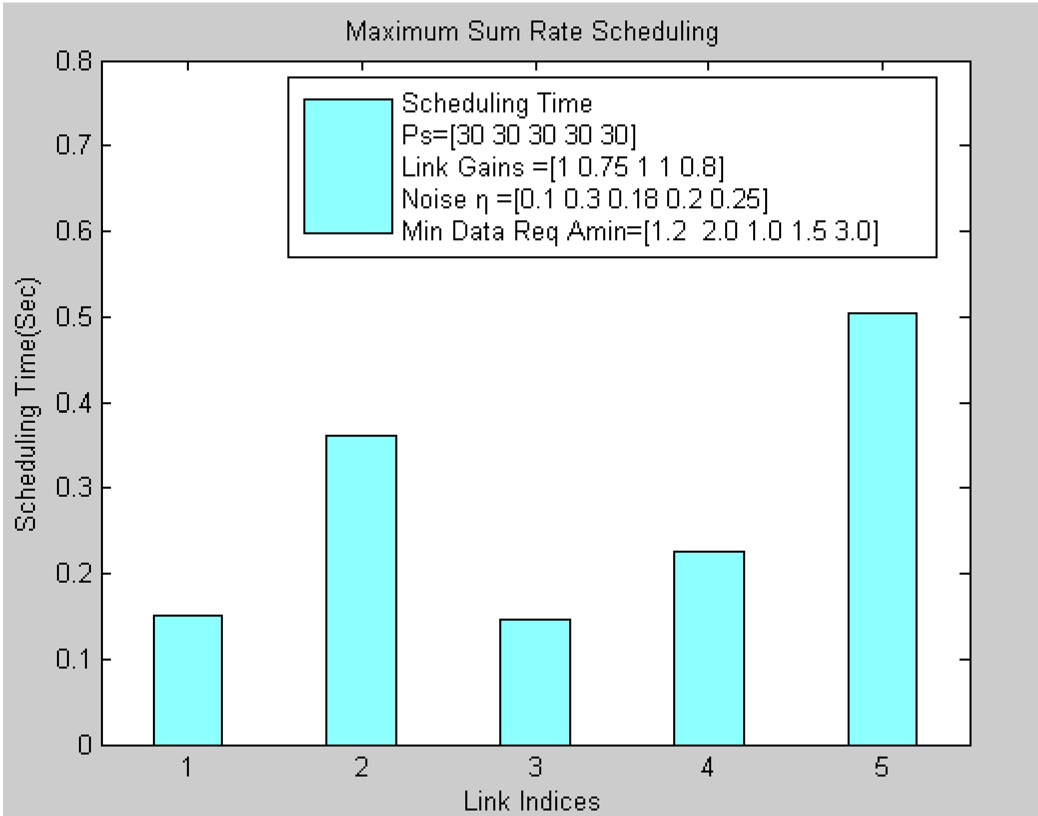


Figure 4.6 Scheduling Time in Maximum Sum Rate Scheduling at Amin ≠ 0

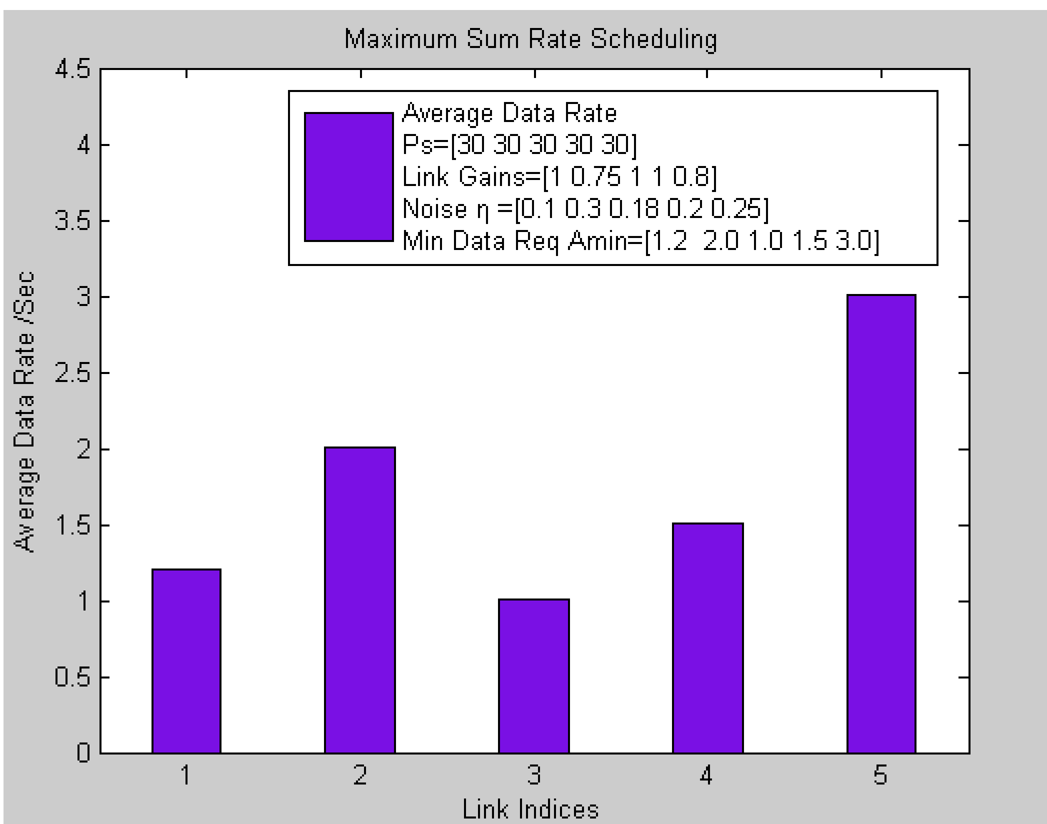


Figure 4.7 Average Data Rate in Maximum Sum Rate Scheduling at Amin ≠ 0

Figure 4.6 shows the output of Maximum Sum Rate scheduling algorithm in terms of the scheduling time against the minimum data rate requirement of each link. As each link request minimum rate for its use and then the scheduler assigns time to meet the minimum rate need of individual links but after satisfying the individual rate requirement of each link it will give the rest of time to the best quality link.

Figure 4.7 shows the output of Maximum Sum Rate scheduling algorithm in terms of the average data rate with the minimum data rate requirement of each link. It indicates the data rate against the scheduling time indicated in figure 4.6. The scheduler fulfills the minimum need of each link and if any flexibility exists it will send the data to the best quality links.

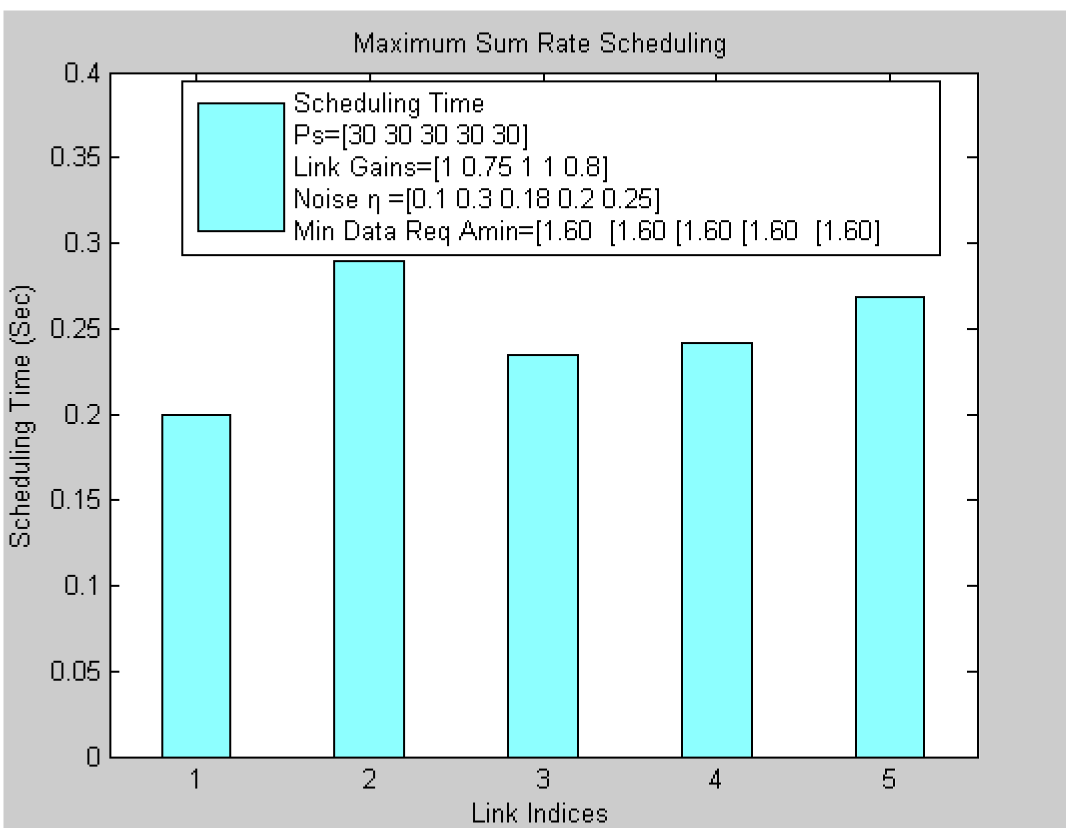


Figure 4.8 Scheduling Time in Maximum Sum Rate a Special Case

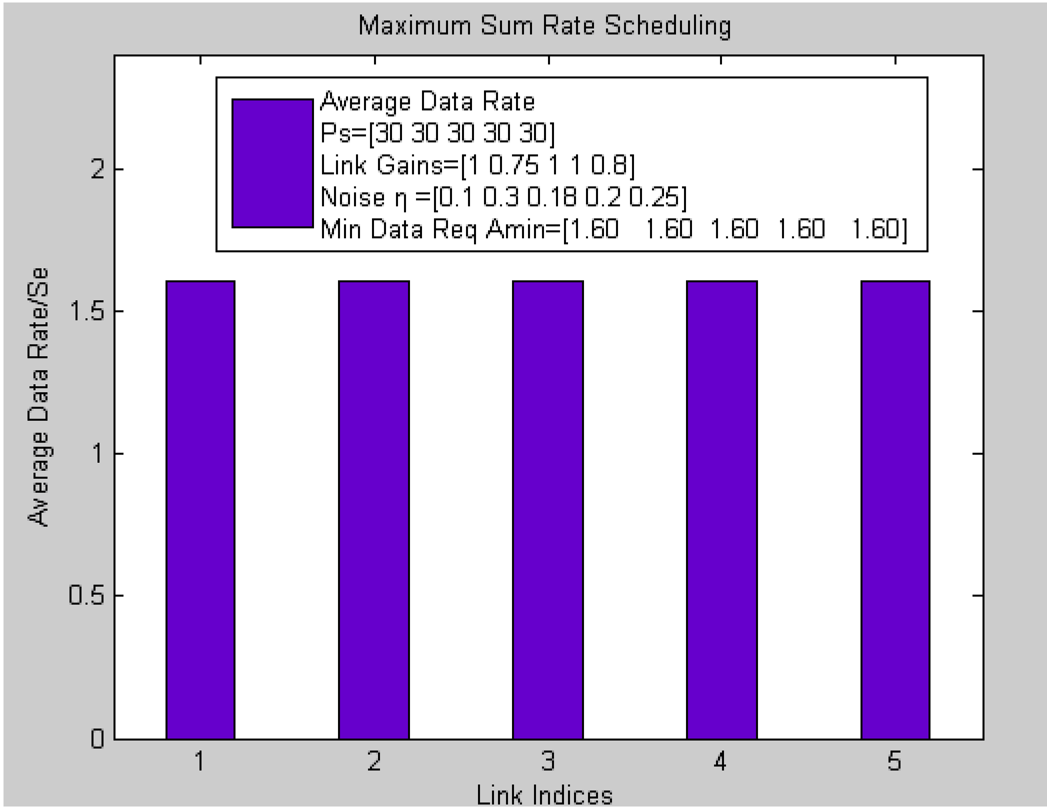


Figure 4.9 Average Data Rate in Maximum Sum Rate a Special Case

Figure 4.8 & 4.9 shows the output of Maximum Sum Rate scheduling algorithm in a special way in which this algorithm show similar behavior as the max-min fair scheduling technique exhibit in term of equal data rate on all links. A special case exhibited in figure 4.9 where minimum data rate requirement of each link is equal to 1.60 and the sum of minimum need equals to the average data rates of all links so the result is the equal data rate on all links.

**4.4 Max-Min Fair Scheduling**

The Max-Min Fair scheduling is the scheduling technique that will maximize the fairness among the given links at the given time. It works on equal sharing principle and hence known as global fairness scheduling algorithm.

The procedure of the Max-Min Fair Scheduling is as follows.

**Step 1:** First call the BasicNetwork to get the data rate matrix C by using

BasicNetwork (N).

**Step 2:** Find the objective function max $A_{min}$ by using f=zeros(1,TMSize+1);

f(1,TMSize+1)= 1;

**Step 3:** Convert the minimization to maximization optimization problem by equating the

f=-f;

**Step 4: :** Set the Equal to constraint by matrix multiplication and equating

R=C*x

For greater than qual to constraint use

Aeq=ones(1,TMSize+1);

Aeq(1,TMSize+1)=0;

beq=[1];

**Step 5:** Set the lower bound by the following equation

lb=zeros (32,1);

The MATLAB script 'MaxMinFair.m', presented in Annex I, simulates the Max-Min Fair Scheduling for Spectrum Sharing in Cognitive Radio Networks. The code is self-explanatory.

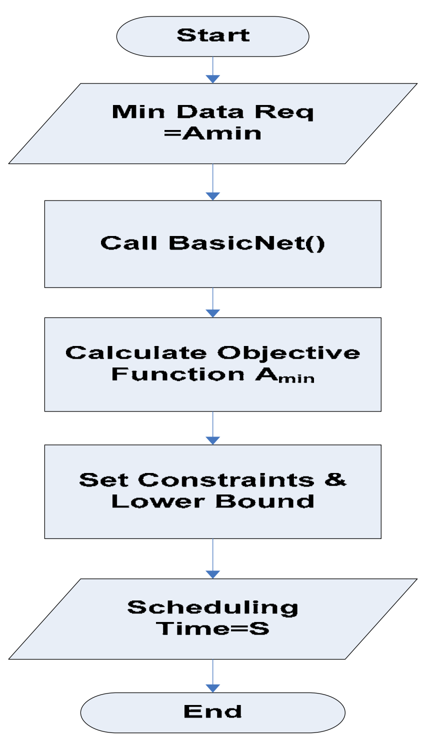


Figure 4.10 Flow Chart for Implementation of Max-Min Fair Scheduling

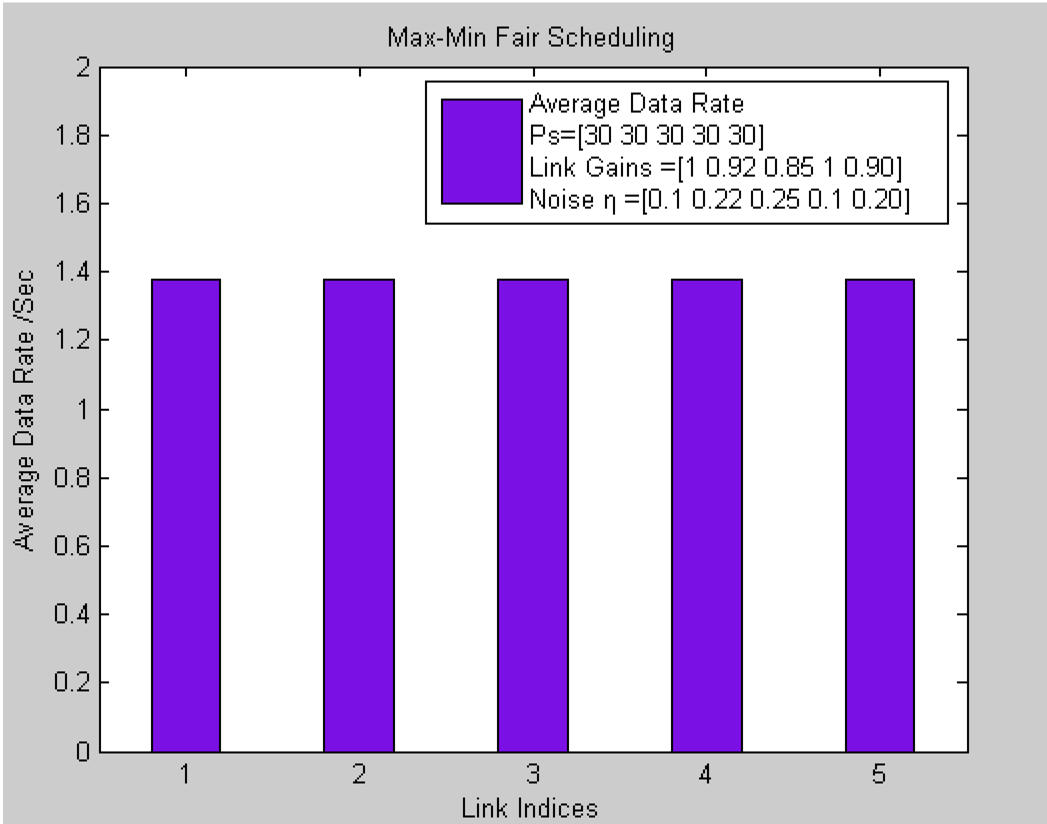


Figure 4.11 Average Data Rate of Links in Max-Min Fair Scheduling

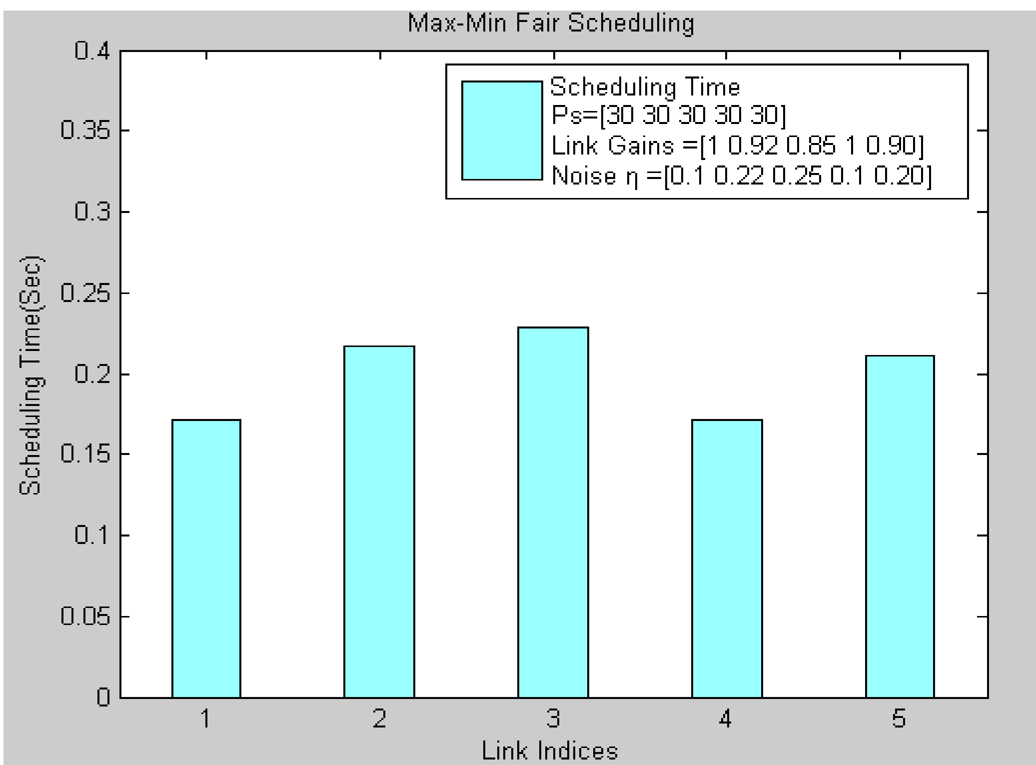


Figure 4.12 Scheduling Time of Links in Max-Min Fair Scheduling

Figure 4.11 & 4.12 illustrates the output of Max-Min Fair scheduling algorithm under the certain value of noise and power. At the given values of noise power sigma the link1 and link 4 has equal noise and power values and link 2.3,4 has high values but the Max-Min Fair scheduling schemes results into equal data rates of all the links but the scheduling time is assigned according to the quality of link in order to get the same data rate. Links that have good quality get minimum time to attain the data rate while poor quality links need more time to achieve the same data rate. As shown in figure that due to the better quality of link the link1and link 4 requires minimum time to achieve the same data rate while the rest of links 2, 3, 5 requires more time to achieve same data rate.

Figure 4.13 & 4.14 illustrates the output of Max-Min Fair scheduling algorithm under the certain value of noise and power. At the given values of noise power sigma the link1 and link 4 has equal noise values and link 2.3,4 has high values but the Max-Min Fair Links

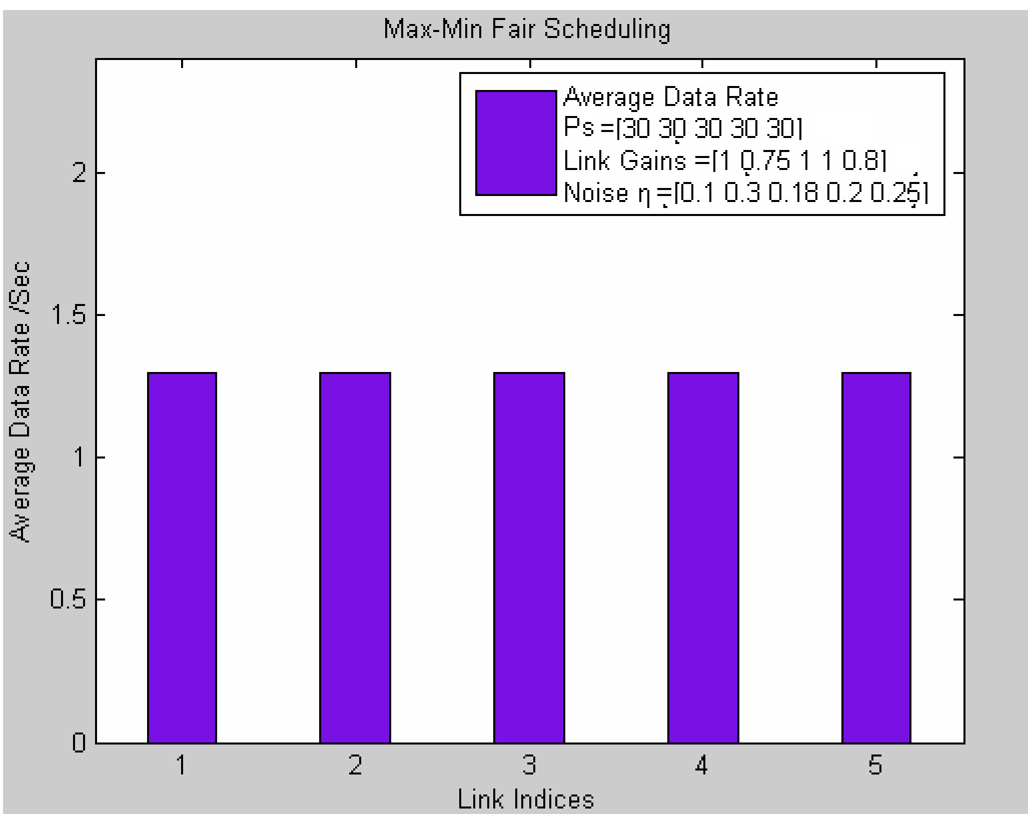


Figure 4.13 Average Data Rate of Links in Max-Min Fair Scheduling

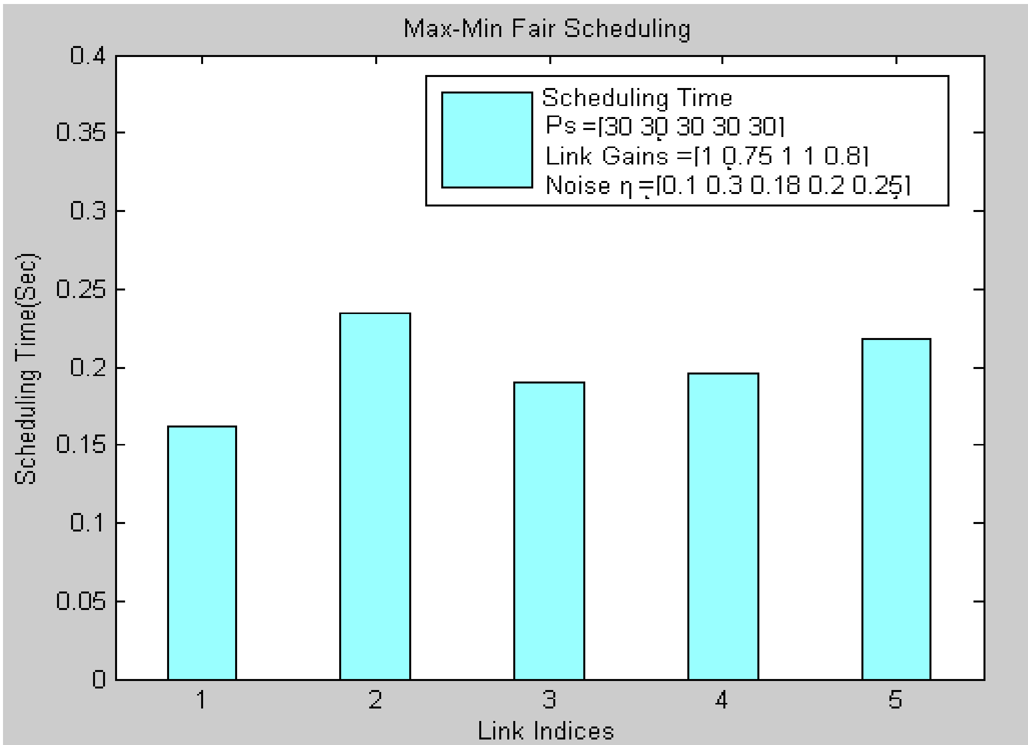


Figure 4.14 Scheduling Time of Links in Max-Min Fair Scheduling

Scheduling scheme results into equal data rates of all the links but the scheduling time is assigned according to the quality of link in order to get the same data rate.

The links that have good quality get minimum time to attain the data rate while poor quality links need more time to achieve the same data rate.

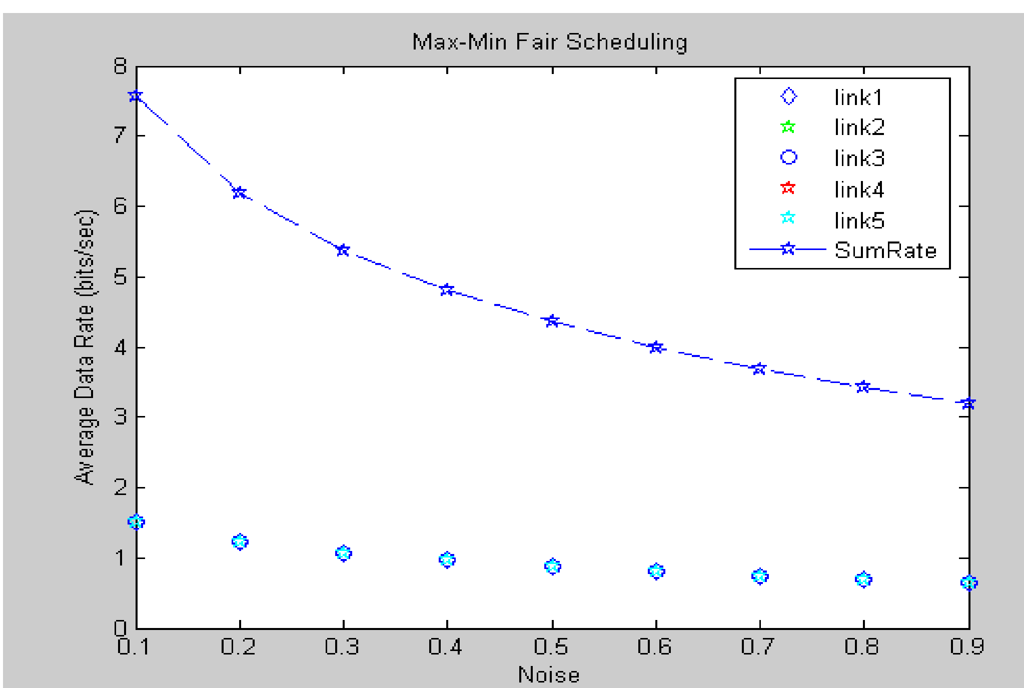


Figure 4.15 Max-Min Fair Scheduling vs Noise Power( η)

Figure 4.15 illustrates the output of Max-Min Fair scheduling algorithm against different values of noise power. The sum rate is decreasing exponentially with the rise in the noise power but all five links have the same data rate at a particular time

**4.5 Proportional Fair Scheduling**

The Proportional Fair scheduling is the scheduling technique that will perform fairness on individual link basis. By evaluating the quality of each link the techniques allocates the data rate according to its quality. This technique can be thought of as the mixture of Maximum sum rate scheduling and Max-Min Fair scheduling. It will solve the problem of both the previous techniques. It maximizes the spectrum utilization keeping in mind the fairness factor.

The procedure of the Max-Min Fair Scheduling is as follows.

**Step 1:** First call the BasicNetwork to get the data rate matrix C by using

BasicNetwork (N).

**Step 2:** Find the objective function max $A_{min}$ by using

myfun(x)**; //X=S;**

**Step 3:** Convert the minimization to maximization optimization problem by equating the

f=-f;

**Step 4:** Set the Equality constraint by matrix multiplication and equating

A=D*S

**Step 5:** Set the lower bound by the following equation

lb=zeros (32,1);

The MATLAB script 'Proportional.m', presented in Annex I, simulates the Proportional Fair Scheduling for Spectrum Sharing in Cognitive Radio Networks. The code is self-explanatory.

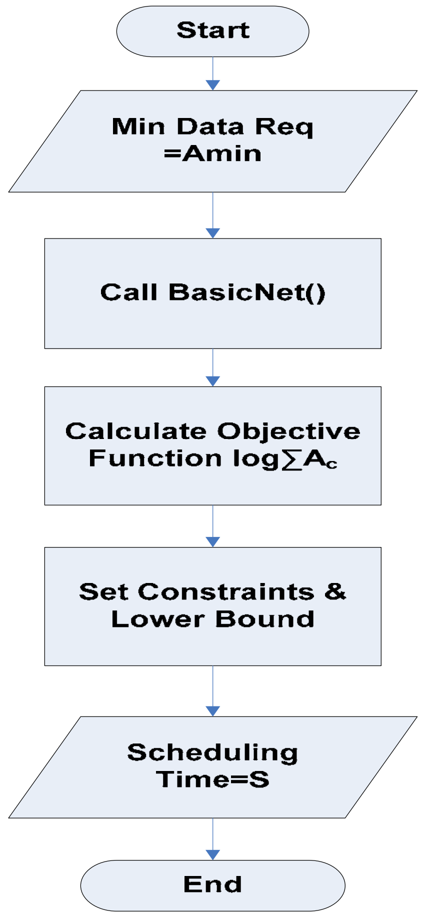


Figure 4.16 Flow Chart for the Implementation of Proportional Fair Scheduling Scheme

The Flow chart explains the step involved in the formation of Proportional Fair Scheduling scheme in the Cognitive Radio Networks. The BasicNet function involves the calculation of data rate the rest of blocks indicate the different steps involved in the procedure. The resultant is the scheduling time allocated to different activated links and the average data rate on each link by multiplying the data rate and the scheduling time assigned to particular link. The interesting point to be noted of this scheme is that the scheduling time is assigned to each link in such a way that all the links get the same data rate.

The objective function here uplifts the minimum data requirement to such a value that it provides equal data rate to all the links by adjusting the scheduling time assign to different transmission modes. Link with best quality takes least time to attains the same value of data rate as compared to the poor quality links.

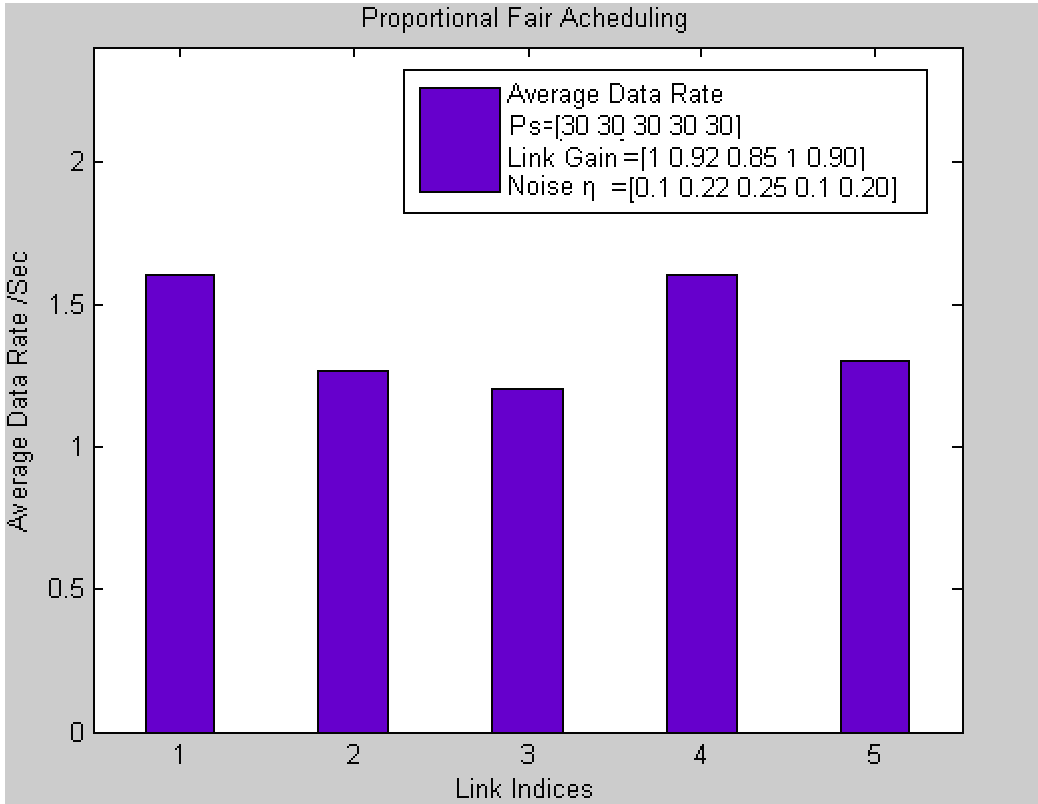


Figure 4.17: Average data Rate in Proportional Fair Scheduling Scheme

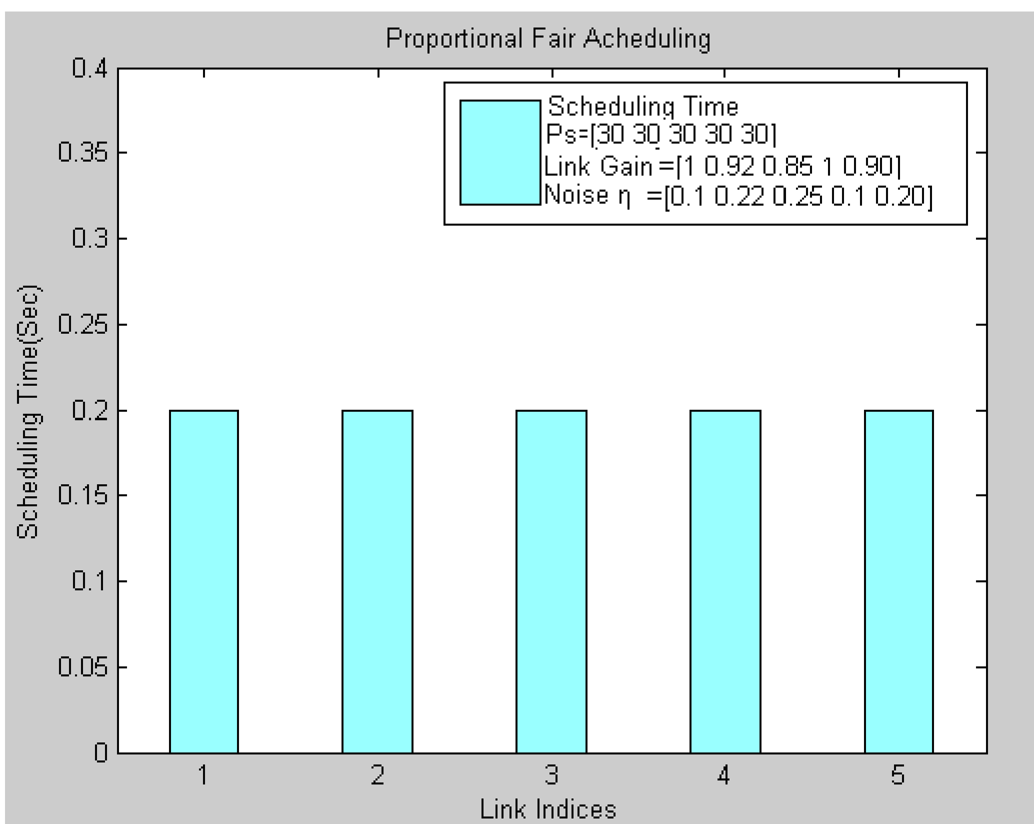


Figure 4.18 Scheduling Time in Proportional Fair Scheduling Scheme

Figure 4.17 illustrates the result of the proportional fair algorithm. The proportional fair algorithm fulfils the requirement of each link according to its link quality.  Link 4 is the most poor among the five links so it will not entertain it. The rest of the links get the data rate according to their link quality. Link 1 and link 5 get the higher data rates as compared to link 2 and link3.

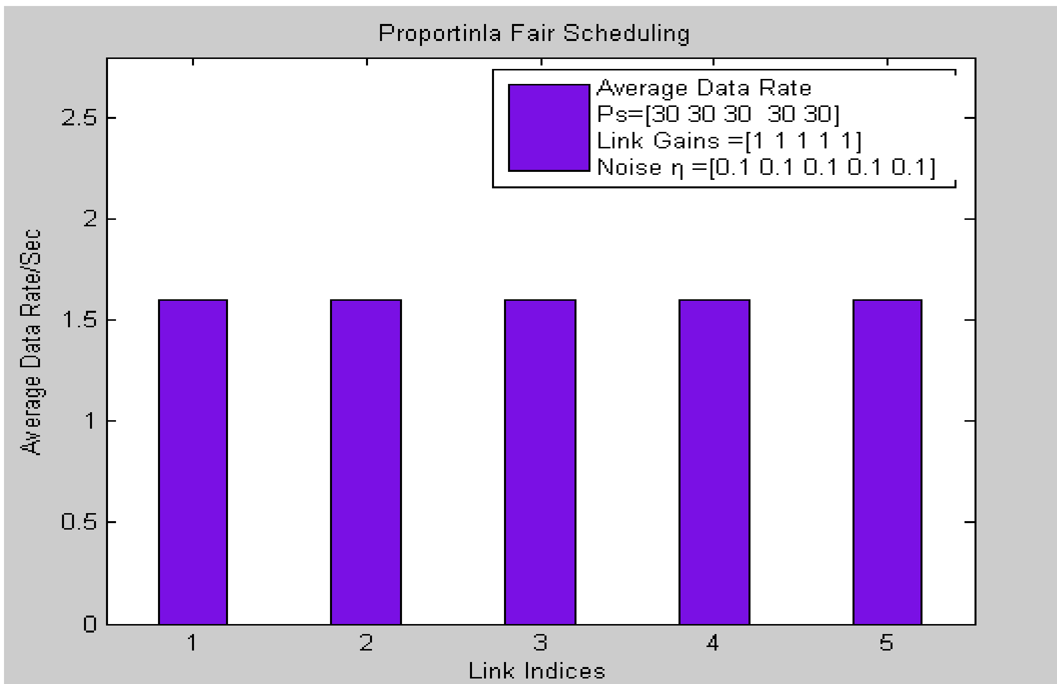


Figure 4.19 Average data Rate in Proportional Fair Scheduling Scheme η

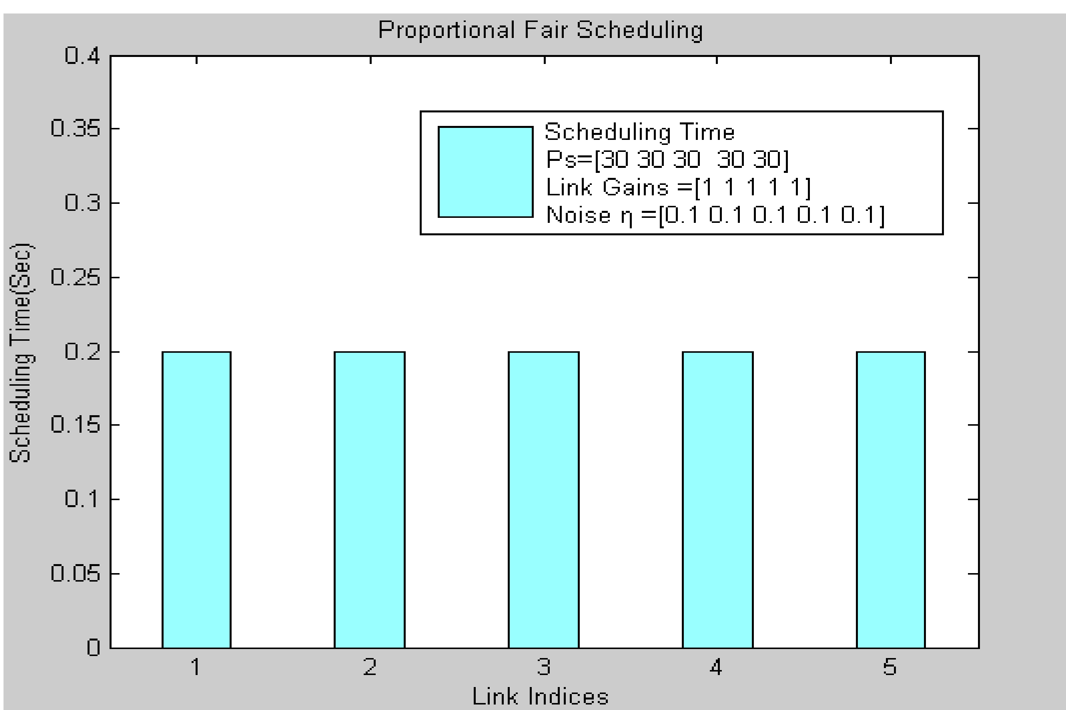


Figure 4.20 Scheduling Time in Proportional Fair Scheduling Scheme

Figure 4.18 illustrates the result of the proportional fair algorithm. The proportional fair algorithm fulfils the requirement of each link according to its link quality. Link 4 is the most poor among the five links so it will not entertain it. The rest of links get the scheduling time according to their link quality. Link1 and link 5 get maximum time as compared to link 2 and link 3.

Figure 4.19 illustrates the average data rate assignment pattern results of the proportional fair algorithm. The proportional fair algorithm fulfils the requirement of each link according to its link quality. Link 4 most is poor among the five links so it will not entertain it. The rest of the links get the data rate according to their link quality. The link1 and link 5 get the higher data rates as compared to the link 2 and link 3.

Figure 4.20 illustrates the scheduling time assignment pattern of the proportional fair algorithm. The proportional fair algorithm fulfils the requirement of each link according to its link quality.  Link 4 is poorer among the five links so it will not entertain it. The rest of links gets the scheduling time according to their link quality. Link 1 and link 5 get the maximum time as compared to the link 2 and link3.

**4.6 Dynamic Spectrum Sharing Scheme**

The three basic scheduling schemes presented in the previous sections are of scheduling on time unit (per second) basis. A dynamic scheme that is presented in this section will take the user's data requirement in bits/sec and fulfill the user's requirement by utilizing the scheduling schemes presented in the last sections. It will accept the requests of users according to the available links and then schedule them in a way to fulfill the user requirement in the least possible time. The scheme is designed in a way that it maximizes the utilization of each link by segmenting the user's data need in to small chunks and sending them on different links.

The procedure of the Dynamic Spectrum Sharing scheme is as follows.

**Step 1:** First read the text file to fetch the number of users equal to the available links

Dfid = fopen ('Dynamic.txt');

**Step 2:** Assign the user ID to each user

Users (i,1)=1;

**Step 3:** Call the scheduling scheme to get the resulted average data rate on each link.

Schedule(r).

**Step 4:** Fulfil the user data need according to link data rate and if there is still data remaining then subtract the original request from the serviced data

r(j)=r(j)-Users(CurrentUser,2).

**Step 5:** If any of the current CR users is serviced completely then read the next user from the file and assign the new ID to that user.

Users (CurrentUser,2)= Users(CurrentUser,2)-Temp;

The MATLAB script 'Schedule.m', presented in Annex I, simulates the Proportional Fair Scheduling for Spectrum Sharing in Cognitive Radio Networks. The code is self-explanatory.

The Flow chart explains the step involves in the formation of Dynamic Scheduling Scheme in the context of Cognitive Radio Networks. The BasicNet function involves the calculation of data rate the rest of blocks indicate the different steps involves in the procedure. The resultant is the data rate allocated to different CR users. The users waiting in the queue are serviced in First Come First Served (FCFS) fashion. If the link has greater capacity than the user requested then the data of some other user is transmitted over that link in order to maximize the throughput of link. Since the Dynamic Spectrum Sharing Scheme also supports mobility so that if some user requires more data to transmit than its data can be sent over more than one links. When any of the users is serviced completely than the next user is brought in to the servicing area and this process is repeated over the time until all the CR users are serviced.

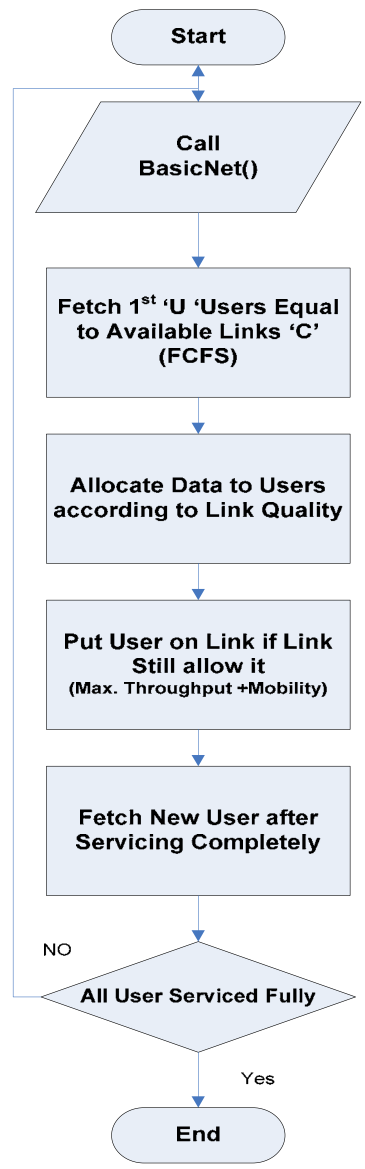


Figure 4.17 Flow Chart for the Implementation of Dynamic Scheduling Scheme

The Dynamic Scheduling Scheme presented in the last article will successfully distribute the available links between the demanding CR users. In the next sections case studies are presented in order to further extend the understanding of existing and proposed spectrum sharing scheme.

### 4.7 The Case Studies

#### 4.7.1 Case Study of Existing Spectrum Sharing Techniques

A case study is presented in order to further elaborate the functioning of three scheduling scheme.

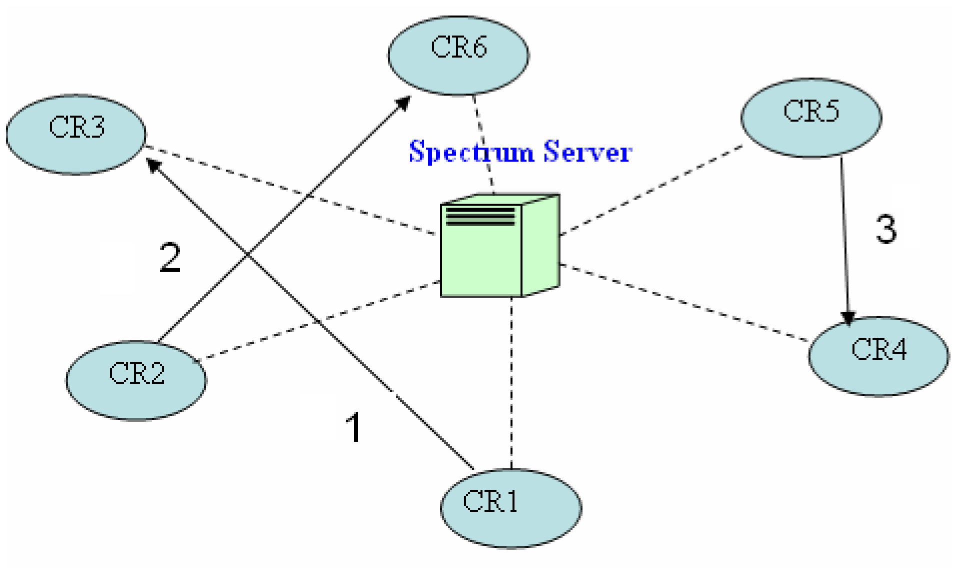


Figure 4.21 Spectrum Server with Six CR Users

There are total six CR users in the intra-network environment and they are forwarding the control information to the spectrum server by the control channel indicated by the dashed line. The Spectrum Server then forwards the sharing information to the CR user on the control channel. In the current network there are six transmitters and three receivers which can be depicted as follow.

- CR1 → CR3 Over link 3
- CR2 → CR6 Over link 1
- CR4 → CR5 Over link 2

And minimum data rate requirement of each user is obtained through the Poisson model is described in the table below. The CR1 demands data rate of 2 bits/Sec in order to transmit its data while the CR2 and CR5 have requested 0.5 and 1.2 bits/Sec.

| User | Minimum Data Request ($A_{min}$) |
|---|---|
| CR1 | 2.0 |
| CR2 | 0.5 |
| CR5 | 1.2 |

Table 4.1: CR Users with their Minimum Data Requirement

#### 4.7.1.1 Basic Network Calculation

In order to apply the scheduling schemes there is a strong need to develop a frame work. This frame work will calculate the basic quantities like signal to interference ratio, data link and link gain of each individual link. The basic calculations are presented as follows.

Users **U**=6, Channel **C**=3, Transmission Modes t = 8  0 → 7

$$Ps=\begin{bmatrix}30 & 30 & 30\end{bmatrix}$$

$$\sigma=\begin{bmatrix}0.1 & 0.25 & 0.2\end{bmatrix}$$

$$G=\begin{bmatrix}1 & 0.4 & 0.4\\ 0.4 & 0.65 & 0.4\\ 0.4 & 0.4 & 0.75\end{bmatrix}$$

$$t=\begin{bmatrix}0 & 0 & 0 & 0 & 1 & 1 & 1 & 1\\ 0 & 0 & 1 & 1 & 0 & 0 & 1 & 1\\ 0 & 1 & 0 & 1 & 0 & 1 & 0 & 1\end{bmatrix}$$

$$D=\begin{bmatrix}0 & 0 & 0 & 0 & 8.0 & 1.25 & 1.25 & 0.81\\ 0 & 0 & 5.70 & 0.96 & 0 & 0 & 0.96 & 0.59\\ 0 & 6.90 & 0 & 1.05 & 0 & 1.05 & 0 & 0.66\end{bmatrix}$$

$$A\,c=\sum_{i=t} Dct.x_t$$

The main objective of scheduling scheme is to find the scheduling time S and assign it to different transmission modes.

### *4.7.1.2 Maximum Sum Rate Scheduling Results*

$$\max 1^T \begin{bmatrix} 0S_1+ & 0.S_2+ & 0S_3+ & 0S_4+ & 8.0S_5+ & 1.25S_6+ & 1.25S_7+ & 0.81S_8 \\ 0S_1+ & 0.S_2+ & 5.70S_3+ & 0.96S_4+ & 0.S_5+ & 0S_6+ & 0.96S_7+ & 0.59S_8 \\ 0S_1+ & 6.90S_2+ & 0S_3+ & 1.05S_4+ & 0.S_5+ & 1.05S_6+ & 0S_7+ & 0.66S_8 \end{bmatrix}$$

$$DS \geq A^{min} = \begin{bmatrix} 0S_1+ & 0.S_2+ & 0S_3+ & 0S_4+ & 8.0S_5+ & 1.25S_6+ & 1.25S_7+ & 0.81S_8 \\ 0S_1+ & 0.S_2+ & 5.70S_3+ & 0.96S_4+ & 0.S_5+ & 0S_6+ & 0.96S_7+ & 0.59S_8 \\ 0S_1+ & 6.90S_2+ & 0S_3+ & 1.05S_4+ & 0.S_5+ & 1.05S_6+ & 0S_7+ & 0.66S_8 \end{bmatrix} \geq \begin{bmatrix} 2 \\ 0.5 \\ 1.2 \end{bmatrix}$$

$$1^T S \leq 1 = [S_1 + \; S_2 + \; S_3 + \; S_4 + \; S_5 + \; S_6 + \; S_7 + \; S_8]$$

$$S \geq 0 = [S_1, \; S_2, \; S_3, \; S_4, \; S_5, \; S_6, \; S_7, \; S_8]$$

**Results:**

**Scheduling Time St** $= [0 \quad 0.17 \quad 0.09 \quad 0 \quad 0.74 \quad 0 \quad 0 \quad 0]$

**Average Data Rate Ac=** $\begin{bmatrix} 5.9193 \\ 0.5 \\ 1.2 \end{bmatrix}$

This is the result of MSRS under particular network conditions. It is clear from the result that MSRS maximizes the average data rate on all links. It will select the best link for the transmission of data after satisfying the minimum data rate of individual's users. The link 1 in the MSRS gets the maximum time due to its best quality.

### *4.7.1.3 Max-Min Fair Scheduling Results*

**max $A_{min}$** = max [ 0 0 0 0 0 0 0 $A_{min}$]

**Subject to**

$$A=DS \quad \begin{bmatrix} 0S_1+ & 0.S_2+ & 0S_3+ & 0S_4+ & 8.0S_5+ & 1.25S_6+ & 1.25S_7+ & 0.81S_8 \\ 0S_1+ & 0.S_2+ & 5.70S_3+ & 0.96S_4+ & 0.S_5+ & 0S_6+ & 0.96S_7+ & 0.59S_8 \\ 0S_1+ & 6.90S_2+ & 0S_3+ & 1.05S_4+ & 0.S_5+ & 1.05S_6+ & 0S_7+ & 0.66S_8 \end{bmatrix}$$

$$A \geq Armin.1 = A \geq [2 \quad 0.5 \quad 1.2] * \begin{bmatrix} 1 \\ 1 \\ 1 \end{bmatrix}$$

$$1^T S = 1 = [S_1 + \; S_2 + \; S_3 + \; S_4 + \; S_5 + \; S_6 + \; S_7 + \; S_8]$$

$$S \geq 0 = [S_1, \; S_2, \; S_3, \; S_4, \; S_5, \; S_6, \; S_7, \; S_8] \geq 0$$

**Results:**

**Scheduling Time(S) St =** $\begin{bmatrix} 0 & 0.33 & 0.39 & 0 & 0.28 & 0 & 0 & 0 \end{bmatrix}$

$$\textbf{Average Data Rate Ac} = \begin{bmatrix} 2.2539 \\ 2.2539 \\ 2.2539 \end{bmatrix}$$

This is the result of MMF under particular network conditions. It is clear from the results that MMF schedules in a way that all the links gets the same data rate. It is clear from the result that the sum rate decreases due to the poor quality links. The link 2 due to its poor quality gets the maximum time in order to reach the same data rate point.

#### *4.7.1.4 Proportional Fair Scheduling Results*

$$\max \sum_c \log Ac = \max\ [0+0+0+0+0+0+0+0+0+(\log r_1)+(\log r_2)+(\log r_3)]$$

**Subject to**

$$\text{A=DS=} \begin{bmatrix} A1 \\ A_2 \\ A_3 \end{bmatrix} = \begin{bmatrix} 0S_1+ & 0.S_2+ & 0S_3+ & 0S_4+ & 8.0S_5+ & 1.25S_6+ & 1.25S_7+ & 0.81S_8 \\ 0S_1+ & 0.S_2+ & 5.70S_3+ & 0.96S_4+ & 0.S_5+ & 0S_6+ & 0.96S_7+ & 0.59S_8 \\ 0S_1+ & 6.90S_2+ & 0S_3+ & 1.05S_4+ & 0.S_5+ & 1.05S_6+ & 0S_7+ & 0.66S_8 \end{bmatrix}$$

$$\mathbf{1^T S = 1} = \begin{bmatrix} S_1+ & S_2+ & S_3+ & S_4+ & S_5+ & S_6+ & S_7+ & S_8 \end{bmatrix}$$

$$\mathbf{S \geq 0} = \begin{bmatrix} S_1, & S_2, & S_3, & S_4, & S_5, & S_6, & S_7, & S_8 \end{bmatrix} \geq 0$$

**Results:**

**Scheduling Time (Sec)** = $\begin{bmatrix} 0 & 0.3334 & 0.3334 & 0 & 0.3332 & 0 & 0 & 0 \end{bmatrix}$

$$\textbf{Average Data Rate Ac} = \begin{bmatrix} 2.66 \\ 1.91 \\ 2.57 \end{bmatrix}$$

This is the result of MMF under particular network conditions. It is clear from the result that MMF schedules in a way that all the links gets the same data rate. It is clear from the result that the sum rate decreases due to the poor quality links. The basic idea behind PPF is to assign same scheduling time to all links so that the links with better quality gets the more data rate as compared to low quality links.

### 4.7.2 Case Study of Proposed Dynamic Spectrum Sharing Scheme

A case study is presented in order to further elaborate the functioning of Dynamic scheduling scheme. In the current case there are five transmitters and three links available for transmission in an intra network Cognitive Radio Networks The minimum and the maximum data requirements of each user is depicted in the table 4.2.

| **User ID** | **$A_{min}$** | **Maximum Need** |
|---|---|---|
| 1 | 0.5 | 4 |
| 2 | 1.0 | 1 |
| 3 | 0.5 | 2 |
| 4 | 0.5 | 3 |
| 5 | 1.0 | 1 |

Table 4.2: CR User with Maximum and Minimum Data Need

Here $A_{min}$ indicates the minimum data rate requirement and maximum need indicates the size of file that the users want to transmit.

#### *4.7.2.1 Dynamic Scheduling With the Maximum Sum Rate Scheduling Scheme*

The schedule result by the Dynamic Sharing scheme by using the Maximum Sum Rate scheme internally is shown in the table 4.3. The Maximum Sum Rate Scheme after first of all fullfil the minimum requirement $A_{min}$ of each user and then according to the link quality assigns the rest of data to the allocated user. The Dynamic Scheduling Scheme will bring the first three CR users from the queue and then services them on different links. In order to consider the objective of maximizing the throughput after allocating the links to different CR users it should continuously checks the capacity of link and During the first time unit (sec) it finds the capacity of link 2 still accommodate more data so it segments the data equal to capacity of link 2 and sends it over link 2. The Dynamic scheme also supports the mobility as you can see that the some data of user 1 is send over link one and some data over link 2.

<table>
<tr><th rowspan="2">Links</th><th colspan="2">Time Unit 1</th><th colspan="2">Time Unit 2</th><th colspan="2">Time Unit 3</th></tr>
<tr><th>User</th><th>Data Rate</th><th>User</th><th>Data Rate</th><th>User</th><th>Data Rate</th></tr>
<tr><td rowspan="2">Link 1</td><td rowspan="2">1</td><td rowspan="2">0.5</td><td rowspan="2">3</td><td rowspan="2">0.5</td><td>5</td><td>1.00</td></tr>
<tr><td>3</td><td>0.5</td></tr>
<tr><td rowspan="2">Link 2</td><td>2</td><td>1</td><td>1</td><td>0.84</td><td rowspan="2">4</td><td rowspan="2">1</td></tr>
<tr><td>1</td><td>2.65</td><td>4</td><td>1.55</td></tr>
<tr><td>Link 3</td><td>3</td><td>0.5</td><td>4</td><td>0.5</td><td>3</td><td>0.5</td></tr>
</table>

Table 4.3: Schedule of Dynamic Sharing With MSRS

This scheme is also Dynamic in the sense that it will bring the users in first come first served ( FCFS) fashion, servicing each of them and if the users are serviced fully it will bring the next few user.

Lastly it can also be visualized that the Dynamic Scheduling Scheme also takes care of the changes occurring in the radio environment as you can see the capacity of link 2 is different in first and second time units. In the first second the capacity of link 2 is 3.65 bits/sec but during the second time unit it goes down to 2.39 bits/sec.

Figure 4.21-4.23 depict the results of Dynamic Scheduling Scheme for every time unit. The bar chart representation of the tabular entries further elaborates the functioning of the proposed Dynamic Scheduling Scheme.

Figure 4.25- 4.30 indicate the tabular behaviour of Max-Min and Proportional Fair Schemes in the form of bar charts.

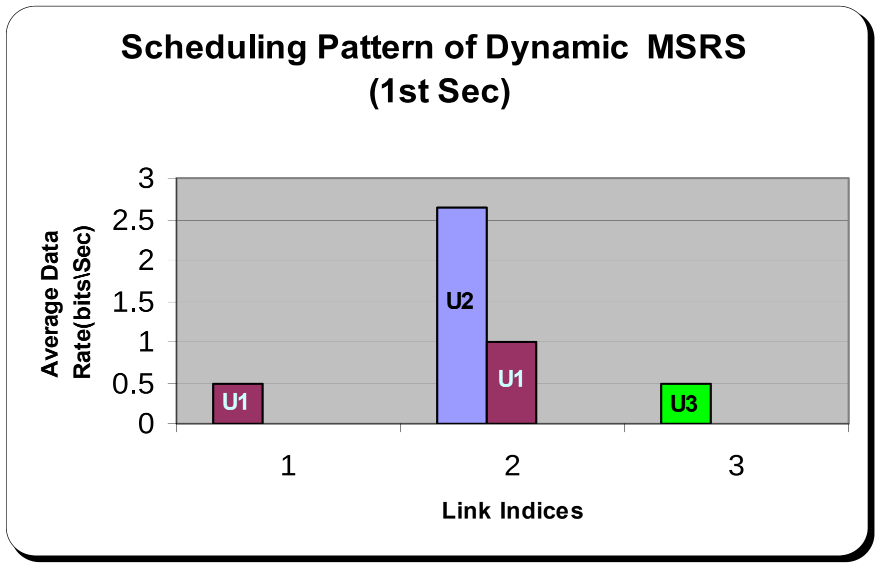


Figure 4.22: Scheduling Behaviour of MSRS during 1st Sec

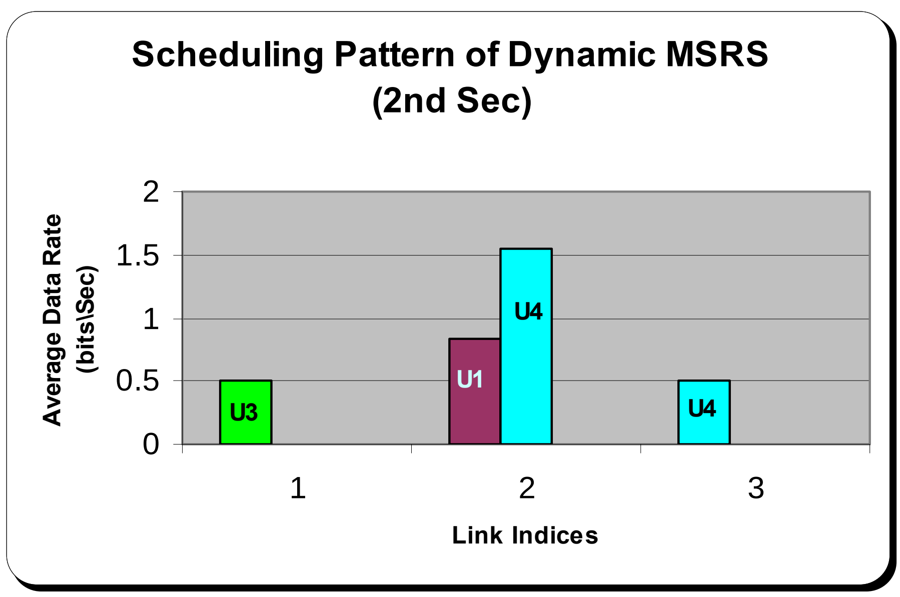


Figure 4.23: Scheduling Behaviour of MSRS during 2nd Sec

Figures 4.22 – 4.24 explain the working of the proposed Dynamic Scheduling Scheme in the graphical form. The bars indicate the links and the labels of users, indicating the particular user being served on particular link at particular links. The multiple bars on same link index indicate the throughput maximization behaviour.

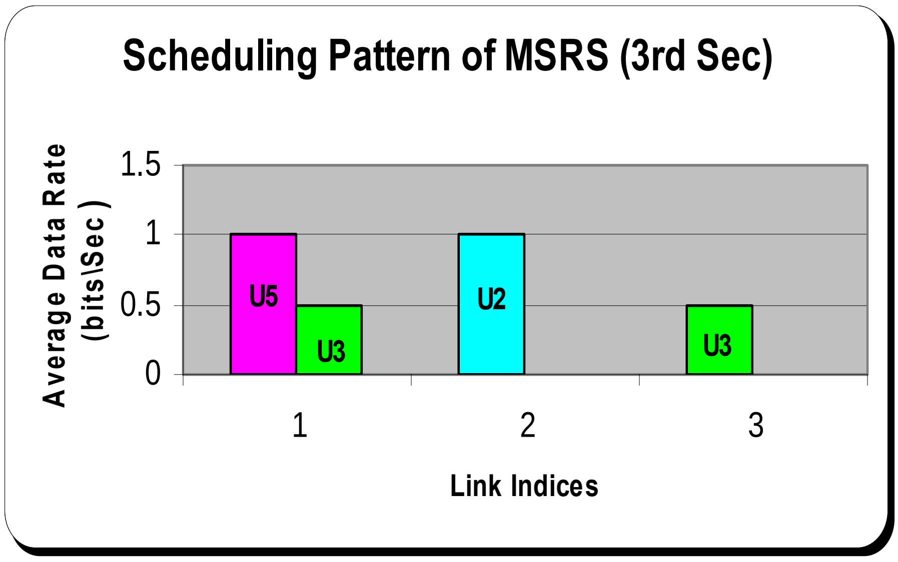


Figure 4.24: Scheduling Behaviour of MSRS during 3rd Sec

#### 4.7.2.2 Dynamic Scheduling With the Max-Min Fair Scheduling Scheme

The schedule result by the Dynamic Sharing scheme by using the Max-Min Fair Scheme internally is shown in the table 4.4. The Max-Min Fair Scheme allocates the data to all users on each link equally but if some user has minimum requirement than that available on the link it will segment the data according to the algorithm and sends it over the same link. The Dynamic Scheduling Scheme will bring the fist three CR users from the queue and serve them on different links. In order to consider the objective of maximizing the throughput after allocating the links to different CR users, It continuously checks the capacity of link and during the first time unit (sec) it finds out that the capacity of link-2 can accommodate more data so it segments the data equal to that the link-2 and sends it over link 2. This Dynamic scheme also supports the mobility as you can see some data of user 1 is send over link 1 and some data is send over link 2.

The mobility is an important factor for the implementation of Cognitive Radio Network in order to avoid interference to the primary or licensed user. The mobility support will help to cater the effect of interference issues in Cognitive Radio Networks.

| Links | Time Unit 1 | | Time Unit 2 | | Time Unit 3 | |
|---|---|---|---|---|---|---|
| | User | Data Rate | User | Data Rate | User | Data Rate |
| Link 1 | 1 | 1.38 | 3 | 0.61 | 4 | 0.95 |
| | | | 4 | 0.72 | | |
| Link 2 | 2 | 1.00 | 1 | 1.34 | 5 | 1.00 |
| | 1 | 0.38 | | | | |
| Link 3 | 3 | 1.38 | 4 | 1.34 | 1 | 0.90 |

Table 4.4: Schedule of Dynamic Sharing With MMF

This scheme is also Dynamic in the sense that it brings the users in first come first served ( FCFS) fashion serves each of them and if the users are serviced fully it will bring the next user.

Lastly it can also be visualized that the Dynamic Scheduling Scheme also takes care of the changes occurring in the radio environment as you can see the capacity of link 2 is different in first and second time units. In the first second the capacity of all the links is 1.38 bits/sec but during the second time unit it goes down to 1.34 bits/sec.

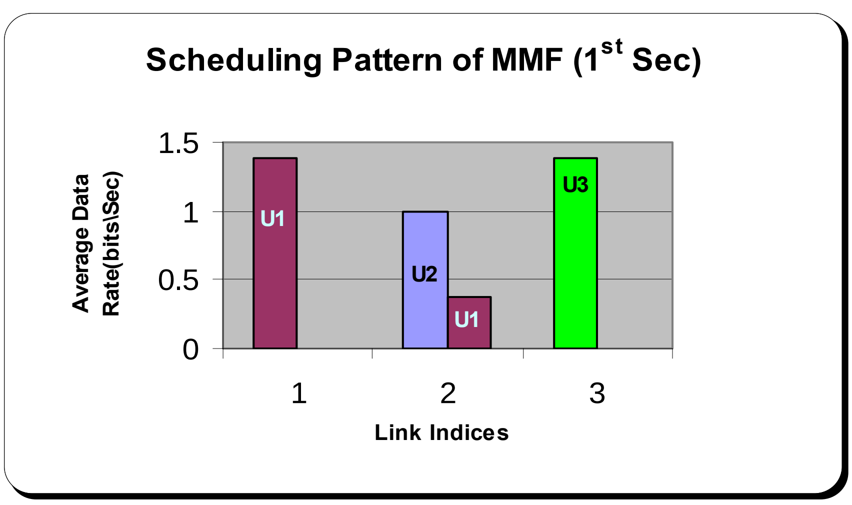


Figure 4.25: Scheduling Behaviour of MMF during 1st Se

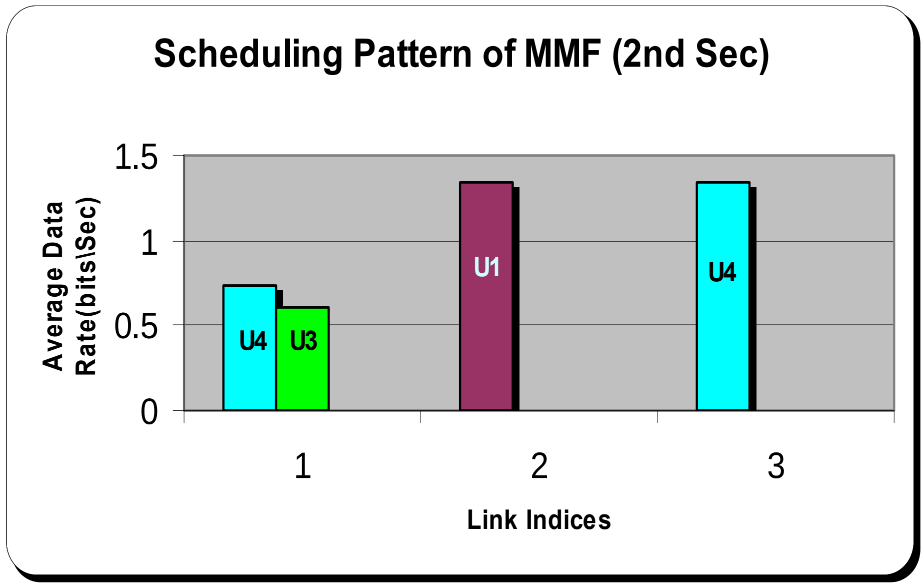


Figure 4.26: Scheduling Behaviour of MMF during 2nd Sec

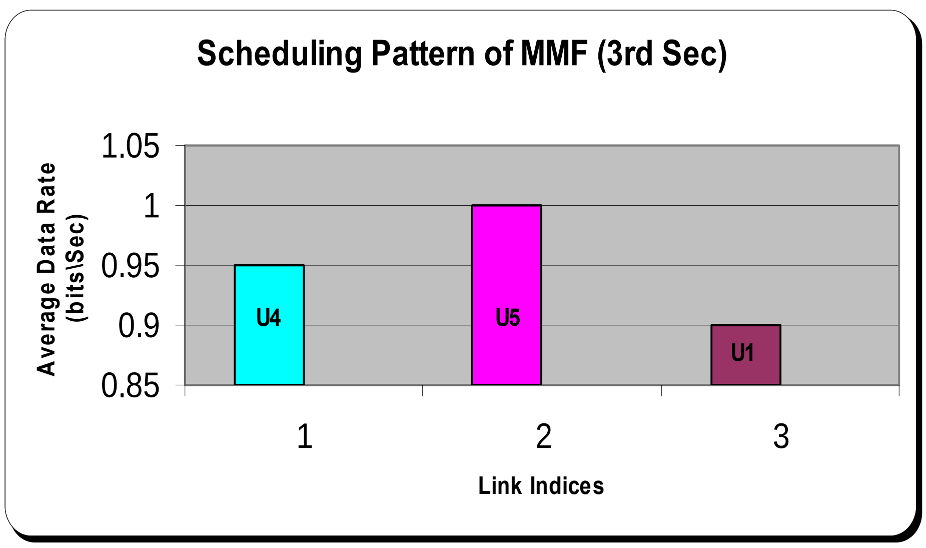


Figure 4.27: Scheduling Behaviour of MMF during 3rd Sec

#### *4.7.2.3 Dynamic Scheduling With Proportional Fair Scheduling Scheme*

The schedule result by the Dynamic Sharing scheme by using the Maximum Sum Rate scheme internally is shown in the table 4.3. The Maximum Sum Rate Scheme first of all fulfils the minimum requirement ($A_{min}$) of each user and then according to the link quality assigns the rest of the data to the allocated user. The Dynamic Scheduling Scheme will bring the first three CR users from the queue and serve them on different links. In order to consider the objective of maximizing the throughput after allocating the links to different

CR users, It continuously checks the capacity of link and during the first time unit (sec) it finds out that the capacity of link-2 can still accommodate more data so it segments the data equal to that the link 2 can send and then send it over link 2. This Dynamic scheme also support the mobility as you can see that the some data of user 1 is send over link one and some data is send over link 2

| | Time Unit 1 | | Time Unit 2 | | Time Unit 3 | |
|---|---|---|---|---|---|---|
| **Links** | **User** | **Data Rate** | **User** | **Data Rate** | **User** | **Data Rate** |
| **Link 1** | 1 | 1.31 | 3 | 0.75 | | |
| | | | 4 | 1.00 | | |
| | | | 5 | 1.00 | | |
| **Link 2** | 2 | 1.00 | 1 | 0.5 | | |
| | 1 | 0.65 | | | | |
| **Link 3** | 3 | 1.24 | 4 | 1.98 | 1 | 1.31 |

Table 4.5: Schedule of Dynamic Sharing With PPF

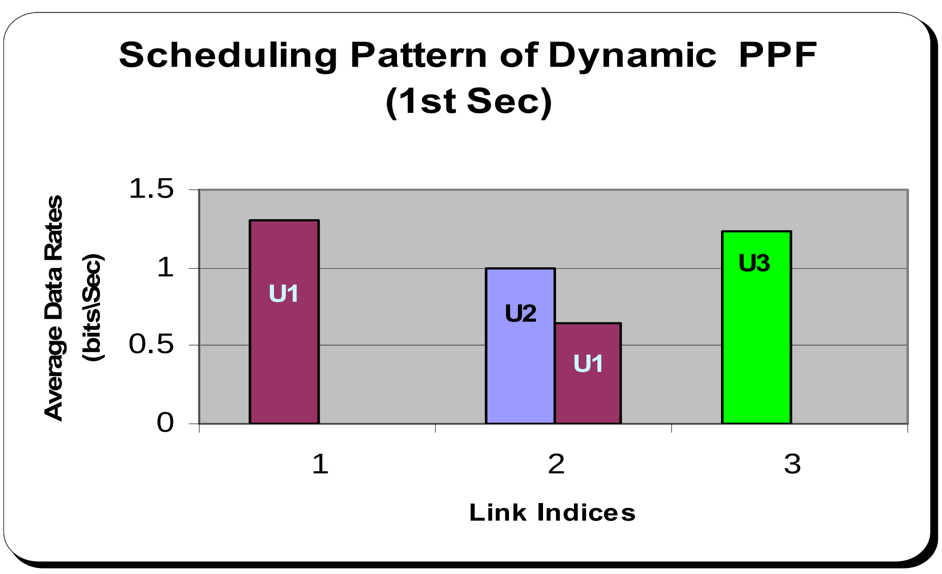


Figure 4.28: Scheduling Behaviour of PPF during 1st Sec

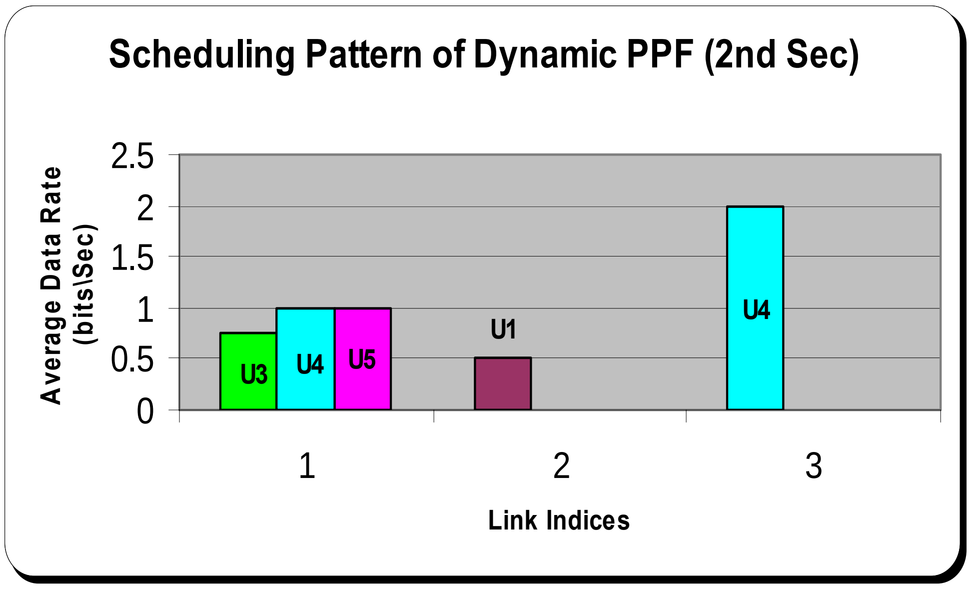


Figure 4.29: Scheduling Behaviour of PPF during 2nd Sec

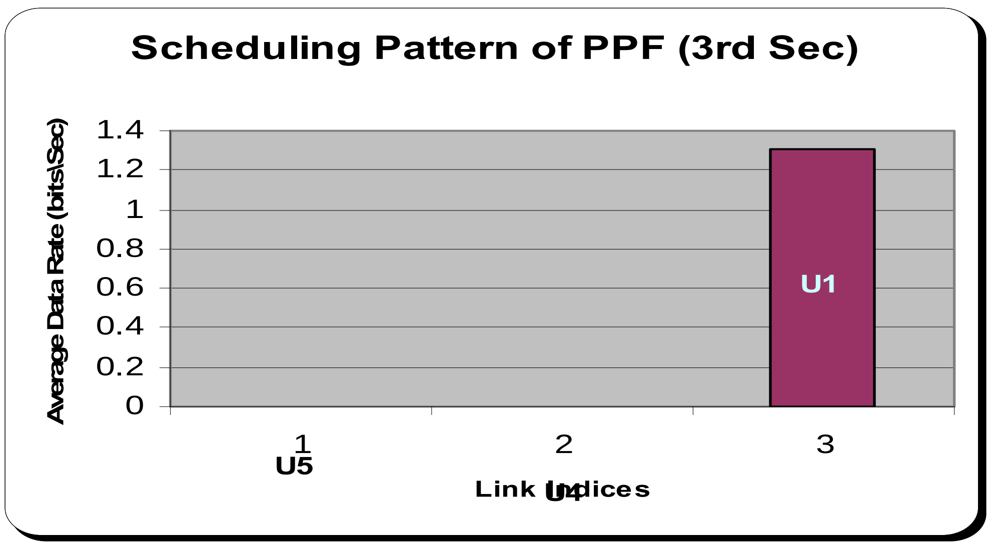


Figure 4.30: Scheduling Behaviour of PPF during 3rd Sec

**4.8 Summary**

The designed test program is written in MATLAB. The program comprises of three major techniques (i.e Max Sum Rate, Max-Min Fair and Proportional Fair Scheduling Schemes).

*Chapter 5*

# COMPARISON AND ANALYSIS

## 5.1 Introduction

In this chapter, the results of the algorithms and techniques, given in Chapter 2, have been presented. For experimentation the network is considered under different SIR ratio and different number of users with different data rate requirements, and In this chapter a comparison of all scheduling techniques is presented. In the end the results of newly proposed dynamic scheduling scheme is compared with individual techniques.

## 5.2 Comparison of Scheduling Based Spectrum Sharing Techniques

Now consider some metrics on the basis of which we can compare Scheduling based Spectrum Sharing techniques. There are three performance evaluation factors on the basis of which the comparison is done.

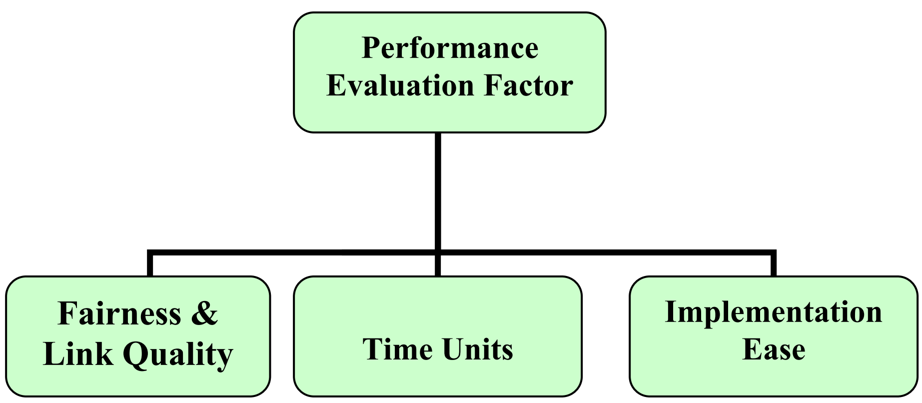


Figure 5.1 Performance Evaluation Factors

### 5.2.1 Fairness

The fairness is considered to be one of the critical factors during the design of any sharing scheme. The fairness ensures to provide the opportunity to each and every node or user participating in the sharing process. In case of unfairness few users enjoy the usage of resources while other may have to wait long to get opportunity to use the shared resources.

Maximum Sum Rate Scheduling is a good spectrum sharing scheme in Cognitive Radio Networks in case of maximizing the throughput by selecting the best quality links but it doesn't take into account the fairness criteria. At zero minimum data rate requirement it shows totally unfair behavior towards the low quality links. It selects the best available links in terms of least noise power, link gains and tries to send all the data on these particular links which is unfairness to the other links.

Max-Min Fair Scheduling is sort of round robin spectrum sharing scheme in Cognitive Radio Networks in case of providing the equal data rates to all the links but it doesn't take into account the link quality criteria. It adjusts its scheduling time in a way to provide equal data rate to all the links.

Proportional Fair Scheduling is another spectrum sharing scheme in cognitive radio networks that considered both the factors of link quality and the fairness criteria. It will be the best technique among the three presented technique if we considered both the fairness and link quality factors at the same time.

The table compares the three techniques on the basis of the link quality and fairness issues. It is clear from the table that increasing minimum data rate requirement of each link in maximum sum rate scheduling scheme decreases the sum of the data rates on all links. Further increment in the value of $A_{min}$ to 1.32 Maximum Sum Rate scheduling scheme staring behaving like Max-Min Fair scheme allocates same data rate on all links. By observing the individual data rates on each link it is clear that maximum sum rate scheduling scheme selects the best available links as it does with the link number 1 and link number 4. It shows no interest towards the low quality links, but by controlling the minimum data rate requirement it will also fulfils the fairness criteria but at the same time it neglects the quality of the links. The Max-Min Fair algorithm provides the global fairness to all links as shown in the table by allocating 1.32 data rate to all links but it doesn't care about the quality of links. So Max-Min Fair scheme is the best scheme if fairness is the only criteria for comparison. The Proportional Fair scheduling scheme fulfils both the fairness and link quality factors. It will allocate the data rate according the quality of link. So it will satisfy the fairness criteria on the individual link basis. Hence the proportional fair scheme is the best scheme if both factors of link quality and fairness are under consideration.

Table 5.1 Comparison of Scheduling Schemes

| **Sum Rate** | **Power (db)** | **Noise Variance (η)** | **Minimum Average Data Rate Requirement Max-Sum Rate** | | | | | **Max-Min Fair** | **Proportional Fair** |
|---|---|---|---|---|---|---|---|---|---|
| | | | **$A_{min}$ 0** | **$A_{min}$ 0.5** | **$A_{min}$ 0.75** | **$A_{min}$ 1** | **$A_{min}$ 1.32** | | |
| **Link 1** | 30 | 0.1 | 3.95 | 2.95 | 2.96 | 2.31 | **1.32** | 1.32 | 1.60 |
| **Link 2** | 30 | 0.2 | 0.00 | 0.50 | 0.75 | 1.00 | **1.32** | 1.32 | 1.20 |
| **Link 3** | 30 | 0.2 | 0.00 | 0.50 | 0.75 | 1.00 | **1.32** | 1.32 | 1.20 |
| **Link 4** | 30 | 0.1 | 4.05 | 3.03 | 2.01 | 1.65 | **1.32** | 1.32 | 1.60 |
| **Link 5** | 30 | 0.2 | 0.00 | 0.50 | 0.75 | 1.00 | **1.32** | 1.32 | 1.20 |
| | | **Sum Rate** | 8.00 | 7.48 | 7.22 | 6.96 | 6.60 | 6.60 | 6.80 |

Figure 5.2 shows the behavior of the same techniques in graphical way. The max-min fair scheduling scheme shows a straight line indicating equal data rates to all available links while the Maximum Sum Rate scheme shows only two valid entries showing the selection of best available links and the zigzag points show the outcomes of the proportional fair scheme.

There exists a special case where the maximum sum rate scheduling scheme exhibit the behavior of max-min fair scheme. If all the users in maximum sum rate scheduling scheme requires data rate that is equal to the sum of the average data rate on all links than all the users gets the same data rate. This case is represented in the Table 5.1 when the minimum data rate requirement Amin is 1.32.

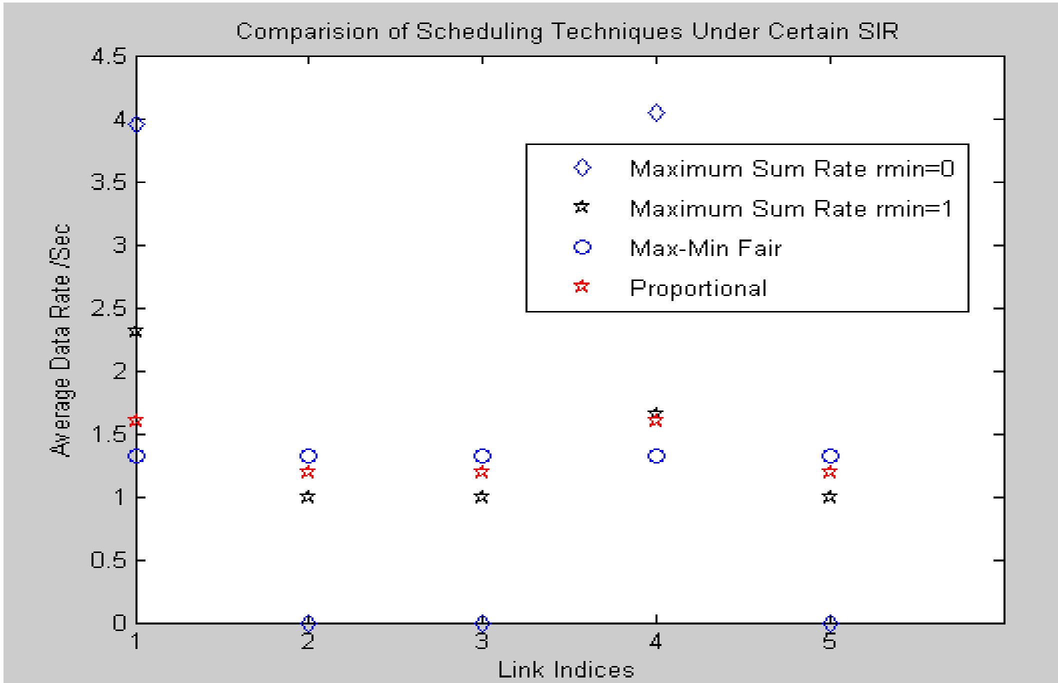


Figure 5.2 Comparison of Scheduling Based Spectrum Sharing Schemes

Hence, by observing the experimental results in Table and figure 5.1 it is concluded that proportional fair scheduling is the best technique in term of fairness and link quality factors.

### 5.2.2 Time Units (Sec)

The dynamic scheduling scheme proposed in the thesis can compare the three scheduling based spectrum sharing schemes in terms of the time units it requires to fulfill the need of individual users by considering the radio environment to be remains same for specific time units. The Maximum Sum Rate scheduling as previously known selects the best quality links so it will fulfill the need of the users in least time units while the Max-Min Fair scheme provides equal data rate so that it will take the most of the time and that Proportional Fair scheduling scheme takes the time is less than the max-min fair scheme and greater than maximum sum rate scheduling. Different sinarios are created to shows the comparison among the three schemes.

Table 5.2 Maximum Data Need of Different Users

| User ID | Maximum Need |
|---|---|
| 1 | 5 |
| 2 | 3 |
| 3 | 2 |
| 4 | 1 |
| 5 | 4 |
| 6 | 2 |
| 7 | 2 |
| 8 | 1 |

Table 5.3 Maximum Sum Rate Scheduling Different Time Units

| | Time Unit 1 | | Time Unit 2 | | Time Unit 3 | |
|---|---|---|---|---|---|---|
| **Link** | **User** | **Data Rate** | **User** | **Data Rate** | **User** | **Data Rate** |
| **Link 1** | 1 | 3.603387 | 5 | 3.603387 | 4 | 0.379077 |
| | | | | | 7 | 2.00 |
| | | | | | 1 | 0.135690 |
| **Link 2** | 2 | 1.32 | 1 | 1.32 | 5 | 0.396613 |
| | | | | | 6 | 0.923387 |
| **Link 3** | | | | | | |
| **Link 4** | 3 | 2.00 | 2 | 1.68 | 1 | 0.076613 |
| | 4 | 0.620923 | 6 | 0.940923 | 8 | 1.00 |
| **Link 5** | | | | | | |

Table 5.4 Max-Min Fair Scheduling Different Time Units

| | Time Unit 1 | | Time Unit 2 | | Time Unit 3 | | Time Unit 4 | |
|---|---|---|---|---|---|---|---|---|
| **Link** | **User** | **Data Rate** | **User** | **Data Rate** | **User** | **Data Rate** | **User** | **Data Rate** |
| **Link 1** | 1 | 1.323227 | 3 | 0.676773 | 7 | 1.323227 | | |
| | | | 2 | 0.353545 | | | | |
| | | | 7 | 0.292909 | | | | |
| **Link 2** | 2 | 1.323227 | 6 | 1.323227 | 6 | 0.676773 | | |
| | | | | | 5 | 0.030318 | | |
| | | | | | 7 | 0.383863 | | |
| | | | | | 1 | 0.232274 | | |
| **Link 3** | 3 | 1.323227 | 5 | 1.323227 | 5 | 1.323227 | 1 | 0.151589 |
| **Link 4** | 4 | 1.00 | 1 | 1.323227 | 1 | 1.323227 | | |
| | 1 | 0.323227 | | | | | | |
| **Link 5** | 5 | 1.323227 | 2 | 1.323227 | 8 | 1.00 | | |
| | | | | | 1 | 0.323227 | | |

Table 5.5 Proportional Fair Scheduling Different Time Units

| | **Time Unit 1** | | **Time Unit 2** | | **Time Unit 3** | |
|---|---|---|---|---|---|---|
| **Link** | **User** | **Data Rate** | **User** | **Data Rate** | **User** | **Data Rate** |
| **Link 1** | 1 | 3.603387 | 5 | 3.603387 | 4 | 0.379077 |
| | | | | | 7 | 2.00 |
| | | | | | 1 | 0.135690 |
| **Link 2** | 2 | 1.32 | 1 | 1.32 | 5 | 0.396613 |
| | | | | | 6 | 0.923387 |
| **Link 3** | | | | | | |
| **Link 4** | 3 | 2.00 | 2 | 1.68 | 1 | 0.076613 |
| | 4 | 0.620923 | 6 | 0.940923 | 8 | 1.00 |
| **Link 5** | | | | | | |

Table 5.2 shows eight users with their maximum data requirement. There are five links available for the transmission of the data. The dynamic scheduling scheme can use any of the three sharing techniques to fulfill the data requirement of these eight users. The scheduling behavior of each scheduling technique is depicted in the table 5.3 through 5.5. The dynamic scheduler pick the first five users from the queue on first come first served basis and fulfils their need by assigning them particular link. The scheme is designed in such a way to maximize the throughput.

Table 5.3 shows the scheduling pattern of dynamic scheduling scheme with the use of Maximum Sum Rate scheduling algorithm. It is clear from the table entries that all the users are served in short span of three seconds. During the first second, four users are serving and in the second time unit the one of the five users is served completely so newer user is brought in to the serviced area and similarly the next two users are brought in during the last time unit.

Table 5.4 shows the scheduling pattern of dynamic scheduling scheme with the use of Max-Min Fair scheduling algorithm. It is clear from the table entries that all the users are serviced during the first time unit and the user number 1 is serviced twice on two different links to maximize the throughput. Two new users are brought in the serviced area during the second time unit.

Table 5.5 shows the scheduling pattern of dynamic scheduling scheme with the use of Proportional Fair scheduling algorithm. It is clear from the table entries the all the users are serviced during the first time unit and the user number 1 is serviced twice on two different links to maximize the throughput. Two new users are brought in the servicing area during the second time unit.

Table 5.6 Scheduling Behavior of Different Schemes

**Link Gains (G)**

| | | | | |
|---|---|---|---|---|
| 1 | 0.2 | 0.4 | 0.4 | 0.4 |
| 0.4 | 0.5 | 0.4 | 0.4 | 0.4 |
| 0.3 | 0.4 | 0.5 | 0.4 | 0.4 |
| 0.1 | 0.4 | 0.3 | 1 | 0.4 |
| 0.1 | 0.4 | 0.1 | 0.2 | 0.5 |

**Power (dB) (p)**

| | | | | |
|---|---|---|---|---|
| 30 | 30 | 30 | 30 | 30 |

**Noise Power (sigma)**

| | | | | |
|---|---|---|---|---|
| 0.1 | 0.2 | 0.2 | 0.1 | 0.2 |

| **Scheduling Scheme** | **Case I** | **Case II** | **Case III** | **Case IV** |
|---|---|---|---|---|
| | **Users/ Data** | **Users/ Data** | **Users/ Data** | **Users/ Data** |
| | **100 / 10** | **1000/10** | **5000/10** | **10000/10** |
| **Max-Min Fair** | 152 | 1512 | 7558 | 15115 |
| **Max Sum Rate** | 133 | 1326 | 6628 | 13256 |
| **Proportional Fair** | 148 | 1480 | 7396 | 14792 |

Table 5.6 illustrates the behavior of different scheduling based spectrum sharing schemes in terms of time units consumed for different number of users with their data requirement. The link quality of each link can be visualized by the link gain matrix and the vector of noise contents. The results are taken for four different cases each case is differentiated with different number of CR users. In first case there are 100 users and each have maximum data need of 10. The three schemes are compared by allowing each of them to fulfill need of each user in given time units and it is clear from all of the four given cases that the maximum sum rate scheduling scheme is the best scheme among the three schemes in terms of time units required to fulfill the need of each of specified CR user.

Table 5.7 Scheduling Behavior of Different Schemes at Reduced Power

**Link Gains (G)**

| | | | | |
|---|---|---|---|---|
| 1 | 0.2 | 0.4 | 0.4 | 0.4 |
| 0.4 | 0.5 | 0.4 | 0.4 | 0.4 |
| 0.3 | 0.4 | 0.5 | 0.4 | 0.4 |
| 0.1 | 0.4 | 0.3 | 1 | 0.4 |
| 0.1 | 0.4 | 0.1 | 0.2 | 0.5 |

**Power (dB) (p)**

| | | | | |
|---|---|---|---|---|
| **15** | **15** | **15** | **15** | **15** |

**Noise Power (sigma)**

| | | | | |
|---|---|---|---|---|
| 0.1 | 0.2 | 0.2 | 0.1 | 0.2 |

| **Scheduling Scheme** | **Case I** | **Case II** | **Case III** | **Case IV** |
|---|---|---|---|---|
| | **Users/ Data** | **Users/ Data** | **Users/ Data** | **Users/ Data** |
| | **100 / 10** | **1000/10** | **5000/10** | **10000/10** |
| **Max-Min Fair** | 170 | 1693 | 8461 | 16922 |
| **Max Sum Rate** | 148 | 1473 | 7363 | 14726 |
| **Proportional Fair** | 165 | 1648 | 8239 | 16478 |

Table 5.7 illustrates the behavior of different scheduling based spectrum sharing schemes in terms of time units consumed for different number of user with their data requirement. The link quality of each link can be visualized by the link gain matrix and the vector of noise contents. The results are taken for four different cases at reduced power approximately half of the power as taken in the table 5.6 each case is differentiated with different number of CR users. In first case there are 100 users and each have maximum data need of 10. The three schemes are compared by allowing each of them to fulfill need of each user in given time units and it is clear from all of the four given cases that the maximum sum rate scheduling scheme is the best scheme among the three schemes in terms of time units required to fulfill the need of each of specified CR users. As it is clear from the table that the reduction in the transmitter power reduces the data rate of each link hence requires more time units to fulfill the same data need of the user depicted in the table 5.6.

Table 5.8 Scheduling Behavior of Different Schemes at Reduced Link Gains

**Link Gains (G)**

| | | | | |
|---|---|---|---|---|
| **0.5** | 0.2 | 0.4 | 0.4 | 0.4 |
| 0.4 | **0.25** | 0.4 | 0.4 | 0.4 |
| 0.3 | 0.4 | **0.25** | 0.4 | 0.4 |
| 0.1 | 0.4 | 0.3 | **0.5** | 0.4 |
| 0.1 | 0.4 | 0.1 | 0.2 | **0.25** |

**Power (dB) (p)**

| | | | | |
|---|---|---|---|---|
| 30 | 30 | 30 | 30 | 30 |

**Noise Power (sigma)**

| | | | | |
|---|---|---|---|---|
| 0.1 | 0.2 | 0.2 | 0.1 | 0.2 |

| **Scheduling Scheme** | **Case I** | **Case II** | **Case III** | **Case IV** |
|---|---|---|---|---|
| | **Users/ Data** | **Users/ Data** | **Users/ Data** | **Users/ Data** |
| | **100 / 10** | **1000/10** | **5000/10** | **10000/10** |
| **Max-Min Fair** | 193 | 1923 | 9613 | 19225 |
| **Max Sum Rate** | 167 | 1661 | 8305 | 16609 |
| **Proportional Fair** | 186 | 1859 | 9295 | 18590 |

Table 5.8 illustrates the behavior of different scheduling based spectrum sharing schemes in terms of time units consumed for different number of users with their data requirement. The link quality of each link can be visualized by the link gain matrix and the vector of noise contents. The results are taken for four different cases at reduced link gains approximately half of the link gains as taken in the table 5.6 each case is differentiated with different number of CR users. In first case there are 100 users and each have maximum data need of 10. The three schemes are compared by allowing each of them to fulfil the need of each user in given time units and it is clear from all of the four given cases that the maximum sum rate scheduling scheme is the best scheme among the three schemes in terms of time units required to fulfill the need of each of specified CR users. As it is clear from the table that the reduction in the link gains reduced the data rate of each link hence requires more time units to fulfill the same data need of the user depicted in the table 5.6.

Table 5.9 Comparison of Scheduling Schemes in Term of Time Units

No. Of Users =**100**
Max Data Rate Requirement =**10**

| **Technique** | **Time Units** |
|---|---|
| Max Min Fair | 152 |
| Maximum Sum Rate | 133 |
| Proportional Fair | 148 |

The table 5.9 and figure 5.2 together explains the time units consumed by the different schemes under certain transmitter power, link gains and noise values. It is clearly shown that the Maximum Sum Rate scheduling consumes least time units to fulfill the same data requirement of users.

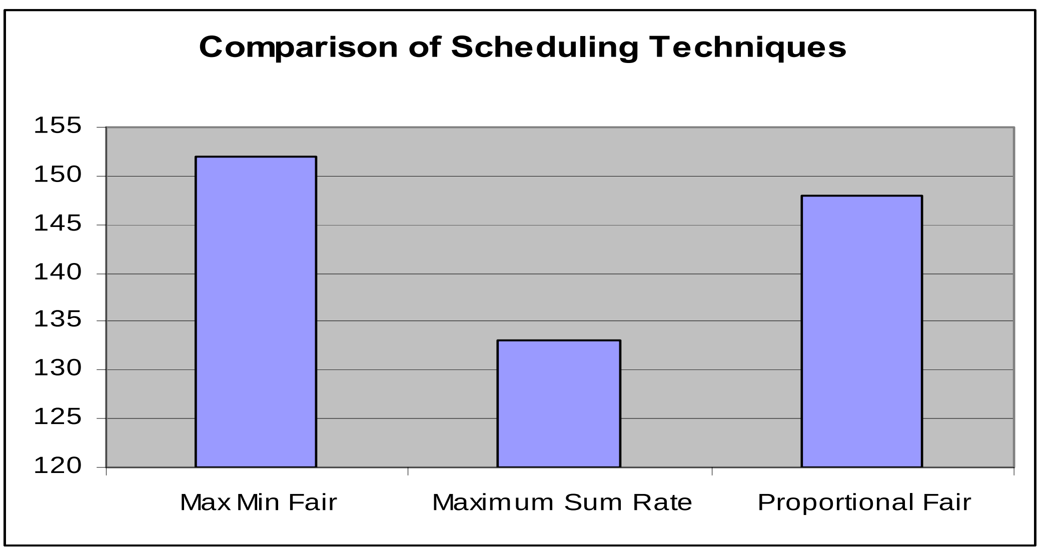


Figure 5.3 Time Units of Different Spectrum Sharing Techniques

### 5.2.3 Ease for Implementation

The Maximum Sum Rate Scheduling and Max-Min Fair scheduling schemes are based on linear program that is easy to implement while the Proportional Fair scheduling scheme is difficult to implement due to its nonlinear nature.

## 5.3 Summary

This chapter provides the results of the applied technique on various types of scheduling based spectrum sharing techniques. The result analysis clearly shows that the maximum sum rate scheduling is the best technique in terms of the time constraint.

*Chapter 6*

# CONCLUSION

## 6.1 Overview

With the increase in demand of radio spectrum the current inefficient spectrum utilization criteria fails to fulfill the requirements for future wireless technologies so there is a strapping need to find new ways for the efficient utilization of available spectrum. The Cognitive radio technology is seems to be a technology that can resolve the issues regarding the spectrum usage. The Cognitive Radios find opportunities for their transmission by scanning the radio spectrum and find space for their use.

This research was aimed towards the optimum utilization of the scanned spectrum by efficient sharing schemes. The primary requirement of a spectrum sharing system is its real time processing and decision making. The proposed methodology has been implemented on a desktop PC and requires MATLAB support for simulation.

Firstly, all the spectrum sharing techniques are compared on the basis of noise power and the time to fulfill user requirements. By comparing these techniques it is concluded that Maximum Sum Rate scheduling schemes give maximum data rate by selecting the best available links from the available pool but it cannot fulfill the fairness criteria. According the fairness and link quality criteria the proportional fairness scheme is the best among the three presented spectrum sharing schemes.

A dynamic scheduling scheme is proposed to fulfill the data requirements of users by the use of three mentioned scheduling schemes. The Maximum Sum Rate scheduling shows the best results in term of serviced time for data requirements of different users.

Finally it is concluded that every sharing scheme has its own advantages under certain conditions, Therefore by using the results of different techniques at the same time better results can be obtained.

In this thesis main issues associated with spectrum sharing techniques are highlighted. Performance of these spectrum sharing techniques limits due to uncertainty in the requirements of different users.

### 6.2 Future Work

Most of the research on spectrum sharing is mainly focused on conceptual implementation point of view. One of the important areas for the research is to focus on application. The utilization of three schemes according to the application will be an interesting work. If certain network application need constant data rate then the choice will be the Max-Min Fair scheduling. If priority will be the selection criteria then the proportional fair scheme will be the best choice. If the time constraint is the criteria then the Maximum Sum Rate scheduling scheme will be the best choice.

Another area for research is Cross Layer Communication in which spectrum sharing and higher layer functionalities can help in improving Quality of Service (QoS).

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# Annex 1

**MATLAB Code of Basic Network**

The MATLAB script 'BasicNetwork.m', presented below, simulates the basic network model considered for the Spectrum Sharing in Cognitive Radio Networks. The code is self-explanatory and consists of following parts.

**Parameters**

The system parameters are set in this part. The parameters are: (i) the power, 'p'; (ii) the noise , 'sigma'; (iii) link gain, 'G'; (iv)number of cognitive radio users, 'N'; (v) number of links , 'L'; (vi) transmission modes, 'TM Size'; (vii)signal to interference ratio of each link, 'yl'; (viii) data rate of each link, '$c_L$'.

## MATLAB script NetworkModel.m

```
close all;
clear all;
function [L N TMSize c p G tm]=NetworkModel()
%
%    PARAMETERS
%

%
% power of each Link   size 1xL
%
        p=ones(1,L);
        p=p*30;
 %
% Noise variance  size 1xL Randomly generated
 %
        a=0;b=1;
        sigma = a + (b-a) * rand(1,L);
%
% link Gain of size LxL Randomly generated
%
        a=0;b=1;
        G = a + (b-a) * rand(5);
        a=1;b=2;
        for i=1:L
                G(i,i)= a + (b-a) * rand(1);
        end

%
```

```
%SOURCE: Take input data from user for transmission
%

          N= input ('Number of nodes to Schedule');

%
% Calculation of Number of Links
%
            L=N/2;


%
% Calculation of  Transmission Modes
%
          TMSize=2^L;;


%
% Calculation of Signal to interference ratio & data rate
%
          yli=zeros(L,TMSize);
          c=zeros(L,TMSize);
          a=zeros(L,TMSize);
          b=zeros(L,TMSize);
          r=zeros(L,1);



 for j=1:1:L
      for i=1:TMSize

            a(j,i)=tm(i,j)*G(j,j)*p(j);

        if   j==1
              b(j,i)=(tm(i,2)*G(j,2)*p(2)+tm(i,3)*G(j,3)*p(3)+tm(i,4)*G(j,4)*p(4) +
              tm(i,5)*G(j,5)*p(5))+sigma(1,j)^2;

        elseif  j==2
              b(j,i)=(tm(i,1)*G(j,1)*p(1)+tm(i,3)*G(j,3)*p(3)+tm(i,4)*G(j,4)*p(4)+
              tm(i,5)*G(j,5)*p(5))+sigma(1,j)^2;

            elseif  j==3
               b(j,i)=(tm(i,2)*G(j,2)*p(2)+tm(i,1)*G(j,1)*p(1)+tm(i,4)*G(j,4)*p(4)+
               tm(i,5)*G(j,5)*p(5))+sigma(1,j)^2;

            elseif j==4
               b(j,i)=(tm(i,2)*G(j,2)*p(2)+tm(i,3)*G(j,3)*p(3)+tm(i,1)*G(j,1)*p(1)+
                tm(i,5)*G(j,5)*p(5))+sigma(1,j)^2;
            else
               b(j,i)=(tm(i,2)*G(j,2)*p(2)+tm(i,3)*G(j,3)*p(3)+tm(i,4)*G(j,4)*p(4)+
               tm(i,1)*G(j,1)*p(1))+sigma(1,j)^2;

          end
```

```
                yli(j,i)=a(j,i)/b(j,i);
               c(j,i)=log(1+yli(j,i));
    end
  end
```

### MATLAB Code of Maximum Sum Rate Scheduling

The MATLAB script 'MaximumSumRate.m', presented below, simulates the Maximum Sum Rate for Spectrum Sharing in Cognitive Radio Networks. The code is self explanatory and consists of following parts.

**Objective function**
Objective function is obtained by the matrix multiplication and then sign of function in reversed in order the convert it into maximization problem.

**Constraints**
The constraints are setup by evaluating the conditions that fulfills the maximization problem.

**Lower bound**
The lower bound satisfy the summation restriction on the one sec time of all links

**MATLAB Script MaxSumRate.m**

```
function MaxSumRate(rmin)
QueueOut=1;
[L N TMSize c p G tm]=NetworkModel();
[Rows Cols]=size(c);
f=zeros(1,Cols);
for i=1:Cols
  for j=1:Rows
     f(1,i)= f(1,i)+c(j,i);
  end
end
f=-f;

% Setting constraint Cx>=rmin since it was >= constraint hence
% multiplyinhg by -1 to make it a <= constraint
A=-c;
b=-rmin;

% Adding next constraint 1Tx<=1
[Rows Cols]=size(A);
for i=1:Cols
  A(Rows+1,i)=1;
end
[Rows Cols]=size(b);
```

```
b(Rows+1)=1;
lb=zeros(32,1);

options = optimset('LargeScale', 'off', 'Simplex', 'on');
[x1,fval1,exitflag1,output1,lambda1]= linprog(f,A,b,[],[],lb,[],[],options);
[x,fval,exitflag,output,lambda] = linprog(f,A,b,[],[],lb);

[Rows Cols]=size(x);
Sum=0;

for i=1:Rows
  Sum=Sum+x(i,1);
end

r=c*x;
for i=1:5
  if(r(i)<0.0001)
     r(i)=0;
  end
end
Schedule(r);
```

**MATLAB Code of Max-Min Fair Scheduling**

The MATLAB script 'MaxMinFair.m', presented below, simulates the Max-Min Fair for Spectrum Sharing in Cognitive Radio Networks. The code is self-explanatory and consists of the following parts:

**MATLAB Script MaxMinFair.m**

```
 function Users=MaxMinFair(rmin)
QueueOut=1;

[L N TMSize c p G tm]=NetworkModel();%Generating NW Model

 %Now making the Constraints

f=zeros(1,TMSize+1);
f(1,TMSize+1)=-1;

A1=-c;
[Rows Cols]=size(A1);
for i=1:Rows
   A1(i,33)=1;
end
b=zeros(5,1);
```

```
%Setting Equality Constraints
  Aeq=ones(1,TMSize+1);
  Aeq(1,TMSize+1)=0;
  beq=[1];
  lb=zeros(TMSize,1)

 options = optimset('LargeScale', 'off', 'Simplex', 'on'); %Using the Simplex Method
  [x1,fval1,exitflag1,output1,lambda1]=linprog(f,A1,b,Aeq,beq,lb,[],[],options

  xx=x1(1:TMSize,1);
  r1=c*xx;

 for i=1:5
     if(r1(i)<0.0001)
         r1(i)=0;
     end
  end
  Schedule(r1);
```

**MATLAB Code Proportional Fair Scheduling**

The MATLAB script ‘Proportional.m’, presented below, simulates the Proportional Fair Scheduling schemes for Spectrum Sharing in Cognitive Radio Networks. The code is self-explanatory and consists of the following parts:

**MATLAB Script ProportionalFair.m**

```
function ProportionalFair(rmin)
  QueueOut=1;
  [L N TMSize c p G tm]=NetworkModel();
  clc
  c;
  A3=c;
  [Rows Cols]=size(c);
  for i=1:L
    A3(i,Cols+i)=-1;
  end

  for i=1:Cols
  A3(Rows+1,i)=1;
  end

  b3=zeros(L,1);
  b3(L+1,1)=1;
  b3;
```

```
  x0=zeros(Cols+L,1);
  x0(Cols+1:Cols+L,1)=0.1;
  lb=zeros(TMSize,1);
  x111 = fmincon(@myfun,x0,[],[],A3,b3,lb,[]);
  r3=x111(33:37,1)

Schedule(r3);
```

**MATLAB Code for Dynamic Scheduling on user's Data Request**

The MATLAB script 'Schedule.m', presented below, simulates the Dynamic Scheduling schemes for Spectrum Sharing in Cognitive Radio Networks. The code is self-explanatory and consists of the following parts:

**MATLAB Script Schedule.m**

```
function Schedule(r1)

% r1 =[2.3232;2.3232;2.3232;2.3232;2.3232];

% r1 =[0.3;.3;0.3;0.3;0.3];

rActual=r1;

Dfid = fopen('Dynamic.txt');

ID=65;

TotalTime=10;

TotalUsers=0; %max 5

for i=1:5

[a,cou] = fscanf(Dfid,'%d',1);

  if cou~=0

    Users(i,1)=a;

    Users(i,2)=a;

    Users(i,3)=ID;

    ID=ID+1;
```

```
      TotalUsers=TotalUsers+1;
    else
        break;
    end
end
%%%%%%%%%%%%%%%%%%%%%%%%%%%%
CurrentUser=1;
ExitFlag=0;
NoMoreUserFlag=0;
Time=1;
fprintf('------------------------------SCHEDULE-------------------------------------------');
fprintf('\nIn Time Unit: %d \n',Time);
  while ExitFlag==0
      j=1;
    while j<=5 && ExitFlag==0
      if (r1(:)==0)
        Time=Time+1;
        fprintf('\nIn Time Unit: %d \n',Time);
        r1=rActual;
      end
      if r1(j)~=0 %Links Data Rate is not zero
        if Users(CurrentUser,2)==0
            %Users(CurrentUser,2)=0;
            j=j-1;
        elseif Users(CurrentUser,2)<=r1(j)
            fprintf('User ID %c: Link Num %d  Data Rate
```

```
%f\n',Users(CurrentUser,3),j,min(r1(j),Users(CurrentUser,2)));%make 1 to 2
      r1(j)=r1(j)-Users(CurrentUser,2);
      Users(CurrentUser,2)=0;
      %Entering new User if Present
      [a,cou] = fscanf(Dfid,'%d',1);
      if cou~=0
        Users(CurrentUser,1)=a;
        Users(CurrentUser,2)=a;
        Users(CurrentUser,3)=ID;
        ID=ID+1;
        TotalUsers=TotalUsers+1;
      else
        NoMoreUserFlag=1;
      end
    else
      fprintf('User ID %c: Link Num %d  Data Rate %f\n',Users(CurrentUser,3),j,r1(j));
      Temp=r1(j);
      r1(j)=0;
      Users(CurrentUser,2)= Users(CurrentUser,2)-Temp;
    end
    CurrentUser=CurrentUser+1;
    if CurrentUser==6
      CurrentUser=1;
    end
  end
  if(Users(:,2)<=0)
```

```
 ExitFlag=1;
    end
j=j+1;
    end
  end
% r1
% ExitFlag
```

**MATLAB Code for Main File**

The MATLAB script 'Main.m', presented below, calls all the Scheduling Schemes presented for Spectrum Sharing in Cognitive Radio Networks. The code is self-explanatory and consists of the following parts:

**MATLAB Script Main.m**

```
function main()
 %rmin=[0.25;0.25;0.25;0.25;0.25];
 % a=0;b=1;
   %     rmin = a + (b-a) * rand(1,L);
 Choice=1;
 Algorithm=0;
 while Choice==1
  %user_entry = input('1:Max Min Fair Scheduling\n2:Max Sum Rate Scheduling\n3:Proportional Fair Scheduling\n');
     %if user_entry ==1
        N=10;
        L=5;
```

```
 % The minimum Data requirement is taken through the Poissions Model
   rmin = rand( ‘poissions’, 1:L,1,L)
  [L N TMSize c p G tm]=NetworkModel(L,N);%Generating NW Model
  input('View Result of Max Min Fair');
  r1=MaxMinFair(rmin,L,N,TMSize,c,p,G,tm);
  Algorithm=1;
  Schedule(r1,rmin,Algorithm,L,N,TMSize,c,p,G,tm);
  input('View Result of Max Sum Rate');
  r1=MaxSumRate(rmin,L,N,TMSize,c,p,G,tm);
  Algorithm=2;
  Schedule(r1,rmin,Algorithm,L,N,TMSize,c,p,G,tm);
   input('View Result of Proportional Fair');
   r1=ProportionalFair(rmin,L,N,TMSize,c,p,G,tm);
   Algorithm=3;
   Schedule(r1,rmin,Algorithm,L,N,TMSize,c,p,G,tm);
 Choice=input('Press 1 to Run Again and 2 to Exit\n');
end
```