UNIVERSITY OF CINCINNATI

Date: 8th October, 2008

I, *Sameer Swami*

hereby submit this work as part of the requirements for the degree of:

Master of Science

in:

Computer Science

It is entitled:

*Graph Theoretic Approach to QoS Guaranteed Spectrum Allocation
in Cognitive Radio Networks*

This work and its defense approved by:

Chair: *Dr. Kenneth A. Berman*

Dr. Fred Annexstein

Dr. John V. Franco

Graph Theoretic Approach to QoS Guaranteed Spectrum Allocation in Cognitive Radio networks

A thesis submitted to

Division of Research and Advanced Studies
University of Cincinnati

In partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

in the Department of
Computer Science
College of Engineering
2008

by

Sameer Swami

Bachelor of Technology (Computer Science and Engineering)
UPTU, India.
June 2006

Thesis Advisor and Committee Chair: Dr. Kenneth A. Berman

ABSTRACT

In this thesis work, we focus on the design of a new channel allocation mechanism for the Cognitive Radio based xG networks, based on graph theory. We propose division of the users as well as the channels on the basis of the quality of service constraints. We then analyze the performance of our mechanism incrementally in two steps: (a) Channel allocation in a static environment. (b) Channel allocation in a dynamic environment. In the first scenario, we assume a static channel configuration, wherein the primary users' behavior has been strictly defined according to a schedule. We analyze the performance of our scheme in such an environment taking into account the various performance measures like packet drop rate. We compare our scheme against the bare bones scheme where no priorities are taken into account while allocating channels.

In the second part of our work, we simulate the performance of our algorithm in a dynamic environment, where the behavior of the primary users is arbitrary. In such a scenario, the algorithm must adapt to take into account the changing channel qualities which directly impact the users. We again compare our scheme based on graph theory, against the bare bones scheme where the priorities aren't taken into account as well as against the greedy scheme which simply serves the users based upon their priorities. We show that our approach delivers vast improvements in packet drop rates compared to the random channel allocation scheme.

To my family,

Acknowledgements

I express sincere gratitude towards my advisor and mentor Dr. Kenneth A. Berman for his constant support, guidance, and encouragement during the course of my MS.

I would also like to thank Dr. Fred Annexstein and Dr. John Franco, for obliging to serve on my thesis committee and for their valuable comments.

In the course of my graduate life at Cincinnati, I have had the benefit of interacting with fellow graduate students, and would like to thank them all for their valuable suggestions.

I would particularly like to thank members of the CDMC lab with whom I have collaborated and often discussed my research.

Lastly, I thank members of my family for their constant support and love during this journey.

Contents

LIST OF FIGURES	IV
LIST OF TABLES	V
1. INTRODUCTION.....	1
1.1 ORGANIZATION OF THE DOCUMENT.....	4
2. COGNITIVE RADIOS AND xG NETWORKS.....	5
2.1 INTRODUCTION.....	5
2.2 COGNITIVE RADIO.....	8
2.2.1 <i>The Cognitive Cycle</i>	10
2.2.2 <i>Re configurability</i>	12
2.3 xG NETWORK.....	13
2.3.1 <i>xG network architecture</i>	13
2.3.1.1 <i>Primary network</i>	13
2.3.1.2 <i>xG network</i>	14
2.3.2 <i>xG network functions on licensed band</i>	15
2.3.2.1 <i>Spectrum management</i>	16
2.3.2.2 <i>Spectrum analysis</i>	17
2.3.2.3 <i>Spectrum decision</i>	17
2.3.2.4 <i>Transmitter-receiver handshake</i>	17
2.3.2.5 <i>Spectrum mobility</i>	18
2.4 xG NETWORK APPLICATIONS.....	19
3. RELATED WORK.....	20
3.1 SPECTRUM SHARING TECHNIQUES.....	20
3.2 INTER-NETWORK SPECTRUM SHARING.....	22

3.2.1 <i>Centralized Inter-network spectrum sharing</i>	23
3.2.2 <i>Distributed Inter-network spectrum sharing</i>	24
3.3 INTRA-NETWORK SPECTRUM SHARING.....	25
3.3.1 <i>Co-operative intra-network spectrum sharing</i>	25
3.3.2 <i>Non-cooperative intra-network spectrum sharing</i>	27
4. PRIORITY ASSIGNMENT.....	29
4.1 INTRODUCTION.....	29
4.2 PRIORITY ASSIGNMENT ON CHANNELS IN A SPECTRUM.....	29
4.3 PRIORITY ASSIGNMENT ON SECONDARY USERS.....	31
5. DYNAMIC MATCHING IN A VERTEX PRIORITY WEIGHTED BIPARTITE GRAPH.....	34
5.1 INTRODUCTION.....	34
5.2 TOPOLOGY OF GRAPH.....	38
6. PRIORITY OPTIMAL GREEDY HUNGARIAN ALGORITHM.....	42
6.1 INTRODUCTION.....	42
6.2 PRIORITY FUNCTION.....	44
6.3 PRIORITY OPTIMAL MATCHING ALGORITHM.....	45
7. SIMULATION MODEL.....	51
7.1 THE SYSTEM MODEL.....	51
7.2 IMPLEMENTATION.....	53
7.2.1 <i>Queue Management</i>	54
7.2.2 <i>Algorithm Implementation</i>	55
7.2.3 <i>Program Description</i>	56

8. PERFORMANCE IN A STATIC ENVIRONMENT.....	58
8.1 INTRODUCTION.....	58
8.2 SIMULATION RESULTS.....	60
8.2.1 <i>Priority 0 SUs packet drop rate</i>	60
8.2.2 <i>Priority 1 SUs packet drop rate</i>	61
8.2.3 <i>Priority 2 SUs packet drop rate</i>	62
8.2.4 <i>Summary of results</i>	63
9. PERFORMANCE IN A DYNAMIC ENVIRONMENT.....	64
9.1 INTRODUCTION.....	64
9.2 SIMULATION RESULTS.....	66
9.2.1 <i>Priority 0 SUs packet drop rate</i>	66
9.2.2 <i>Priority 1 SUs packet drop rate</i>	68
9.2.3 <i>Priority 2 SUs packet drop rate</i>	70
9.2.4 <i>Throughput increase</i>	72
9.2.5 <i>Throughput dependence upon PUs</i>	74
9.2.6 <i>Prioritized users delay analysis</i>	75
9.3 SUMMARY OF RESULTS.....	76
10. CONCLUSION AND FUTURE DIRECTIONS.....	79
10.1 CONCLUSION.....	79
10.2 FUTURE DIRECTIONS.....	80
BIBLIOGRAPHY	82

List of Figures

FIGURE 2.1 FCC SPECTRUM ALLOCATION.....	5
FIGURE 2.2 FCC SPECTRUM UTILIZATION	6
FIGURE 2.3 SAMPLE USAGE OF THE SPECTRUM.....	6
FIGURE 2.4 COOPERATION AND COORDINATION AMONG MODULES.....	8
FIGURE 2.5 SPECTRUM HOLE CONCEPT.....	9
FIGURE 2.6 COGNITIVE CYCLE.....	10
FIGURE 2.7 xG NETWORK ARCHITECTURE	13
FIGURE 2.8 xG NETWORK ON LICENSED BAND	15
FIGURE 3.1 INTRA NETWORK SPECTRUM SHARING	22
FIGURE 4.1 TYPES OF CHANNELS	30
FIGURE 4.2 FLOW DIAGRAM FOR GROUPING STRATEGY	32
FIGURE 4.3 PRIORITY ASSIGNMENT TO SECONDARY USERS.....	33
FIGURE 5.1 MATCHING IN A BIPARTITE GRAPH.....	35
FIGURE 5.2 MODELING ALLOCATION AS MATCHING.....	36
FIGURE 5.3 DYNAMIC NATURE OF ALLOCATIN.....	38
FIGURE 5.4 TYPES OF FREE CHANNELS.....	39
FIGURE 6.1 AUGMENTING PATH IN BIPARTITE GRAPH	43
FIGURE 7.1 SYSTEM MODEL	52
FIGURE 7.2 FLOW DIAGRAM FOR PROPOSED SCHEME	53
FIGURE 7.3 CLASSES USED IN SIMULATION	57
FIGURE 8.1 PRIORITY 0 SUs PACKET DROP RATE.....	60
FIGURE 8.2 PRIORITY 1 SUs PACKET DROP RATE	61
FIGURE 8.3 PRIORITY 2 SUs PACKET DROP RATE	62
FIGURE 9.1 PRIORITY 0 SUs PACKET DROP RATE	66
FIGURE 9.2 PRIORITY 1 SUs PACKET DROP RATE	68
FIGURE 9.3 PRIORITY 2 SUs PACKET DROP RATE	70
FIGURE 9.4 THROUGHPUT PERFORMANCE	72
FIGURE 9.5 THROUGHPUT VARIATIONS WITH PU ARRIVAL	73
FIGURE 9.6 TIME SPENT IN DROPPED QUEUE BY SUs	74
FIGURE 9.7 PERFORMANCE ON JAINS FAIRNESS INDEX	75

List of Tables

TABLE 9.1 PERCENTAGE IMPROVEMENT IN NUMBER OF PACKETS DROPPED FOR PRIORITY 0 USERS OVER THE SCHEME WITHOUT PRIORITY	68
TABLE 9.2 PERCENTAGE IMPROVEMENT IN NUMBER OF PACKETS DROPPED FOR PRIORITY 1 USERS OVER THE SCHEME WITHOUT PRIORITY	70
TABLE 9.3 PERCENTAGE IMPROVEMENT IN NUMBER OF PACKETS DROPPED FOR PRIORITY 2 USERS OVER THE SCHEME WITHOUT PRIORITY	72

Chapter 1

1. Introduction

The current wireless networks are regulated by a fixed spectrum assignment policy, i.e. the government agencies assign the channels to license holders on a long term basis for specific large geographical areas. The usage of the spectrum varies vastly as the spectrum usage is concentrated on certain portions of the spectrum while large portions remain underutilized. According to Federal Communications Commission (FCC), temporal and geographical variations in the utilization of the assigned spectrum range lie between 15% to 85%. In the past few years there has been a dramatic increase in the access to the limited spectrum for mobile services. This increase has brought into question the effectiveness of current channel assignment policies.

The limitations in the availability of spectrum as well as the current inefficiencies in its usage have led to the development of the field of cognitive radios whose premise is to utilize the available spectrum opportunistically. *Dynamic Spectrum Access* policy is expected to solve the inefficiencies in spectrum usage. This policy is aimed to be implemented by intelligent radios known as cognitive radios.

The benefit expected to be accrued from the use of cognitive radios is higher bandwidth to mobile users via heterogeneous wireless architectures by using dynamic spectrum access techniques. The efficiency in the use of the current spectrum can be increased by

opportunistic access to the licensed bands without interfering with the current users.

There is a huge portfolio of issues which need to be tackled due to the broad range of available spectrum as well as diverse Quality-of-Service (QoS) requirements of applications.

We model the channel allocation problem, in a network using cognitive radios, into the problem of computing a matching in a bipartite graph. We propose the application of Dr. Berman's algorithm, which incorporated priorities on the vertices of the graphs, for solving this problem. The algorithm was initially designed with a view to ensure fairness and balance load in a client-server network. We made slight modifications to the algorithm to suit our purpose. The algorithm is based upon growing a maximum-sized augmenting tree at a requesting user. In order to meet the quality of service constraints, we customize the topology of the graph to reflect the requirements of the requesting users. The algorithm now computes a matching which reflects the channel assignment for the current schedule of user transmission. The algorithm re-computes the matching whenever there is a change in the network topology due to the arrival of Primary Users or a change in the users' requirements.

We simulate two scenarios in order to verify the efficacy of our algorithm. In the first scenario, we have a **Static Environment** where we assume that the channel configuration would be stable, i.e. the primary users' behavior has been predefined. We start by matching the user having the highest priority, and go on until all the users are matched or until we can no longer improve the priority values of the unmatched users. We use

Poisson distribution with arrival rate $\lambda = 0.5$, to define the behavior of the users. After the current user requests have been served, the algorithm would re compute the matching for the unmatched users.

In a **Dynamic environment**, we assume that the Primary users can arrive with a small probability which we model as a Poisson distribution with arrival rate λ . For different usage patterns, we plot the throughput variations for different arrival rates of the licensed users. In such an environment, the channel quality changes according to presence of the Primary users and the algorithm has to adapt to the changing network topology.

In both the scenarios, we compare the performance of our scheme against the random channel allocation scheme. Random channel allocation does not take the user priority or channel priority into consideration. Since there aren't any benchmark channel allocation schemes for Cognitive radio networks in place yet, current research compares any new proposed scheme to the random allocation model. Simulation results show that we are able to get significant improvements in the packet drop rate for the users using our scheme. However, the one drawback we introduce is the presence of jitter because of the channel re-allocation being done in our scheme. We give the simulation jitter values for all the users.

1.1 Organization of the document

The rest of the document is organized as follows. Chapter 2 gives a brief background of the Next Generation (xG) networks and the cognitive radio technology upon which they are based. Chapter 3 gives a brief overview of some of the current channel allocation schemes which are in use in the xG networks as well the general mobile transmission paradigm. In Chapter 4, we describe our criteria for grouping the channels and the users keeping in mind the Quality of Service (QoS) constraints. Chapter 5 discusses the how we modeled the channel allocation problem into a matching problem utilizing graph theory concepts. In, Chapter 6 we introduce our algorithm and give a detailed description as to how it has been applied to allocate channels in a cognitive radio based network. Chapter 7 gives a detailed description of our system model and the allocation scenario. In Chapter 8, we talk about how we applied our algorithm to the channel allocation problem in a static environment. We present the results and our interpretations. The same is done in a much more rigorous manner for the dynamic scenario in the 9th chapter. Chapter 10 concludes with our some of our observations and future directions of research which can be pursued.

Fig. 2.2 FCC spectrum utilization

The idea of opportunistically utilizing the spectrum has motivated the genesis of a new networking paradigm, referred to as Dynamic Access Network (DAN) or Cognitive radios. We provide a brief overview of the cognitive radio technology.

Fig. 2.3 Sample usage of the spectrum in tests conducted New Jersey.

Cognitive radios were designed with a view to utilize the ‘white spaces’ or gaps within the transmissions. As per the FCC, a Cognitive Radio is a radio ‘*capable of changing its operating characteristics based on interaction with the environment in which it operates*’. The FCC adopted an NPRM on 13 May 2004 proposing “to allow unlicensed radio transmitters to operate in the broadcast TV spectrum at locations where that spectrum is not being used”. These are frequency channels allocated for TV broadcasting that are not used in given areas. Specifically, the FCC has proposed to allow unlicensed operation in the spectrum used by TV channels 5 and 6 (76 – 88 MHz), 7 through 13 (174 – 216 MHz), 14 through 36 (470 – 608 MHz), and 38 through 51 (614 – 698) MHz. The proposed new rules would allow the operation of both fixed/access and personal/portable broadband devices on a noninterference basis. The Cognitive radios function as the enabling technology in these Next Generation (xG) networks.

The main functions for cognitive radios in xG networks can be summarized as follows:

- Spectrum Sensing: Detection of the unused portions of the spectrum and efficiently utilizing them without interfering with the current users.
- Spectrum Management: Providing the best channel according to the user requirements.
- Spectrum Mobility: allowing various users to maintain communications without interference while migrating to different channels.
- Spectrum Sharing: sharing the available spectrum among the current users fairly.

We will focus our attention on the spectrum management functionality of the cognitive radios. Fig. 2.4 gives the architecture of the xG networks. There is a need for cross-layer

design for the network keeping in mind the significant amount of interactions that take place. There is also a need for the spectrum sensing and spectrum sharing modules to co-operate among themselves in order to enhance the spectrum efficiency.

Fig. 2.4 Cooperation and Coordination among the modules. [3]

2.2 Cognitive radio

Cognitive Radio is the key enabling technology in xG networks that allows dynamic access of spectrums.

The two main characteristics associated with them are:

- *Cognitive capability:* the cognitive radio has an ability to sense and obtain information from its radio environment. It cannot obtain this information just by monitoring the power in some frequency band but requires the use of more sophisticated techniques. They are required in order to obtain the temporal and spatial variations in radio environment as well as to avoid interference with

current users. The unused portion of the spectrum is identified and suitable operating parameters can be selected. [4]

- Reconfigurability: this refers to the capability of the radio to be programmed according to the radio environment. The cognitive radio can be programmed to transmit and receive on variety of frequencies and to use different spectrum access technologies based on its hardware design. [5, 6]

As the major portion of the spectrum has already been assigned, the challenge is to share the licensed spectrum without interfering with the transmission of other licensed users as shown in Fig. 2.5 [10].

Fig. 2.5 Spectrum Hole Concept. [3]

The cognitive radio enables the usage of temporally unused spectrum, which is referred to as *spectrum hole* or *white space* [7]. If this band is used by a licensed user, the

cognitive radio moves to another spectrum hole or stays in the same band, altering its transmission power level or modulation scheme to avoid interference.

2.2.1 The Cognitive Cycle

The cognitive capability of a cognitive radio provides real time interaction with its environment to determine the operating parameters as well as adapt to the dynamic radio environment. In the figure below we see the entire operation referred to as a *cognitive cycle*. [7, 8, 9]

Fig. 2.6 Cognitive Cycle

We look at the three principal functions performed in the cognitive cycle: *spectrum sensing*, *spectrum analysis* and *spectrum decision*.

The steps involved in the cognitive cycle are as follows:

1. Spectrum Sensing: the cognitive radio is responsible for monitoring the available spectrum bands, keep track of the transmissions on those channels and then detect the spectrum holes.
2. Spectrum Analysis: During this phase the characteristics of the holes are estimated.
3. Spectrum decision: the requirements of the transmission such as the bandwidth, data rate and the transmission mode are determined. The cognitive radio then chooses the best possible spectrum available for the transmission in accordance with the spectrum characteristics and user requirements.

After the spectrum decision is made, the user can start transmitting on the chosen spectrum band. However, there are a multitude of factors which can change the environment in which the cognitive radio is operating. These factors could range from the return of the primary user to the transmitting portion of the spectrum to user movement and traffic variation. The cognitive radio must have the capability to sense its operating environment and if its current spectrum band becomes unavailable, the *spectrum mobility function*, as described later, is performed in order to select the next operating spectrum in order to provide seamless transmission.

2.2.2 Reconfigurability

Reconfigurability refers to the capability of cognitive radios to change the operating frequency while transmitting without making any changes to the hardware configuration.

This capability is central in order for the cognitive radio to adapt itself to the ever changing environment. Some of the operating factors which can be reconfigured for a cognitive radio are:

- Operating frequency.
- Modulation.
- Transmission power.
- Communication Technology.

These parameters can be reconfigured not only at the beginning of the transmission but also during the actual transmission. In our problem formulation, we assume a simplified hardware design which has the capability of varying the operating frequency only. We do not take into account a cognitive radios' capability to change its other operating parameters. Thus, in the event of a change in the operating environment such as the return of a licensed user, the cognitive radio has no recourse besides having to change its operating frequency.

2.3 xG network

2.3.1 xG network architecture

The Next Generation (xG) network is the wireless communication network which utilizes the cognitive radio. The xG network can be divided into two major functional components, i.e. the primary network and the xG network. Fig. 2.5 shows the major components of the architecture. A brief description of the two components follows [3].

Fig. 2.7 xG network architecture. [3]

2.3.1.1 Primary network

Primary network refers to an existing network infrastructure which is held by a licensed user, one having exclusive rights over that channel. An example would be

the TV channels that transmit over licensed channels. The major components are as follows:

- Primary user: A primary user is someone who has a license over the use of a specific portion of the spectrum. The operation is controlled by the primary base station which is unaware of the operations of any other users in the network. They do not make any modifications to their operating parameters in order to accommodate other secondary users.
- Primary base-station: Base station is a fixed infrastructure network component which is licensed to transmit on specific portions of the spectrum.

2.3.1.2 xG network

The xG network does not have a licensed band to operate in. This network, which may be deployed with a fixed infrastructure or using an ad-hoc network, opportunistically seeks to utilize the gaps in the primary users' transmissions. The major components of an xG network are as follows:

- xG user: An xG user has no license to operate in the spectrum. He is also termed as the secondary user. An xG user accesses the medium in an opportunistic manner.
- xG base station: This is a fixed infrastructure component which provides access to the transmission medium for the secondary users. It has xG capabilities.

- Spectrum broker: This is a centralized entity responsible for sharing the spectrum among the various xG networks.

2.3.2 xG network functions on licensed band

xG network can operate on both licensed as well as unlicensed band. In our work, we focus on the functionality of the network while it is operating on the licensed part of the spectrum.

As we have shown previously, there are temporally unused spectrum holes in the licensed part of the spectrum. xG networks can be deployed to specifically exploit these spectrum holes through the use of cognitive radio technology. We depict the architecture of such a network where an xG network is functioning besides the primary network at the same location and band.

Fig. 2.8 xG network on licensed band [3]

The presence of primary users on the licensed band poses various design and operational challenges for xG network. Although the primary basis for operation is the detection of the best possible channel of communication, a part of the functionality is devoted to the detection of the primary users, whenever they return to transmit on the channel. The most important architectural issue in this design is *interference avoidance with the primary users*. Also, the xG network must vacate the channel it is transmitting on, upon the arrival of the primary user. The xG user must then move on to the next best available transmitting channel in a process called *spectrum handoff*.

2.3.2.1 Spectrum Management

The unused bands sensed by the xG networks are spread across a wide range of frequencies. These holes show a large variation in their spectrum characteristics with respect to operating time as well as the neighboring users. The quality of these channels needs to be estimated in order to implement the best channel allocation functionality *guaranteed* by the xG networks. In order to achieve this, there are a range of spectrum management functions which need to be performed. These functions are classified as *spectrum sensing*, *spectrum analysis* and *spectrum decision*. While spectrum sensing can be performed by the lower layers in the OSI architecture, the analysis and decision functions need to be implemented in the upper layers. Our primary concern lies with the spectrum allocation wherein we analyze the Quality of Service of a particular channel and then assign it to a waiting user.

2.3.2.2 *Spectrum Analysis*

The various channels which are used by the cognitive radios have varying quality characteristics in time due to the changing radio environment in which they operate. In order to allocate the best available channels to the requesting user, we need to estimate the characteristics of the channels as they become available. These characteristics are influenced by the primary user activity; therefore we need to keep track of the channels' operating parameters such as the frequency and the bandwidth. We define the quality of a channel using various different parameters such as interference level, channel error rate, path-loss, link layer delay and the holding time.

2.3.2.3 *Spectrum decision*

Once these parameters have been estimated, we determine the data rate, acceptable error rate, delay bound, the transmission mode and the bandwidth according to the requirements of the users. The spectrum management function must be aware of the quality offered by every channel as well as the requirements of a particular user.

2.3.2.4 *Transmitter- receiver handshake*

Once the user has been granted access to a specified channel, the intended recipient must be made aware of the channel on which it is to expect the transmission. There is a handshake protocol between the sender and the recipient which coordinates this access. There could be other parties involved in this communication as well.

2.3.2.5 *Spectrum Mobility*

xG networks aim to make available the best possible transmitting frequency to the transmitting radio or the cognitive radio. In order to do that, the network must keep track of the changes which might be happening in the radio environment that might affect the quality of the channels. Also, this information must be made available to the cognitive radios which are transmitting in order for them to change the transmitting channels as they see fit. *Spectrum Mobility* is the process where the transmitting radio changes its frequency of transmission [3]. The transmissions proceed smoothly in such scenarios because of the *Spectrum Handoff* function provided by the network. The handoff which occurs due to spectrum mobility is different as compared to that in normal transmission scenarios. Different protocols being implemented in the layers of the network architecture must modify their parameters with operating frequency. *Spectrum Handoff* should also be transparent to the higher layers so that the changes in operating parameters are resolved at the lower layers of the architecture. There also need to be provisions in order to compensate for the latency caused by the changes in the transmitting frequency. As we know, a cognitive radio can adapt to the changes in the transmitting frequency. The protocols running in different layers need to change their parameters every time a user changes the frequency he is transmitting on. *Spectrum mobility management* aims to make these transitions as smooth as possible. This means that applications running on cognitive radios should experience a lower delay and negligible performance degradation in the event of a spectrum handoff. In order to achieve that, it is essential that the mobility management function knows in advance how long the handoff is going to take. This duration depends upon the algorithm which computes the channel which a user

would be assigned to. After this duration is known, the mobility function must make sure that performance is not degraded.

2.4 xG network applications

Leased networks: The primary network can provide a leased network to secondary users by allowing the secondary users to opportunistically use the spectrum. This would help to increase the efficiency of the network as a whole. The major concern throughout would be not to let the service of the primary user deteriorate.

Emergency Network: This usage was first proposed in [10]. In the event of natural disasters or calamities, the existing network infrastructure might fail or might not be enough for emergency usage. In these situations, emergency personnel might be able to establish emergency networks in order to take care of the communications requirements. Such emergency networks would require a large bandwidth to satisfy the communication requirements. xG networks can step up to fill the void in such a scenario. They would be able to exploit the existing network infrastructure in order to better utilize it and increase communication efficiency.

Military networks: Another area of application for cognitive radios is the battlefield. They would enable the military to choose arbitrary communication bandwidths and other transmission parameters in order to provide secure communication channels in war zones. xG networks would allow personnel to perform handoff in order to find secure spectrum bandwidth for themselves as well as the receiving party [3].

Chapter 3

3. Related work

3.1 Spectrum sharing techniques

A wide variety of techniques have been formulated for the operation of the Cognitive radios. A distinct functionality which sets apart a Cognitive radio is its spectrum sharing capability. Various techniques employed for spectrum sharing can be classified into three categories viz. *architecture based*, *spectrum allocation behavior* and *spectrum allocation technique*. An overview of these techniques follows.

Architecture based: Architecture based techniques can be subdivided based upon the location where the decision making process occurs.

Centralized spectrum sharing: The spectrum allocation and access functions are controlled by a centralized entity. Some of these solutions are described in [11, 12, and 13]. All the xG nodes forward their requirements to a centralized entity which plans out an access schedule trying to satisfy as much of the nodes as possible.

Distributed spectrum sharing: These schemes are proposed for areas where the infrastructure cannot be constructed. The access decisions have to be made by the xG nodes on the basis of their local operating environment. Some of these applications are analyzed in [14, 15, 16, 17, 18, 19].

Spectrum Allocation Behavior: The second classification is based upon the spectrum access behavior programmed into the xG nodes.

Cooperative Spectrum sharing: In these allocation schemes, the transmission occurs keeping in mind the effect on nodes in the vicinity. [11, 14, 15, 16, 18]. The information about interference being caused due to transmission by a node is made known to other nodes as well as the spectrum allocation algorithm.

Non cooperative Spectrum sharing: These solutions only consider the node at hand while ignoring the effect on other nodes. This sort of behavior is also referred to as *selfish*. Even though these schemes might be inefficient in their use of spectrum, they are practically more suitable because of the reduced communication between other nodes.

Spectrum Access Technique: This classification is based upon the access technique as explained below.

Overlay Spectrum sharing: In this technique, the node accesses the portion of the spectrum that has not been used by the licensed user. [11, 14, 16, 17, 18, 19, 20]. The goal is to reduce the interference being caused to the licensed user.

Underlay Spectrum sharing: This technique utilizes the spread spectrum techniques developed for the cellular networks. They require the use of a spectrum allocation map after which the node can transmit at power levels which do not interfere with the primary users. They are described in detail in [15].

We will now present some of the current spectrum access techniques which are combinations of the three classifications mentioned earlier.

3.2 Inter-network spectrum sharing

xG networks aim to provide unlicensed users access to the licensed portion of the spectrum for transmission. Consequently, we might have a situation where multiple systems are functioning in overlapping spectrum and space. There is a need to regulate and coordinate access to the spectrum in such a scenario. The figure below illustrates two different systems operating in the same radio environment.

Fig. 3.1 Intra Network Spectrum Sharing [3]

Till date, the solutions for conflict free access in Inter-network systems have involved static assignment of frequency bands or a centralized entity controlling the allocation of frequency bands among the participating networks. The protocols presented here give a high level view of the challenges which are faced when we need interoperability between different networks. A common theme right through these schemes is the need for shared control channel for communication among the users. We give a brief overview of the current research being done in this area.

3.2.1 Centralized inter-network spectrum sharing

The Common Spectrum Coordination Channel is proposed in [21] for coexistence of the IEEE 802.11b and IEEE 802.6 networks. This provides the first step for the operation of the open spectrum systems. In this solution each node is assumed to be equipped with a cognitive radio and low bit-rate, narrow band radio. The nodes achieve interoperability by broadcasting CSCC messages. Each node determines the channels it can use based upon the interference levels and further refines its selection by controlling the transmission power levels. According to simulation results, the CSCC improves throughput by 35-160% whenever there is a vacant channel to transmit. This solution has however been rejected as being insufficient for the xG networks as it requires changes to be made to every node in the system.

In [22], competition among the users is also considered. The authors propose a Spectrum Policy Server (SPS) to coordinate the demands of the various xG operators. Every operator bids for spectrum usage indicating the money they will pay for the desired duration of usage. The SPS selects from these bids with a goal of maximizing its profits. Similarly, the operators accept bids from the various users while the users too have an option of selecting which operator to bid to, depending on the type of traffic they need to transmit.

The problem of channel allocation to a set of users in a centralized Cognitive Radio system is investigated utilizing the concepts of graph theory in [31]. The author proposes three possible formulations of the problem and explains the relationship of these constraints to physical limiting factors. In the first formulation, the total power used in the system while fulfilling user rate requirements is minimized. The authors model the

solution as one of finding a minimum weight matching in a bi-partite graph. In the second formulation, power constraints per channel are further enforced. The last formulation is concerned with minimizing the impact on each user if the primary user returns. This problem has been mapped to a Maximum Flow Minimum cost problem, which has been solved by a variation of the Ford-Fulkerson algorithm by augmenting along the minimum cost path. For the first problem formulation, the author has proposed an $O(N^2K)$ algorithm where N is the number of users in the system and K is the number of channels. In [32], the authors propose a greedy approximation algorithm to the channel allocation problem. This scheme is shown to perform well in the low SNR regime. The stated goal of their allocation scheme is to minimize the sum power while meeting user requested rates. They also develop a heuristic method to estimate the power penalty for the case where users have individual rate requirements. They present the interference measurements taken at the BWRC to detect the presence of the primary users which are then used to formulate a statistical channel model combining Rayleigh fading and the detection of primary users.

3.2.2 Distributed inter-network spectrum sharing

A Distributed QoS based dynamic channel reservation (D-QDCR) scheme has been proposed in [23] which were designed for spectrum access to the Wireless Internet Service Providers (WISP). In this scheme, the base station of a WISP competes against other BSs in order to allocate a portion of the spectrum according to the QoS requirements of its users. The contention amongst the BSs is resolved in a distributed manner. This decision is made based upon the payload and the QoS guarantees desired by

the users of a BS. Among the users themselves, there are a host of policies which can be used to determine the access schedule. The protocol uses separate data and control channels in order to coordinate the actions of the users.

3.3 Intra-network spectrum sharing

A large body of work has concentrated on the need to coordinate access to the spectrum among the users of an xG network. We give a brief background on the work done in the field of Intra-network spectrum sharing.

3.3.1 *Co-operative intra-network spectrum sharing*

A local bargaining LB scheme has been proposed in [14] that ensures better spectrum utilization as well as fairness to the users. The protocol divides local users into groups. Every group has a poverty line which determines the minimum amount of time each user needs the spectrum to be allocated. The scheme makes sure that each user remains above this poverty line thus ensuring fairness.

In [18], the authors note that not all of the users in a network share the same channels. Rather, there is localization in terms of the users which can transmit on common channels. Keeping this in mind as well as the fact that there might not be a common control channel, the paper proposes a clustering algorithm which groups neighboring users. The users in this group can select a control channel for communication which provides distributed sensing and spectrum sharing. This approach has been shown to outperform the common control channel schemes. They also provide higher resilience as whenever a primary user occupies the control channel, the group can select another channel to serve as the control channel.

The Dynamic Open Spectrum sharing MAC protocol (DOSS-MAC) extends the use of the concept of busy tone from ad-hoc networks and adapts it for use in an xG network. Thus, every transmitter and receiver, while communicating, sends a busy signal on the associated busy tone channel.

In the Single channel and multiple channel asynchronous distributed pricing (SC/MS-ADP) protocol proposed in [15], the transmit power determination is also included in the spectrum sharing protocol. Accordingly, each node announces its interference price to the other nodes. A node utilized this information from its neighboring nodes to allocate a channel and afterwards determine its transmission power to avoid interference with the other nodes present in the system. Using this scheme multiple users can share the same channel by adjusting their transmission power. This scheme has been shown to be superior to the selfish scheme where a user transmits with no regards to interference being caused to his neighbors.

A centralized solution to the spectrum sharing problem utilizing a fixed infrastructure has been proposed in [11]. In the Dynamic Spectrum Access protocol (DSAP), allows a central entity to lease portions of the spectrum to users in a limited geographical region. DSAP consists of clients, DSAP server and relays for relaying information to clients not directly in the range of the server. The clients transmit their local channel conditions to the server which enables the construction of a global Radio Map. Using this Radio Map, the server can lease portions of the spectrum to the clients for a fixed interval of time.

3.3.2 Non-cooperative intra-network spectrum sharing

Device Centric Spectrum (DCSM) has been designed to be an opportunistic spectrum access protocol. In DCSM, the users allocate channels based on the interference patterns. Every user follows a set of 5 rules which govern the way the user is to access a channel while there is no collaboration among the users. In case of collision, random assignment rules are used to resolve the contention. Results show that even though the DCSM results in lower utilization and efficiency, the communication overhead is reduced to a large extent.

A variation of the IEEE 802.11 MAC protocol have been proposed in [17] utilizing the RTS-CTS exchange as well as the Network Allocation Vector (NAV) scheme. This work assumes the co-existence of a GSM network along with the xG network. The control signals can be exchanged using the GSM as a backbone in case of occupation of the control channel by the primary user. Every xG node listens to the broadcast channel of the GSM as well as the control channel of the xG network and constructs its own NAV. Channel allocation is done using this NAV locally.

As a final word, we would like to point out that the current trend while developing solutions for the channel allocation problem has been to employ game theory. There are a couple of works in this area which merit our attention. In [33], the authors propose a game theoretic framework to analyze the behavior of cognitive radios for distributed adaptive channel allocation. They have defined two different objective functions for the spectrum sharing games, which capture the utility of selfish users and co-operative users, respectively. Based on the utility definition for cooperative users, they show that the

channel allocation problem can be formulated as a potential game, and thus converges to a deterministic channel allocation Nash equilibrium point. They also propose a no-regret learning implementation for both scenarios and it is shown to have similar performance with the potential game when cooperation is enforced. The learning algorithm also accommodates selfish users, and requires less knowledge about the game and less implementation overhead. They show that cooperation based spectrum sharing etiquette improves the overall network performance at the expense of an increased overhead required for information exchange.

Some game theoretic models for cognitive radio networks have been presented in [35], which has identified potential game formulations for power control, call admission control and interference avoidance in cognitive radio networks. The convergence conditions for various game models in cognitive radio networks are also investigated in [36].

Chapter 4

4. Priority assignment

4.1 Introduction

For good performance, Quality of Service (QoS) is of particular concern for the continuous transmission allowing service providers to guarantee uninterrupted service within tolerable end-to-end delay limits. Every SU (secondary user or the unlicensed users) has its own QoS-guarantees that include bit error rate (BER), delay, and throughput requirements for its successful transmission. These QoS requirements need to be satisfied while implementing any spectrum allocation scheme. We aim to group the channels and the SUs based upon these parameters in order to ascertain the level of QoS guarantees they provide or need. These guarantees allow us to associate priorities with the SUs and the channels, thus paving the way for our priority optimal matching algorithm to function.

4.2 Priority assignment on channels in spectrum

In this section, we characterize free channels based on the occupancy of their adjacent channels by the Primary Users (PUs) also known as the licensed users. The channel priority take into consideration the spectral mask imposed by the FCC on the allowed transmission power of the SUs. We now deal with the classification of the channels. Consider any free channel i , i.e. $i \neq 1$ and $i \neq N$, where N is the total number of channels available. In this case, it has two adjacent neighbors. Each adjacent neighbor is either

occupied by a PU or free. This results in three different types of free channels based on the number of free adjacent neighbors [24]. The number of possible free adjacent channels is either 0, 1 or 2. The three types are depicted in Fig. 4.1 (a), (b) and (c), respectively. The three types of free channels are defined formally as below.

Fig. 4.1 Types of free channels [24]

- **Type I channel:** It is a free channel i having a primary user as the $(i - 1)^{st}$ neighbor and a free channel as the $(i + 1)^{st}$ neighbor, or vice-versa, making three contiguous channels $(i - 1)^{st}$, i , and $(i + 1)^{st}$ as *Occupied, Free, Free* or *Free, Free, Occupied* as shown in Fig. 4.1 (a).
- **Type II channel:** It is a free channel i with two PUs as the $(i - 1)^{st}$ and $(i + 1)^{st}$ neighbors as shown in Fig. 4.1 (b).
- **Type III channel:** It is a free channel i with two free channels as $(i - 1)$ and $(i + 1)$ neighbors, resulting in three contiguous free channels as shown in Fig. 4.1 (c).

It is intuitive that Type III channel with adjacent free channels is preferred to Type II and Type I channels. The reason behind this assertion is that the spectral mask on a Type III channel is much higher than the spectral mask in Type I or Type II channels. Hence, Type III can support higher transmission power requirements, which in other words support higher BER requirements [24].

4.3 Priority assignment on Secondary Users

Now, we define the priorities on the secondary users (SUs) and group them accordingly. The SU priorities are assigned based on the delay d and the required service time T_{th} of their individual applications. We can define the link throughput δ as the number of bits received correctly per second with R as the transmission rate and L as the packet length. We can thus define,

$$\delta = ML f(\beta) / R \quad \text{-----} \quad (1)$$

where ML/R b/s is the transmission rate of M payload bits and $f(\beta)$ is the packet success rate, also defined as the probability of receiving a packet correctly. This probability is defined as a function of signal to interference noise ratio (SINR) since higher the SINR, better is the bit error rate (BER) which in turn, results in higher packet success probability. We define bit error rate as probability of one bit to be erroneous among the given data bits and is given by $P_e(e)$. Therefore the probability of receiving error free packet, $f(\beta)$ [25], is given by:

$$f(\beta) = (1 - P_e(e))^L \quad \text{-----} \quad (2)$$

Combining Eqs. (1) and (2), the throughput can be defined as:

$$\delta = ML (1 - P_e(e))^L / R \quad \text{-----} \quad (3)$$

From the above equation we can see that the throughput is directly proportional to the packet success rate, which in turn, depends on the BER.

Fig. 4.2 Decision Tree for the grouping strategy

The required service time T_{th} is based on BER and the throughput requirements.

Unfortunately, accurate prediction of service traffic is not possible because of indeterministic value of channel capacity. Hence, to develop an approximate estimation, we have:

$$T_{th} \approx NL / C \quad \text{-----} \quad (4)$$

Where C is the Shannon bound on the channel capacity and N is the number of packets to be transmitted. Substituting the value of L from Eq. (4) in Eq. (3), we have

$$\delta = MT_{th}C (1 - P_e(e))^L / NR \quad \text{-----} \quad (5)$$

From (5), the expression for T_{th} can be written as:

$$T_{th} = \delta NR (1 - P_e(e))L / MC \quad \text{-----} \quad (6)$$

Utilizing the decision tree model (J48 algorithm) we group these packets in to priorities 0, 1, and 2. This classification is shown in Fig. 4.2. The user requests at the first checking condition of Fig. 2 are classified based on their BER. If $BER < 10^{-7}$ they are categorized as priority 0. Else these requests are classified according to the second checking condition for delay and the throughput. The values for this checking condition is based on the statistical data obtained from [26], whose sample data is provided in Fig. 4.3. If the condition is satisfied, the requests are grouped as Priority 1. Otherwise, they are grouped into Priority 2. The grouping strategy is illustrated in Fig. 4.3.

Multimedia Services	Throughput (Kbps)	Delay (ms)	Error Rate	Secondary User's
Secure Transactions	8-32	40	10E-7	SU1
Video Telephony	64-384	40-90	10E-6	SU2
Electronic mail	1.2-9.6	100	10E-6	SU3
Electronic newspaper	2.4-2000	400	10E-6	SU4
Remote Service	1.2-9.6	100	10E-6	SU5
Data base access	2.4-768	200+	10E-6	SU6

Priority Allocation Table

Secondary User's (SUs)	Priority
SU1	0
SU2	1
SU3	2
SU4	2
SU5	2
SU6	2

Fig 4.3 Priorities assigned to the requests generated by the SUs

Chapter 5

5. Dynamic matching in a vertex priority weighted bipartite graph

5.1 Introduction

Our work has been motivated by the need to bring user requirements as well as the channel quality into consideration while addressing the channel assignment problem. Even though these problems have been addressed in previous research work, they have always been looked upon as two disjoint issues. Research has focused upon what the user requirements are in terms of the various operating parameters desired such as the Bit Error Rate (BER), the maximum delay tolerable, the transmission power requirements etc. Various schemes classifying channel quality in wireless transmissions have also been proposed. However, these are not isolated problems as Quality of Service (QoS) guarantees for any user depend on the quality of channels available for transmission. We thus need to formulate a scheme which brings the SU QoS as well as the channel quality on the same page. This inspires our idea for proposing a new channel allocation scheme for the cognitive radio networks based on dynamic priority matching. The algorithm models the centralized spectrum decision functionality performed by the base station (BS) in an xG network. We represent the secondary users, as well as the channels, as the nodes of a bipartite graph.

Bipartite graph is defined as a graph whose vertices can be divided into two disjoint sets S and C such that every edge connects a vertex in S to one in C ; that is, S and C are independent sets. Equivalently, a bipartite graph is a graph that does not contain any odd-length cycle.

Given a graph $G = (V; E)$, matching M in G is a set of pair wise non-adjacent edges, i.e., no two edges share a common vertex as shown in Fig.5.1 below.

Fig. 5.1 Matching M in a bipartite graph.

We model the problem of channel allocation as a matching in a bipartite graph G with a set of vertices V connected to a set of edges E . Mathematically, it can be expressed as $G = (V = S \cup C; E)$, where S and C represent the SUs and the channels, respectively. Within G , there is an edge, e ; $e \in E$ whenever it is possible for a SU s to transmit on the channel c , where $c \in C$ and $s \in S$. Thus, the channel allocation problem is transformed into a

matching problem in the bipartite graph. In Fig. 5.2, we show diagrammatically how a matching corresponds to channel allocation at a given point of time. Please note the correspondence with Fig. 5.1.

Fig. 5.2 Modeling dynamic allocation as a matching in a bipartite graph

We associate priorities with the nodes of the bipartite graph. In order to make the model simple, we assume that all the channels have same characteristics and thus have no weights attached.

It is to be noted that channel allocation at a given point of time would be dependent upon certain factors such as the availability of the channels, their priorities and the priorities associated with the requests being generated. The allocation would also change as the request of a particular SU is satisfied or upon the return of a PU. We illustrate the dynamic nature of the allocation in Fig. 5.3 below.

Fig 5.3 Dynamic nature of the allocation

Fig 5.3 represents the changes which are occurring in the allocation over a period of time.

These changes might occur due to some of the factors stated earlier. Each figure represents the state of the allocation at any given point in time.

The bipartite graph constructed would have weights (representing the priorities), associated with the vertices (SUs and channels, respectively) while the edges, which represent the communication links, are all assumed to be similar. Thus, we can say that we have *modeled channel allocation as a dynamic matching problem in a node priority weighted bipartite graph*.

5.2 Topology of the graph

In order to make it easier to follow this section, please refer to Fig. 5.4. below (Fig. 4.1 has been copied below as Fig. 5.4 for convenience).

Fig. 5.4 Types of free channels [24].

The decisions made while designing the topology of the graph can all be attributed to the need to maximize the transmitting power, while simultaneously avoiding interference to the PUs which are currently transmitting. One of the requirements for opportunistic access to the spectrum in an xG network is that all such operations must be transparent to the PUs. The interference caused by a PU to a PU in an adjacent band is negligible because of the very high operating power levels for both. However, the interference experienced by an adjacent SU cannot be ignored as it uses lower transmitting power in order to mitigate the interference to the PUs.

The topology of the graph G needs to be decided in a way that no SU is allowed to transmit on a channel which cannot support its QoS requirements. As explained in the previous chapter, priority 0 SUs require channels which can support high throughput and have lower values for the Bit Error rate. Therefore, the priority 0 SUs are connected by edges to type III channels. As explained in Chapter 4, Type III channels are the highest

quality channels having minimum interference from the PUs' presence. A SU transmitting on type III channels can have very high transmission power and thus, higher throughput and lower BER values. These channels are, therefore, ideal for transmission by priority 0 SUs. Transmission on channels of type I and II, by SUs having priority 0, would cause them to lose packets. The reason being that due to the presence of PUs on adjacent channels, the transmitting power threshold would have to be set to low values in order to avoid interference to the PUs. Low transmission power translates to higher BER and consequently, lower throughput. Therefore, in our graph G , there are no edges connecting SUs with priority 0 and channels of type I and II.

Priority 1 users' requirements of BER and throughput are less stringent as compared to priority 0 users. Applications belonging to priority 1 group are more fault tolerant and can therefore transmit using lower transmission power. Thus, along with channels of type III, they can also transmit on channels of Type I. Type I channels have only one adjacent PU and can therefore support transmission power lower than type III but higher than type II channels. Priority 1 users can make use of these channels along with type III channels. Therefore, in our graph G , we have edges connecting priority 1 users to channels of type I and III. It is to be noted that we do not place edges from priority 1 users to type II channels so as to avoid any packet loss.

Priority 2 SUs group consists of applications which are highly fault tolerant while also being capable of sustaining higher delay values. Such users can transmit using minimal transmitting power and thus can use channels having two neighboring PUs.

Consequently, they are the only group of SUs which can utilize channels of type II. In our graph, we have edges joining SUs with priority 2 to type I, II and III channels. A more formal definition of the channel priorities, in terms of the priority function, is given in Chapter 6.

It needs to be mentioned that even though priority 0 users may transmit on type I and II channels, they would lose packets because of the higher BER as they would not be able to transmit at their optimum power levels. The same argument holds for a priority 1 user seeking to transmit on type II channels. We have assumed a simple model where such an event will not occur.

Chapter 6

6. Priority Optimal Greedy-Hungarian Algorithm.

6.1 Introduction

A matching in a graph G is a set of edges which are pair wise vertex disjoint. A matching which spans all the vertices of a graph is called a perfect matching. The most well known algorithm for determining a perfect matching in a graph, provided it exists, is the Hungarian algorithm [27]. The algorithm utilizes the concept of M -alternating paths in order to determine a perfect matching. For a matching M in graph G , we say that a vertex v of the graph is M -matched if there is an edge in M incident on v . An alternating path is one in which the edges alternately belong to M and $E(G)/M$. An M -augmenting path is one in which the starting and ending vertices are both M unmatched. The algorithm proceeds by finding an M -augmenting path P through which we can augment the size of the matching by 1. We do this by removing the edges of M belonging to P followed by adding the remaining edges of P to M . The Hungarian algorithm always seeks to find an augmenting path in the graph. As long as an augmenting path exists, the size of the matching can be increased by 1. If no such path exists, the algorithm returns the current matching.

In order to compute a matching M in the bipartite graph G , constructed in Chapter 5, we utilize the notion of alternating paths as given in the Hungarian algorithm. An alternating path consists of edges which are alternately in M and not in M . Given a matching M , an augmenting path is an alternating path which starts from and ends on free (unmatched vertices), as shown in the Fig. 6.1.

Fig. 6.1 An augmenting path in a bipartite graph.

In order to find a priority-optimal matching M , we grow a maximum sized augmenting tree which consists of all possible augmenting paths starting from an unmatched vertex. In the graph G , an unmatched vertex would translate to a SU which has generated a request to transmit. As we compute a matching M in the graph G , we optimize the priority values on both the user as well as the channel sides by using a greedy strategy. In order to achieve this, we develop a priority function which should be optimized by choosing the best priority value at every step. We also aim to match as many users as allowed by the topology at any given point of time.

6.2 Priority Function

We introduce the priority function $\pi(s)$ and $\pi(c, t)$ which specifies the priority associated with the SUs and the channels. The priority function assigns a constant value to a user based on his QoS requirements which include the throughput, BER and delay values. This priority value is assumed to remain constant for a user over all the requests he generates. The priority function π maps the users into three distinct groups 0, 1 and 2 as specified in Chapter 4.

For the channels, the function π assigns a value which varies over time. This is due to the fact that the channel priorities are dependent upon the presence of the PUs in the adjoining channels. The PUs occupy channels over a period of time during which the priorities of the adjacent channels are modified. This results in time instant t being input to priority function along with other parameters such as throughput and BER while assigning priorities to the channels. The time t , in effect, denotes the dependence of the priority values upon neighborhood conditions. The function π assigns the following values to the channels at any given point of time;

$$\pi(\text{type III}) = 0,$$

$$\pi(\text{type I}) = 1,$$

$$\pi(\text{type II}) = 2.$$

These values follow from the discussion of the topology of the graph in Chapter 5. For both the user and the channel side, we follow the convention of lower values denoting higher priority. Thus, 0 represents the group of highest priority users among all the users while a channel with priority 0 supports the best quality transmission.

6.3 Priority optimal matching algorithm

We propose a priority optimal matching algorithm which represents a greedy version of the Hungarian algorithm. Our algorithm utilizes the concept of augmenting paths introduced in the Hungarian algorithm. The Priority-optimal matching algorithm grows a maximum-sized augmenting tree i.e. a tree consisting of all possible augmenting paths from an unmatched vertex. An augmenting tree has the following properties:

- The root r of T is an M -unmatched vertex belonging to S ;
- For each odd integer i less than the depth of T , each edge of T joining a vertex at level i to a vertex at level $(i+1)$ belongs to M ; and
- The leaf nodes might belong to either C or S .

Here S corresponds to the set of SUs while C represents the set of channels, respectively.

If all the vertices in S are M -matched, we have a perfect matching and the algorithm either terminates or waits until the time the topology of the graph changes.

In order to grow a maximum sized augmenting tree, we proceed as follows. The root of the tree is initialized to consist of a single vertex r , which is currently unmatched. This is chosen to be the SU with the highest priority among all the waiting SUs. The sets C' and S' denote the subset of vertices of C and S , which belong to the tree. At each stage of growing the tree, we encounter one of the following three cases:

- Neighborhood $(S') - C'$ is empty. In this case there already exists a perfect matching, and the algorithm returns the current matching. On the other hand if the neighborhood $(S') - C'$ is non-empty, we choose c to be the vertex in that set and

s to be any vertex adjacent to c in S^t . Then we have one of the following two cases:

1. Vertex c is matched. Then we augment the tree by adding the edges sc and cs' , where s' is the vertex to which c has been matched.
2. Vertex c is unmatched. Here we augment the matching.

The pseudo code of the algorithm follows.

```

1: Input: A bipartite graph  $G = (V = S \cup C; E)$  representing a user-channel network,
        request priority function  $\pi$ ,  $\pi$ -optimizing matching, and
        a SU  $s \in S$ 

2: Output: a  $\pi$ -optimizing matching

3: Compute a maximum size  $M$ -augmenting tree  $T$  rooted at  $s$ 

4: if       $T$  has a leaf node which is a channel then

5:      Compute an augmenting path  $P$  in  $T$  from  $s$  to the leaf channel node  $c^*$  that
        minimizes  $\pi(c; M(c) + 1)$  over all channel leaf nodes  $c$  of  $T$ 

6:      return  $M \text{ SYMMDIFF } E(P)$ 

7: else

8:      Compute user leaf node  $s^*$  that minimizes  $\pi(s; M(s))$  over all user leaf nodes  $s$ 
        of  $T$ 

9: end if

10: if       $\pi(s; M(s) + 1) < \pi(s^*; M(s^*))$  then

11:      Compute the path  $Q$  in  $T$  from  $s$  to  $s^*$ 

12:       $M \text{ SYMMDIFF } E(Q)$ 

13: else

14:      return  $M$ 

15: end if

```

Priority optimal Matching algorithm.

The input to the algorithm is the bipartite graph $G = (V = S \cup C; E)$, which represents a secondary user-channel network. The topology of the graph is decided according to the rules described in Chapter 5. The priority function π determines the priority of the individual user requests as well as those of the channels. We must note that as the channels' types, and therefore their priorities, might change over a period of time, the topology of the graph also varies. We also input an unmatched vertex s , representing an SU, to the algorithm. It is to be noted that s is the SU having the highest priority as defined by π . The algorithm outputs the updated matching M after checking if the current SU request can be satisfied.

The algorithm begins by computing the maximum sized augmenting tree T rooted at the requesting SU s . If T contains some leaf nodes which are channels, the algorithm branches off at line 4. Among all the leaf channel nodes, channel c which optimizes the priority function π , is found and the path P from s to c is computed. This signifies that there exists an augmenting path in the tree and we can increase the size of the matching by 1. Therefore, the channels which are currently available are sufficient enough to satisfy the QoS constraints of the requesting users. We then perform the symmetric difference operation SYMM DIFF between the current matching M and path P in order to obtain the updated priority optimal matching M . We define the operation SYMM DIFF as

$$M \text{ SYMMDIFF } E(P) = (M \cup E(P)) / (M \cap E(P)).$$

This operator removes the edges common to both M and P while retaining those that are not. The matching is then updated to consist of these residual edges as specified in Line 6.

However, if the tree T does not contain any leaf channel nodes, the current channels are insufficient to satisfy the QoS requirements of all the SUs in the system. In such a scenario, the leaf nodes consist of all the SUs which are currently transmitting on the channels. We identify the SU s^* which has the lowest priority among all the SUs transmitting and find the path Q from s to s^* . If s^* has a lower priority than the root s , i.e. its π value is greater than that of the root, we can optimize the priority by allowing s to transmit while making s^* wait. The algorithm achieves this in Lines 11 and 12, where we perform the symmetric difference between the current matching M and the path Q . Hence, the higher priority SU s is able to transmit at the expense of s^* . Thus, the average priority value of SUs is optimized at each stage.

The BS always optimizes priorities on both the user and the channel sides. On the user side the highest priority SU is always selected to transmit first provided a channel having required QoS parameters is available. On the channel side, an SU is allocated the highest quality or the highest priority channel which is available. Hence, the priorities on either side are optimized.

This algorithm has been originally proposed in [28]. The author introduced this algorithm in client server network architecture with the goal of balancing load on the servers while ensuring fairness to the clients at the same time. More importantly, the author shows that there exists a maximum M that simultaneously minimizes both the average priority value of a client and the average priority value of a request received by a server. We have considered the same algorithm and applied it to the channel allocation problem in the domain of cognitive radios, making suitable modifications along the way. The complexity of the algorithm has been shown to be of $O|E|$ [28]. The algorithm had been

designed in order to compute B-Matchings. However, since we have assumed the capacity of the communication links to be constant, the B-values associated with all the links is 1. We have also refined the priority function π with the goal of classifying SUs and the channels. In the following chapters, we would show how we have incorporated the priorities within our algorithm as well as the design of the allocation scheme with a view to implement the priority function π .

Chapter 7

7. Simulation Model

7.1 The System Model

Fig. 7.1 shows the system model we have employed. It is a simple abstraction of the xG network with some detailed features being taken out. For our simulations, we have considered the BS which implements the channel allocation algorithm. The BS scans the channels in order to determine the channel types while also accepting the SUs requests to transmit. The BS queues the requests to transmit and determines which channels to allocate in a manner such that the QoS requirements of the SUs are satisfied. For this purpose, it implements the priority optimizing channel allocation algorithm which we have designed. Our model of Cognitive Radio systems is very similar to the IEEE 802.11's infrastructure mode of operation where a group of WLAN users associate with an AP (access point). In our model the Base Station (BS) serves the purpose of the AP. We envision a group of cognitive radios controlled via the BS. The available spectrum is divided into channels. The CR users rely on the centralized entity BS for spectrum sensing, PU detection as well as channel allocation.

Fig. 7.1 System Model

In our system model, we assume the presence of an underlying control that is used by the CR users to communicate with the BS.

7.2 Implementation

The flow diagram in Fig. 7.2 gives the flow of execution of the simulation.

Fig. 7.2 Flow diagram for our proposed scheme.

At each iteration, the program (or the BS, whose functionality it emulates) checks for the presence of newly arrived SU requests. Upon arrival they are enqueued into a queue. The BS employs four queues with a view to implement the priority function π for the SUs. Queue management is a part of packet classification and satisfying QoS requirements.

The packet flows being generated by the SUs are identified, classified and then placed in queues according to the set of rules defined in the following section.

7.2.1 Queue Management

The latency of a SU can be defined as the queuing delay and the delay in switching between channels due to the arrival of a PU as well as a higher priority SU. For cognitive radio users, this parameter can be critical for QoS-guarantees. Our proposed queue management technique incorporates ways to reduce latency while allocating channels with QoS requirements. We employ four queues whose queuing rules are as defined below:

- The first queue, dropped queue, is for packets which are withdrawn due to arrival of PUs as well as higher priority SUs; this queue is implemented to take latency into consideration and minimize it to within tolerable limits of end to end delays;
- The second queue is for packets of priority 1, third queue for packets of priority 2 while the fourth queue is for packets having priority 3;
- When a request for transmission arrives it goes into the appropriate queue based upon its priority. The queues are ordered using the arrival time of requests;
- Round-robin is used for de queuing requests from the queues. The BS first scans the dropped queue. If a request with associated priority 0 is waiting, the BS first attempts to allocate a channel to this user provided a channel with required operating parameters is available.
 - If there is no priority 0 user in the dropped queue, the BS checks the second queue for any waiting priority 0 users;

- If no users with priority 0 are waiting, the BS scans the dropped queue followed by the third queue, i.e. the priority 1 users queue, in order to ascertain if a priority 1 user is waiting to transmit; and
- The BS repeats the same procedure for priority 2 users, where it first scans the dropped queue followed by the fourth queue reserved for user requests with priority 2.

7.2.2 Algorithm Implementation

After classifying and en-queuing the SUs' packets, the BS checks for the arrival of PUs in the system. The PUs do not wait upon any SUs and start transmitting allowing a time interval of 2 s for the SU to vacate the channel. Their arrival also changes the channel types, which necessitates a change in the allocation for the SUs as well. The SUs occupying the channels requested by the PUs as well as those occupying the adjacent channels have their channels de-allocated, and their packets are moved into the dropped queue. Meanwhile, the channel types are re-calculated and updated as defined in Chapter 4. At this point of time, the BS re-computes the matching and allocates channels for all the PUs and SUs whose requests can be satisfied. Any SU which might have been kicked off by one of the higher priority SUs is en-queued into the dropped queue. The simulation is executed for 2 s before running the algorithm again. 2 s is the maximum tolerable delay for packets belonging to the PUs [30]. During that time interval we can assume that the channel conditions are static and the SUs can keep transmitting unhindered.

7.2.3 Program Description

Fig. 7.3 below gives a high level overview of the classes which comprise the system. The class Secondary Users contains the information about the priority of the particular user along with other bookkeeping information such as the number of packets generated, the total number of packets transmitted, the time it has spent in queues waiting for its packets to be transmitted and the time it has had the channels for. Time class keeps track of the global time for all the classes. It generates timestamps for use by the other classes. The SUs packets are associated with a timestamp and en queued into the appropriate queue depending upon their priority. The queue class contains several attributes associated with every request such as the client number, the time at which the request was generated, the maximum delay that the request can sustain together with the total number of packets. The channel class encapsulates the attribute priority which is associated with every channel object. The BS scheduler class scans the queues and the available channels and forms the bipartite graph G . It next computes the matching M which allocates the channels to the appropriate SU. Any request which might not have been satisfied is en queued into the dropped queue together with the SUs which might have been kicked off. The Bookkeeper class is tasked with keeping track of the number of requests which have been generated by an SU, the total time for which an SU got the channel and also the number of packets which were dropped by a particular SU. After the simulation has run for a sufficiently long duration of time, the bookkeeper class outputs required statistical information.

Fig. 7.3 Classes used in the simulation.

It is to be mentioned that while allocating channels to SUs, we have followed the convention of allocating the best available channel to a SU. This rule is part of the specifications of the IEEE 802.22 standards wherein the best possible channel must be made available to a requesting user. Thus, a priority 2 user is allocated a priority 0 channel, if available or a priority 1 channel. If neither of the higher priority channels is available, a priority 2 channel is allocated as a final resort.

Chapter 8

8. Performance in a static environment

8.1 Introduction

We have tried to evaluate the performance of our algorithm in as realistic a scenario as we could envisage. For our work, we define a static environment as one where the behavior of the PUs has been strictly defined i.e. they are assumed to occupy the channels for an infinitely long period of time. Thus, the channels' types remain fixed and the only challenge is presented by the behavior of the SUs. The various parameters which can affect the performance of the scheme are the arrival rate of the SUs, the number of packets they generate as well as the available channel types. For the static scenario, our primary criterion of evaluation has been the packet drop behavior for the SUs belonging to the different priorities. Our work has not only looked at the channel allocation problem as one of computing a matching in the graph, but has also introduced the notion of assigning priorities to the users and the channels in order to improve the QoS guarantees provided by the system. Therefore, we have analyzed the performance of our algorithm in terms of its ability to successfully transmit packets belonging to users having different priorities. We note that this is just a foundation for our simulation of a more complex dynamic environment where the behavior of the PUs is also considered. We present a few elementary results in this section with the aim to develop an understanding of the various parameters involved in the simulation while also studying the effect of assigning priorities among the SUs. We have compared our results against the random channel

allocation scheme which allocates channels without regards to SU priority or channel type [29]. Since there are no current benchmark standards for channel allocation in this area, current research in this field compares results against the random scheme.

In order to ensure fairness, we have maintained the highest quality channel allocation promise in the random scheme which is the bedrock of the QoS-guarantees in cognitive radio technology. We have focused on the proportion of each priority's users in the system rather than on the total number of users in the system. By focusing on the proportion of the users and not the actual number, we have taken out the dependence of the performance on the channels which are available. As we are focusing only on the proportion, we can maintain a constant number of users in the system which ensures that the competition always remains among a fixed number of SUs, which helps to bring out the effect of prioritizing upon the performance. We have assumed that whenever Priority 0 users are forced to transmit on channels of lower quality, there are a fixed percentage of packets which are dropped. Based upon the priorities assigned to the SU requests, we have taken representative values for the packets being generated by the user requests belonging to any particular priority. 10% of all the users in the system are assumed to be PUs. Based on the priority assignments for the SU requests, we have taken representative maximum tolerable delay values as 40 ms for priority 0 users, 200 ms for priority 1 users and 400 ms for priority 2 users [26].

8.2 Simulation Results

8.2.1 Priority 0 SUs packet drop rate

As shown in Fig. 8.1, the packet drop is significantly lower for our scheme, when compared to the random allocation scheme which doesn't take QoS parameters into consideration, as shown in the graph. . We plot the packets dropped on the Y-axis. The proportion of the priority 0 users in the system is shown along the X-axis. The packet drop for priority 0 SUs is null right up to the point when the numbers of channels are sufficient to support the current number of users. After that point, the increase in packet dropping increases linearly with the number of users in the system. For the random allocation, all the users in the system have same priority and hence a priority 0 SU might have to wait upon a priority 1 or 2 SU to transmit. Our allocation scheme, which introduces priorities, eliminates such problems and hence, fewer number of packets are dropped for the high priority 0 users.

Fig. 8.1

8.2.2 Priority 1 user's packet drop rate

In Fig. 8.2, we plot the packets dropped on the Y-axis. The proportion of the priority 1 users in the system is shown along the X-axis. The packet drop rate is slightly higher, compared to the normal allocation scheme, when the proportion of priority 1 users in the system is small. This occurs due to the presence of priority 0 users in the system that displace the transmitting priority 1 users. This effect is visible until the point at which the user proportion is 0.3. After this point there is an exponential decrease in the packets dropped as there are not enough priority 0 users in the system to displace them. We see that the packet drop approaches zero when the majority of users in the system have priority 1 as they have preference in terms of the channel usage.

Fig 8.2

8.2.3 Priority 2 users drop rate

In Fig. 8.3., we plot the packets dropped on the Y-axis. The proportion of the priority 2 users in the system is shown along the X-axis. As expected, the packet drop for our scenario incorporating priorities is higher when compared to the random allocation scheme. The reason is that the lower priority users are being kicked off in our scheme by the higher priority users, which does not happen in the random scheme, and consequently there are more packets dropped. This effect is visible up to point where the proportion of priority 2 users is 0.5 - 0.6. After that point, the number of higher priority users is lowered and thus there aren't enough users to displace the transmitting priority 2 users. Therefore, the packet loss is about the same for both the schemes.

Fig. 8.3

8.3 Summary of results

In this chapter, we presented the results of our allocation method based upon priorities in a static, fixed environment. As we assumed that the PUs' behavior was well defined, the channel types also did not change and thus the scenario is simplified greatly. As our results show, our allocation method compares favorably to the random allocation method for the higher priority users. For priority 0 and 1 SUs, the algorithm has displayed vast improvements as compared to the current channel allocation methods. The packet drop was reduced appreciably for priority 0 SUs, who were given preference over all lower priority SUs in the system. They were able to kick off any lower priority SU which might have been occupying a channel which was suitable for them and thus prevent their packets from being dropped. The same also holds true for priority 1 SUs whose behavior was influenced by the presence of priority 0 SUs. For SUs belonging to both the priority groups, the packet drop increases as their proportion increases simply because our scheme starts emulating the random scheme where all the SUs have the same priority. Our scheme lags behind the random allocation scheme in terms of the number of packets being dropped for SUs belonging to priority group 2 as they are being displaced while transmitting by the higher priority SUs. This effect is more than compensated by the decrease in packet drop for the higher priority SUs.

In the next chapter, we explore our schemes' performance in a much more robust, dynamic environment where the behavior of the PUs is not as constrained. The algorithms' performance in a much more realistic scenario would serve as a better indicator of its efficacy in the real world.

Chapter 9

9. Performance in a dynamic environment

9.1 Introduction

In this Chapter, we evaluate the performance of our algorithm in a realistic, dynamic scenario, where the PUs occupy channels for a period of time and then stop their transmission creating gaps which are exploited by the SUs. We can envisage the PUs as having the highest priority among all the users and thus they can kick off every other user. In terms of the topology of the graph G , the node representing a PU will be connected by an edge to only one of the channels and to none other. In [18], it is shown that for a given topology very limited numbers of common channels exist for each of the users. Thus, while we assume that all the SUs have access to all the channels, it might not be true while actually transmitting. The resultant added complexity in the topology of the graph further serves to bring out the added benefits of our approach in channel allocation. As not every SU with priority 0 is able to transmit on every channel of type III, there might be instances where an SU with priority 0 is made to wait even while a priority 1 SU is transmitting. This fact also separates our scheme from the greedy approach, where we simply replace the lowest priority SU, as the allocation problem is made more challenging and topology independent. Further, while the greedy algorithm would require the same number of synchronizing transmissions [30] as the path length, this would be achieved in one synchronizing step between the transmitter-receiver pairs in our scheme. The time required to achieve this is 2 s [30]. The reason is that the greedy approach would

allocate the channel to only one transmitter in one step and would be able to synchronize only his receiver during that time frame. However, using the matching algorithm, we can better utilize the control channel used to synchronize the receivers and would be able to communicate with all receivers, whose transmitters' operating frequencies have been changed, in one time step.

We again measure the throughput gains for every group of users and compare them against a random channel allocation scheme [29]. Since there are no current benchmark standards for channel allocation in this area, current research in this field compares results against the random scheme. In order to ensure fairness while comparing, we have maintained the highest quality channel allocation promise in the random scheme which is the bedrock of the QoS-guarantees in cognitive radio technology. This implies that while allocating the channels, the random scheme also assigns the best possible channel to the requesting user. We have assumed that whenever Priority 0 users are forced to transmit on channels of lower quality, there are a fixed percentage of packets which are dropped. Based upon the priorities assigned to the SU requests, we have taken representative values for the packets being generated by the user requests belonging to any particular priority. The arrival rate for PUs is determined by Poisson distribution with parameter $\lambda = 0.1$. 20% of all the users in the system are assumed to be PUs. Based on the priority assignments for the SU requests, we have taken representative maximum tolerable delay values as 40 ms for priority 0 users, 200 ms for priority 1 users and 400 ms for priority 2 users [26].

9.2 Simulation Results

9.2.1 Priority 0 SUs packet drop rate

The graph in Fig. 9.1 shows the packet drop behavior for the priority 0 users in the system. We plot the packets dropped on the Y-axis. The proportion of the priority 0 users in the system is shown along the X-axis. Our aim is to evaluate the effect of other users in the system on the number of packets being dropped by the priority 0 users. The total packets transmitted are 276510, i.e., the number of packets generated during the simulation.

Fig 9.1

In Fig. 9.1, we see that the packet loss for the random allocation scheme is considerably higher as compared to our allocation scheme. It is noted that the packet loss for priority-based channel allocation scheme increases uniformly till the point where they comprise 70% of the users in the system. Following the referred point, as shown in Fig. 9.1, a slight decrease in the number of packets dropped is observed, which can be attributed to their complete dominance over all the users. For the random allocation, the number of packets dropped increases up to the point when Priority 0 users comprise 40% of the users. This can be attributed to the fact that higher priority users are waiting for the lower priority users and consequently they are losing packets in higher numbers. After the point when they start comprising a majority in the system, the packets drop start going down as there are not enough lower priority users on which they need to wait upon. The percentage improvements are as shown in the Table 9.1.

Table 9.1

PERCENTAGE IMPROVEMENT IN NUMBER OF PACKETS DROPPED FOR
PRIORITY 0 USERS OVER THE SCHEME WITHOUT PRIORITY

Proportion of priority 0 users	% improvement
0.1	28%
0.2	20%
0.3	13%
0.4	11.60%
0.5	7.70%
0.6	5%
0.7	3.90%
0.8	2.77%

9.2.2 Priority 1 SUs drop rate

The graph in Fig. 9.2 shows the packet drop behavior for priority 1 users in the system.

Again, the values on the Y-axis give the packets dropped while the X-axis shows the proportion of priority 1 users currently in the system. Our aim is to evaluate the effect of other users in the system on the number of packets being dropped by the priority 1 users.

We compare our scheme against the random allocation method. The total number of packets generated is 4699000.

Fig. 9.2

As seen from Fig. 9.2, the packet drop is comparable for both the schemes. For the period when the proportion of priority 1 users is between 0.3 and 0.5, the packet loss is slightly higher for our scheme. This can be attributed to the fact that there is a large number of higher priority users in the system i.e. users with Priority 0, which kick off the lower priority users. Thus, there is a consequent rise in the packets being dropped. This behavior is exhibited until Priority 1 users reach 50% of the total users. After that, there is a sharp decrease in the packets being dropped as the priority 1 users are greater in numbers while the higher priority users go down steadily in numbers. Hence, the number of packets being dropped also goes down as Priority 1 users have unhindered access to the channels of their choice. The percentage improvements are as shown in the Table 8.2. It is clear that the percentage deterioration of our proposed scheme when compared to the random allocation scheme is minuscule within the interval 0.3 to 0.5, i.e., -0.6% to -0.8%, as shown in Table 9.2.

Table 9.2

PERCENTAGE IMPROVEMENT IN NUMBER OF PACKETS DROPPED FOR
PRIORITY 1 USERS OVER THE SCHEME WITHOUT PRIORITY

Proportion of priority 0 users	% improvement
0.1	1.40%
0.2	-0.60%
0.3	-0.20%
0.4	-0.80%
0.5	-0.10%
0.6	2.50%
0.7	2.65%
0.8	2.17%

9.2.3 Priority 2 SUs drop rate

We now analyze the packet drop behavior for the lowest priority users in the system, the Priority 2 users. The graph is as shown in Fig. 11. The total number of packets generated is 2329600.

Fig. 9.3

The packets dropped for the lowest priority users are higher for our allocation scheme as compared with the random allocation scheme. The higher priority clients are able to kick

off the lower priority users causing the consequent larger packet loss. As we increase the number of lower priority clients in the system, more packet loss is experienced as they are kicked off by the higher priority clients. When the number of lower priority clients exceeds 70%, the packet loss drops below that of the random scheme because of the better utilization of channels being provided in our scheme. The percentage improvements are as shown in the Table 9.3. It is shown that the percentage deterioration of our proposed scheme when compared to the random allocation scheme is minuscule over the entire range under consideration, as shown in Table 9.3.

Table 9.3

PERCENTAGE IMPROVEMENT IN NUMBER OF PACKETS DROPPED FOR
PRIORITY 2 USERS OVER THE SCHEME WITHOUT PRIORITY

Proportion of priority 0 users	% improvement
0.1	0%
0.2	-0.00001%
0.3	-0.00002%
0.4	-0.00004%
0.5	-0.00005%
0.6	-0.00001%
0.7	-0.00001%
0.8	-0.00001%

9.2.4 Throughput increase

We next analyze the overall increase in throughput provided by our allocation algorithm as compared to the random allocation scheme. Fig. 9.4 shows the performance of our algorithm against random allocation as the number of users in the system is increased. It is to be noted that the number of PUs in the system has been kept at a constant while increasing the number of SUs.

Fig. 9.4 Throughput performance

It can be seen from the above figure that not only does our algorithm improve the QoS provided to the SUs, it also increases the system throughput. As the number of users increases, the difference in the performance of our algorithm as compared against the random scheme becomes much starker. It is also to be noted from the graph that the drop in throughput is not as severe for our algorithm as the random scheme as it is able to better manage the delay constraints of the applications.

9.2.5 Throughput dependence upon PUs

In this section we analyze the relationship between the throughput of the system and the arrival rate of the PUs. The graph in Fig. 9.5 depicts the variation in system throughput as the arrival rate of the PUs in the system is increased. The factor arrival rate stands for the parameter λ in the Poisson distribution, which the PUs are assumed to follow.

Fig. 9.5 Throughput variations with arrival rate of PUs

Fig. 9.5 clearly depicts the increased throughput provided by our algorithm and also its robustness with respect to the number of PUs arriving in the system. As the number of PUs occupying channels is increased, our algorithm provides a marked gain in throughput compared to the random allocation scheme. The chart was drawn for a constant number of SUs.

9.2.6 Prioritized Users Delay analysis

Fig. 9.6 Time spent in dropped queue with respect to the prioritized SUs

The bar-chart in Fig. 9.6 shows the total time spent by the clients in the dropped queue over the entire period for which the simulations were run. The value on Y-axis gives the time in ms while the values on X-axis represent the priority of a particular client. From Fig. 9.6 we see that the time spent in the dropped queue is negligible for all clients having Priority 0. Priority 0 clients are en-queued in the dropped queue in the event of the arrival of PUs only. Also, they are given a preference over other clients once a channel having the desired parameters becomes available. Consequently, they are en-queued for the least amount of time.

9.2.7 Performance on Jain's Fairness index

Fig. 9.7 shows our algorithms' performance on Jain's fairness index [37]. Jain's index is used to identify underutilized channels. The metric is defined as,

$$\text{fairness} = \frac{(\sum x_i)^2}{(n \cdot \sum x_i^2)}$$

Where x_i represent the individual throughputs achieved by each of the users.

Fig. 9.7 Performance on Jain's fairness index.

As can be seen from the figure, our algorithm consistently outperforms the random scheme, given the same conditions of channel usage and PU behavior. Our algorithm provides much better utilization of the available channels.

9.4 Summary of results

In this chapter we presented results of our algorithms' performance in a dynamic, realistic environment. The arrival and departure of the PUs in the system changes the channel types and also prevents priority 0 SUs from having complete domination over the channels. Since the PUs occupy channels for a longer duration of time, we increased their payload as compared to SUs. The results show that our algorithm performs appreciably in terms of better utilization of the channel resources and brings down the number of packets dropped. Since the high priority SUs, belonging to priority group 0 and 1, have smaller delay thresholds, they cannot be made to wait for long periods of time. The current allocation methods might have lower delay threshold users being made to wait upon users whose delay thresholds are much higher. Consequently, they would cause packet loss. We have proposed our solution with the aim of mitigating this problem by defining priorities and assigning channels based upon these priorities.

Our results indicate a marked improvement in packet transmission for SUs belonging to priority group 0. For lower numbers of priority 0 SUs, the algorithm allocates channels very efficiently and ensures that the higher priority SUs are not made to wait upon the lower priority SUs who might be transmitting. As we have based our priority grouping upon maximum delay values tolerable, our algorithm ensures that applications with high delay threshold wait longer while those with lower delay thresholds are allocated channels on a preferential basis. This allows for better channel utilization and results in lower number of packets being dropped.

For SUs belonging to group 1, there is a slight degradation of performance as the higher priority SUs are able to displace them while transmitting. This degradation was observed

during the intervals when their proportion within the system lies between 20% and 40%. When their numbers are dominant, they exhibit better utilization and a fewer number of packets belonging to them are lost. It must be pointed out that the % degradation as compared to random scheme is marginal and is more than offset by the better utilization provided at other higher numbers as well as that being obtained by priority 0 SUs.

The lower priority users or those belonging to priority group 2 suffer more losses as compared to the random scheme. The reasoning behind this phenomenon is intuitive as they are being made to wait upon other users. Again, we need to note that the increase in the number of packets being lost is miniscule and can be ignored for all practical purposes. The % degradation in packet loss has an upper limit of -0.00005% and is compensated by the higher channel utilization experienced by the higher priority SUs. The throughput curves also show that our algorithm is able to provide higher throughput and better channel utilization.

Thus, we may say that the algorithm combined with our prioritizing scheme certainly provides benefits when compared to random allocation scheme.

Chapter 10

10. Conclusion and Future Directions

10.1 Conclusion

In this thesis work, we have designed a new channel allocation mechanism for the Cognitive Radio based xG networks, based on graph theory. We grouped the users as well as the channels on the basis of the quality of service constraints. We then analyzed the performance of our mechanism incrementally in two steps: (a) Channel allocation in a static environment. (b) Channel allocation in a dynamic environment. In the first scenario, we assumed a static channel configuration, wherein the primary users' behavior has been strictly defined according to a schedule. Our analysis was based upon the various performance measures like packet drop rate and jitter. We compared our scheme against the bare bones scheme where no priorities are taken into account while allocating channels.

In the second part of our work, we simulated the performance of our algorithm in a dynamic environment, where the behavior of the primary users is also a factor. In such a scenario, the algorithm has been adapted to take into account the changing channel qualities which directly impact the users. We compared and contrasted our scheme based on graph theory, against the random allocation scheme. We show that our approach reduces the channel allocation time compared to the greedy mechanism while delivering vast improvements in packet drop rates compared to the current schemes for channel allocation.

10.2 Future Directions

The system model that we have employed is rather simple where we have taken a high level view. Some of the details about the wireless networks were omitted as the focus of the work has been on showing the application of the algorithm in channel allocation. We have taken adjacent channel interference from the PUs as the main classifying criteria for channel quality. However, there are many other factors which might come into play such as the transmitting distance between the user and the base station, the level of interference caused by other transmitting entities, fading and reflection of the signals and so forth. We have consciously not taken them into consideration so as not to make the model complicated and divert from our goal of measuring the algorithms performance. Similarly, there are many other parameters which come into play while determining the QoS constraints for the SUs such as energy consumption, path-loss, link layer delay, holding time. These factors might be incorporated while designing stronger priority functions for classifying SUs and channels. Fuzzy logic might also be used as compared to our use of crisp logic for classifying SU requests.

Utilizing the concept of matchings in order to solve the channel allocation problem, while incorporating priorities, is a novel idea with applications to not just the cognitive radio networks but also more traditional wireless networks. Our priority function incorporates the maximum tolerable delay and the throughput requirements while grouping the SUs. Other factors which might be included in the analysis are the transmission power requirements of the secondary users etc. Utilizing these factors, the priority functions may be refined to group the users into sub-priorities within the broader priority groups.

The added details can be utilized to provide a higher QoS guarantee to the SUs. The topological issues which would come up as a result of such prioritizing can be investigated.

Further, our scheme can be incorporated with concepts from Artificial Intelligence and pattern recognition where the usage pattern of PUs and the SUs can be analyzed and the channels allocated accordingly. Also, predicting the length of duration for which a user requires a channel would also help in making better decisions while allocating channels. Currently, IEEE 802.22 standards specify that the best available channel be allocated to a requesting user. This opens up our scheme to a higher number of channel kickoffs. If in future these standards are modified, it would be interesting to analyze the users' transmission behavior and allocate channels non-optimally with a view to reduce the system kickoffs, by making a prediction upon the future SU requests. Thus, this work opens many avenues for future research.

Bibliography

- [1] FCC, ET Docket No 03-222 Notice of proposed rule making and order, December 2003.
- [2] I.F. Akyildiz, Y. Altunbasak, F. Fekri, R. Sivakumar, “AdaptNet: Adaptive protocol suite for next generation wireless internet”, IEEE Communications Magazine 42 (3) (2004) pp. 128–138.
- [3] I. F. Akyildiz, W.Y. Lee, M. C. Vuran, S. Mohanty, “NeXt generation/dynamic spectrum access/cognitive radio wireless networks: A survey”, Computer Networks 50 (2006) pp. 2128.
- [4] S. Haykin, “Cognitive radio: brain-empowered wireless communications”, IEEE Journal on Selected Areas in Communications 23 (2) pp.201–220, 2005.
- [5] R.W. Thomas, L.A. DaSilva, A.B. MacKenzie, Cognitive networks, in: Proc. IEEE DySPAN 2005, November 2005, pp. 352–360.
- [6] F.K. Jondral, “Software-defined radio-basic and evolution to cognitive radio”, EURASIP Journal on Wireless Communication and Networking, 2005.
- [7] S. Haykin, “Cognitive radio: brain-empowered wireless communications”, IEEE Journal on Selected Areas in Communications 23 (2) (2005) pp. 201–220.
- [8] J. Mitola III, “Cognitive radio: an integrated agent architecture for software defined radio”, Ph.D Thesis, KTH Royal Institute of Technology, 2000.
- [9] R.W. Thomas, L.A. DaSilva, A.B. MacKenzie, Cognitive networks, in: Proc. IEEE DySPAN 2005, November 2005, pp. 352–360.
- [10] D. Maldonado, B. Lie, A. Hugine, T.W. Rondeau, C.W.Bostian, “Cognitive radio applications to dynamic spectrum allocation”, in: Proc. IEEE DySPAN 2005, November 2005, pp. 597–600.
- [11] V. Brik, E. Rozner, S. Banarjee, P. Bahl, “DSAP: a protocol for coordinated spectrum access”, in Proc. IEEE DySPAN 2005, November 2005, pp. 611–614.
- [12] C. Raman, R.D. Yates, N.B. Mandayam, “Scheduling variable rate links via a spectrum server”, in Proc. IEEE DySPAN 2005, November 2005, pp. 110–118.
- [13] S.A. Zekavat, X. Li, “User-central wireless system: ultimate dynamic channel allocation”, in Proc. IEEE DySPAN 2005, November 2005, pp. 82–87.

- [14] L. Cao, H. Zheng, "Distributed spectrum allocation via local bargaining", in Proc. IEEE Sensor and Ad Hoc Communications and Networks (SECON) 2005, September 2005, pp. 475–486.
- [15] J. Huang, R.A. Berry, M.L. Honig, "Spectrum sharing with distributed interference compensation", in Proc. IEEE DySPAN 2005, November 2005, pp. 88–93.
- [16] L. Ma, X. Han, C.-C. Shen, "Dynamic open spectrum sharing MAC protocol for wireless ad hoc network", in Proc. IEEE DySPAN 2005, November 2005, pp. 203–213.
- [17] S. Sankaranarayanan, P. Papadimitratos, A. Mishra, S. Hershey, "A bandwidth sharing approach to improve licensed spectrum utilization", in Proc. IEEE DySPAN 2005, November 2005, pp. 279–288.
- [18] J. Zhao, H. Zheng, G.-H. Yang, "Distributed coordination in dynamic spectrum allocation networks", in Proc. IEEE DySPAN 2005, November 2005, pp. 259–268.
- [19] Q. Zhao, L. Tong, A. Swami, "Decentralized cognitive MAC for dynamic spectrum access", in Proc. IEEE DySPAN 2005, November 2005, pp. 224–232.
- [20] H. Zheng, L. Cao, "Device-centric spectrum management", in Proc. IEEE DySPAN 2005, November 2005, pp. 56–65.
- [21] X. Jing, D. Raychaudhuri, "Spectrum co-existence of IEEE 802.11b and 802.16a networks using CCCC etiquette protocol", in: Proc. IEEE DySPAN 2005, November 2005, pp. 243–250.
- [22] O. Ileri, D. Samardzija, N.B. Mandayam, "Demand responsive pricing and competitive spectrum allocation via spectrum server", in: Proc. IEEE DySPAN 2005, November 2005, pp. 194–202.
- [23] G. Marias, "Spectrum scheduling and brokering based on QoS demands of competing WISPs", in: Proc. IEEE DySPAN 2005, November 2005, pp. 684–687.
- [24] S. Swami, C. Ghosh, R. Dhekne, D. P. Agrawal, K. Berman, "Graph Theoretic Approach to QoS-Guaranteed Spectrum Allocation in Cognitive Radio Networks", submitted to IEEE DySPAN 2008, pp. 3-4.
- [25] R. J. Lavery, "*Throughput Optimization for Wireless Data Transmission*", June 2001, Polytechnic University, pp. 6-8.
- [26] G. Aggelou, "*Mobile Ad Hoc Networks*", McGraw-Hill Pub., 2005, pp. 160.
- [27] K. A. Berman and J. L. Paul, "*Fundamentals of Sequential and Parallel Algorithms*", PWS Publishing Co., 2003.

- [28] K. A. Berman, “*Priority-Optimal B-Matchings and Load Balancing in Client-Server Networks*”, Technical Report, University of Cincinnati, USA.
- [29] J. Ohyun, H. J. Park, and D. H. Cho, “QoS provisioning spectrum management based on intelligent matching and reservation for cognitive radio system,” *2nd IEEE International Conference on Cognitive Radio Oriented Wireless Networks and Communications, CROWNCOM’07*, Orlando, Florida, July 31 - August 3, 2007.
- [30] C. Cordeiro, K. Challapali, D. Birru, S. Shankar, “IEEE 802.22: the first worldwide wireless standard based on cognitive radios”, *Proc. IEEE DySPAN 2005*, November 2005, pp. 328–337.
- [31] S. Mishra, “Channel Allocation in Cognitive Radios”, www.eecs.berkeley.edu/~simm/ee224b_report.doc, May 2005.
- [32] S. Mishra, J. Greunen, “Channel Allocation for Cognitive Radios”, www.eecs.berkeley.edu/~simm/ee224b_report.doc, Spring 2004.
- [33] N. Nie, C. Comaniciu, “Adaptive channel allocation spectrum etiquette for cognitive radio networks”, *Mobile Networks and Applications*, Volume 11 Issue 6, December 2006.
- [34] J. Li, D. Chen, W. Li, J. Ma, “Multi user Power and Channel Allocation Algorithm in Cognitive Radio”, *International Conference on Parallel Processing*, 2007.
- [35] J. Neel, J.H. Reed, R.P. Gilles, “The Role of Game Theory in the Analysis of Software Radio Networks”, *SDR Forum Technical Conference*, November, 2002.
- [36] J. Neel, J.H. Reed, R.P. Gilles. ”Convergence of Cognitive Radio Networks” *Wireless Communications and Networking Conference* 2004.
- [37] Jain, R., Chiu, D.M., and W. Hawe, “ *A Quantitative Measure of Fairness and Discrimination for Resource Allocation in Shared Systems*”. DEC Research Report TR-301, 1984