CHAPTER I

INTRODUCTION

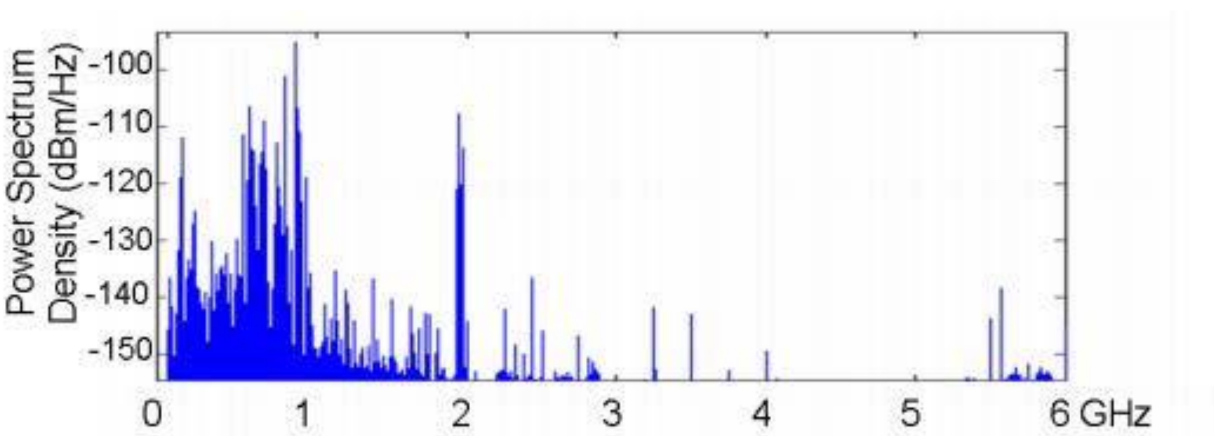
1.1. Introduction and Motivation

The demand for radio frequency spectrum, a scarce and valuable resource, has been increasing significantly due to the increase in number of wireless devices and information sharing in the form of images and videos, which needs higher bandwidth. In the wired communications, the available bandwidth can be increased by laying more cables, whereas in wireless communications, it is a fixed quantity at the given geographical region and is hardly equal to the capacity of just one fibre-optic cable.

Wireless spectrum is generally offered to various wireless communication purposes like satellite communications, terrestrial TV transmissions, military purposes, navigation applications, cellular communications etc., through licensing procedures implemented by respective governments of the countries. In addition to these licensed frequencies, Industrial Scientific and Medical bands (ISM bands), which can be accessed freely by unlicensed users, are also available at various frequency ranges like 49 MHz, 900 MHz, 2.4 GHz, and 5.1 GHz. The main purpose of maintaining these unlicensed ISM frequency bands is to accommodate the needs of Industrial, Scientific and Medical applications like the radio emissions of scanners and other electronic devices used in hospitals and industrial drives which emit some radiation through their operations.

Some electronic systems like wireless LAN equipment, garage door openers, cordless phones, and Bluetooth systems use ISM bands for communication purposes. But, the fast escalation in the number of these devices has resulted in crowded ISM bands, which in turn resulted in higher bit error rates and packet retransmissions by the devices that use these bands. In addition to this, the ISM bands have some restrictions in terms of channel access, capacity and the transmitted power. In the case of licensed bands, this type of congestion will not be there, but the problem is that there are hardly any frequencies left for new services going to be offered.

On the other hand, so many applications like television broadcasters, mobile radio broadcasters, satellite services and navigation services have taken licenses from governments to use major part of the spectrum. But, most of the times it is found that these frequency bands are not being utilized fully, by their licensed users. According to FCC (Federal Corporation Commission) of USA, the licensed users are not even using 30% of the allocated spectrum (FCC, 2008). Figure 1.1 shows the spectrum usage of downtown Berkely that depicts the case of spectrum underutilization (Yang. J, 2005). So there is a need of devising some techniques to utilize the unused portion of the licensed spectrum in such a way that the licensed users are not disturbed. *Cognitive Radio* is a promising technology that exploits the underutilization of spectrum by licensed users, to offer bandwidths to new wireless applications which are in need of spectrum allocations.



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

Figure 1.1. Spectrum utilization measurement (0 to 6 GHz) in downtown Berkely

Cognitive Radio, proposed by Joseph Mitola (Mitola,J., 1998), is an intelligent transceiver (transmitter/ receiver) which can detect the spectrum holes (the frequencies that are not in use by the licensed users, at that time) and change its transmission or reception parameters to make use of those available spectrum holes for its transmission and reception purposes (Thomas, R. W., Friend, D. H., Dasilva, L. A. & Mackenzie, A. B., 2006; Mitola, J. & Maguire, G. Q. ,1999; Mitola,J., 2000; Mitola, J. , 2009).

In the context of cognitive radio networks, the licensed users are called as ‘primary users’ (PUs) and the unlicensed users who attempt to use the spectrum during its unoccupied times, are called ‘secondary users’ (SUs). Figure 1.2 depicts the presence of Spectrum holes at a given geographical area (Akyildiz, I. F., Lee, W. Y., Vuran, M. C. & Mohanty, S., 2008).

After digitization of TV channels, bandwidth requirement of terrestrial TV has got reduced and hence the frequencies thus saved can also be used as spectrum holes (Akyildiz, I. F., Lee, W. Y., Vuran, M. C. & Mohanty, S., 2008). These are known as TV white spaces (TVWS). The concept of cognitive radio networks is shown in Figure 1.3 (Akyildiz, I. F., Lee, W. Y., Vuran, M. C. & Mohanty, S., 2006).

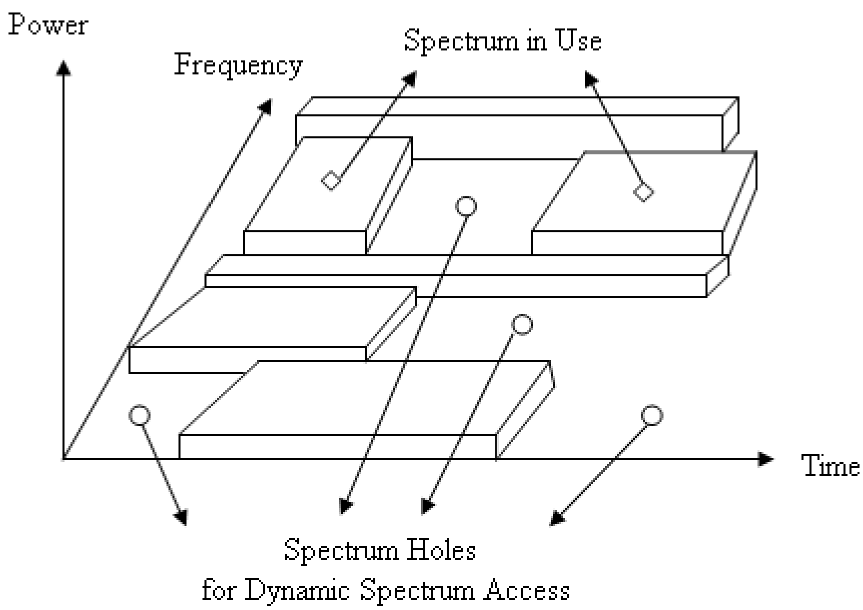


Figure 1.2. Spectrum Holes Illustration

From Figure1.3, it can be understood that, with fixed-spectrum assignment- policy, the spectrum is not being utilized fully in most of the frequency bands, for most of the time. By using the cognitive radio technology, spectrum utilization can be improved to a great extent.

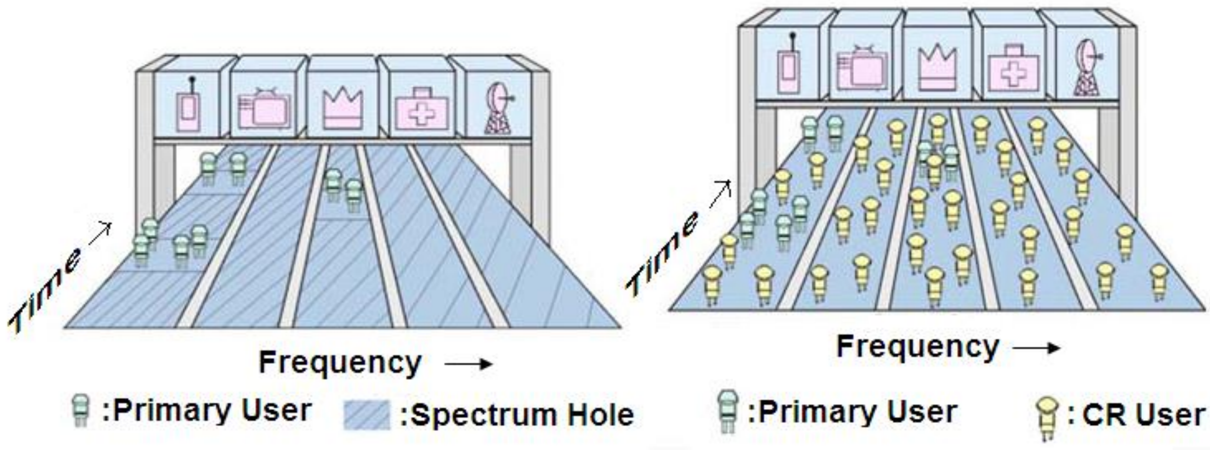


Figure 1.3.(a) Static Spectrum Assignment Policy (b) Cognitive Radio Technology

1.2.Essential Components of Cognitive Radio

The steps involved in cognitive radio network implementation can be understood from its life cycle shown in Figure 1.4 (Akyildiz, I., Lee, W., Vuran, M., Mohanty, S., 2006).

1.2.1. Spectrum Sensing

The first task to be performed by SUs is to sense the spectrum periodically to identify the vacant channels in order to use them for its communication. But the SU should continue the sensing mechanism during its spectrum usage also, to know about the reappearance of PUs, so as to vacate the spectrum immediately, to make it interference-free to the primary user (Mitola, J., 2009; Thomas, R. W., Friend, D. H., Dasilva, L. A. & Mackenzie, A. B., 2006; Cabric, D.,2008; Akyildiz, I. F., Lee, W. Y., Vuran, M. C. & Mohanty, S., 2006).

1.2.2. Spectrum Decision

After identifying the spectrum holes through sensing, the next step in the life cycle is the optimal assignment of these spectrum holes to the requesting SUs, without causing interference to PUs. This can be achieved by modeling the PUs activity, estimation of channel interference, estimation of channel capacity and optimal channel selection (Akyildiz, I. F. , Lee, W. Y., Vuran, M. C. & Mohanty, S., 2008).

The challenges of spectrum decision are (Akyildiz, I. F. , Lee, W. Y., Vuran, M. C. & Mohanty, S., 2008), adaptability in cognitive radio networks, and cooperation in cognitive radio networks.

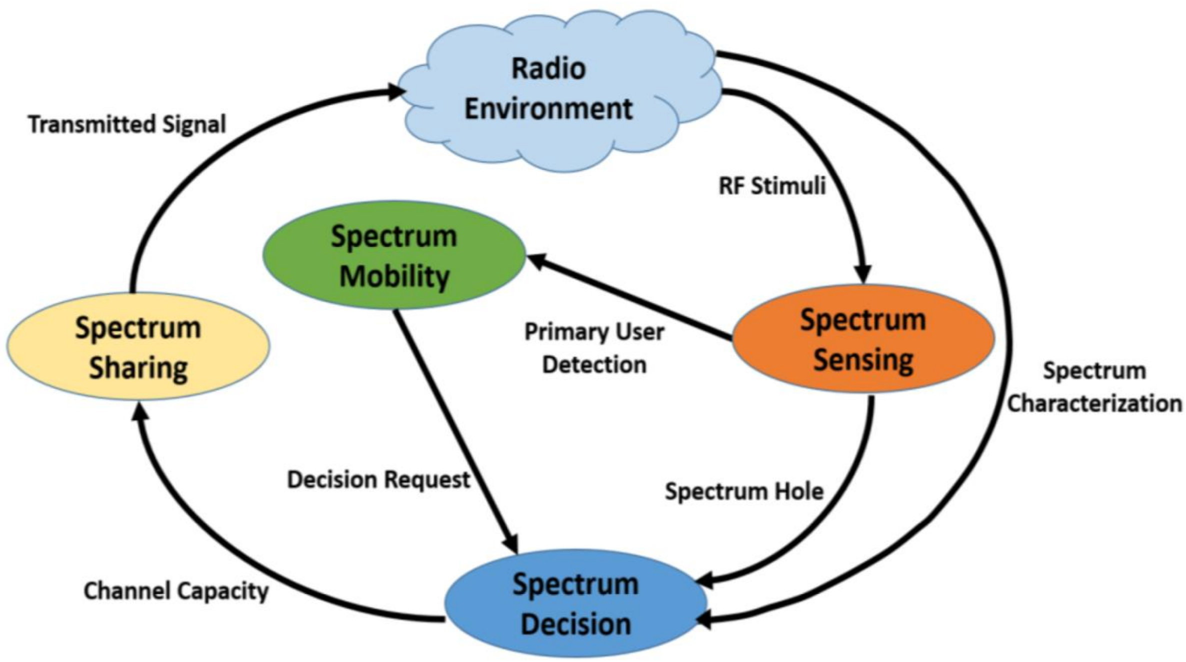


Figure1.4. Life Cycle of Cognitive Radio Network

1.2.3. Spectrum Sharing

The function of spectrum sharing is the optimum allocation of spectrum holes to the requesting SUs. It plays an active role in allocating appropriate frequencies from the available spectrum holes. In the case of spectrum holes that arise from TV white spaces, energy savings also can be achieved by using these low frequencies, which have superior propagation characteristics compared to high frequency microwaves. It also results in less number of active base stations, which saves system energy (Akyildiz, I. F., Lee, W. Y., Vuran, M. C. & Mohanty, S.,2008). For spectrum sharing, SUs should have the knowledge of PUs transmissions and act accordingly.

1.2.4. Spectrum Mobility

The process of vacating the channel when a PU comes back and occupying another spectrum-hole is called spectrum-handoff. The channel switching should be fast such that SUs shouldn't cause any interference to PUs and the Quality of Service (QoS) of SUs should not be degraded.

The challenge of spectrum mobility is (Akyildiz, I. F. , Lee, W. Y., Vuran, M. C. & Mohanty, S., 2008):

- Available vacant channels are continuously changing with respect to time and location. Maintainance of QoS in such circumstances is a major concern.

In this mechanism, care has been taken for the guaranteed QoS for PUs, but no such guarantees are offered for the transmissions of SUs.

1.3. Cognitive Radio Network Architecture

The cognitive radio network can be divided into two sub networks: primary network and secondary network. The users of primary network are licensed users, who can access the spectrum at any time and must not be disturbed by the SUs whereas the users of secondary network should opportunistically utilize the spectrum and should ensure no disturbance to PUs. SUs should have an additional feature of MAC protocol, which should support the frequency hopping of SUs (Ileri, O., Samardzija, D., Sizer, T. & Mandayam, N. B., 2005), for handoff situations.

When SUs desire to use the licensed bands, they should accomplish two important tasks i.e., spectrum sensing (finding the absence or the presence of PUs and to utilize the spectrum in a way that no disturbance occurs to PUs) and spectrum mobility (vacating the channel whenever PU comes back). Optimization of sensing interval is also significant. If sensing interval is very high then accurate sensing results can be obtained but spectrum utilization time will be reduced. On the other hand, if sensing interval is small, then, spectrum utilization time may be more but it may result in sensing errors like *probability of misdetection* and *probability of false alarm*.

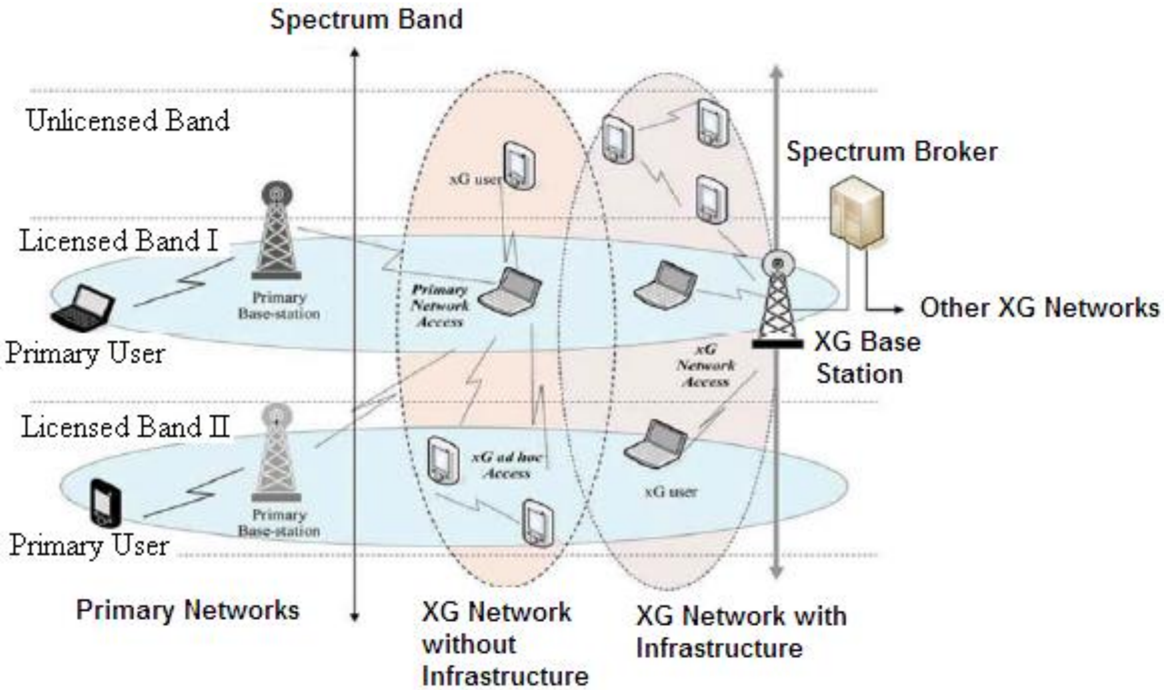


Figure1.5. Cognitive Radio Network Architecture

The network architecture of cognitive radio network is illustrated in Figure 1.5 (Akyildiz, I. F., Lee, W. Y., Vuran, M. C. & Mohanty, S., 2008).

1.4. QoS Provisioning Approaches for Secondary Users

Even though opportunistic channel access is a chance to SUs, it suffers a drawback of being non-deterministic channel access. That means availability of the channels cannot be known in advance and sometimes the secondary users may not get the channels. At some other times, the SUs may have to vacate the channels that are there in their possession, when their primary users return back. In this backdrop it is found to be useful if some kind of determinism can be added to the channel accessing of secondary users. By doing so, it will improve the quality of service (QoS) offered by the secondary network. The work of this thesis deals with the mechanisms that can be adopted to improve the QoS of secondary users of cognitive radio networks.

Blocking probability of secondary users is the metric considered for QoS fulfilment. In literature, different approaches are adopted to satisfy this QoS parameter in cognitive radio networks. Four important approaches of QoS provisioning are enlisted below:

a. Opportunistic scheduling design using Media Access Control (MAC) protocols: The authors of (Hamdi, K., Zhang,W. & Ben Letaief, K.,2007) proposed scheduling schemes, which are aimed to minimize the interference to the primary users, satisfy delay constraints, obtain fairness among secondary users and maximize the system capacity. The authors of (Su, H. & Zhang, X., 2008) proposed two cross layer protocols, which include sensing and packet scheduling. In this, they assumed each SU is provided with two transceivers, one for control channel and the other for sensing and opportunistic usage of unused spectrum bands. The first protocol is random sensing, where it selects the channels randomly for sensing and the second protocol is negotiation based sensing, where it overhears the control channels to select the channels to be sensed.

   In (Chen,W., Letaief, K. & Cao, Z., 2008), successive interference cancellation is considered at physical layer to mitigate SUs' interference to PUs. A joint queue-aware and channel-aware scheduling protocol is proposed at the MAC layer to minimize the packet delays of SUs at given transmit power.

   In (Chen, J., Zhao, M., Tian, J. & Li, S., 2008), they proposed a MAC protocol to guarantee the QoS requirements of distinct SUs to assure transmission synchronization.

   To identify spectrum holes, dynamic ID numbering approach is proposed by (Alshamrani, A., Shen, X. & Xie, L., 2009). In addition, they introduced an efficient but simple sensing algorithm to find optimal number of channels to be sensed and the optimum amount of period to be sensed.

   The authors of (Cai, L.X., Liu, Y., Shen, X., Mark, J.W. & Zhao, D., 2010) proposed a distributed QoS aware MAC protocol in which SUs will decide a set of channels for sensing, based on the patterns followed by PUs, to minimize the number of spectrum handoffs. Further, they applied different random sensing periods for different types of traffic to improve QoS of SUs.

b. Power allocation schemes with QoS requirements of various SUs :

   In (Le, L. & Hossain, E., 2007), the authors proposed an admission control algorithm, which is performed jointly with power/rate control to meet QoS requirement of SUs while maintaining interference to PUs below the tolerable level.

In (Zhang, Y. & Leung, C., 2009), it is aimed to address two issues of resource allocation, namely problem feasibility and false urgency. When resources are not sufficient, then it results in problem feasibility which is overcome with the help of goal programming method. Due to variations of available spectrum, false urgency problem appears, which can be solved by calculating required rate based on queue packets and availability of spectrum.

c. Call admission control mechanisms:

In (Huang, M., Yu, R. & Zhang, Y., 2009), the authors integrated QoS based spectrum handoff mechanism with call admission control. After that, the problem is converted to non-linear optimization, where dropping probability is reduced for a given blocking probability. In (Xue, D., Yu, H. , Wang, X. & Chen, H.H., 2009), the authors developed two call admission control models for constant data and dynamic data capacities to support three types of services, namely handoff voice calls, new voice calls and data calls of different priorities. In the constant data capacity model, some channels are reserved for voice calls and priority is given to handoff voice calls. In the dynamic data capacity model, no channels are reserved but first priority is given to handoff voice calls and second priority is given to new voice calls.

In (Pacheco-Paramo, D., Pla, V. & Bauset, J., 2009), some channels are reserved for spectrum handoffs. Number of channels to be reserved is an important issue, in it. If this number is high, then it will result in more blocking, whereas if this number is small then it will result in more dropping. So they proposed two ways to find optimum number of channels to be reserved. The first method of getting optimum number of channels is aimed at reducing both dropping and blocking probabilities. The objective of second method is to minimize the blocking for given dropping probabilty.

In this (Alshamrani, A., Xie, L. L. & Shen, X., 2010), the authors proposed an admission control scheme and channel allocation policy for cooperative cognitive radio networks. They divided SUs into two groups, namely sensing and accessing groups. The number of SUs in each group is balanced to identify and utilize the available channels efficiently.

d. Application-dependent channel assignments:

In view of challenges faced by voice secondary users, in (Wang, P., Niyato, D. & Jiang, H., 2009) the authors proposed two medium access schemes. The first one is contention based medium access, in which each SU checks for contention. It also supports acknowledgement mechanism which guarantees successful communication. The second one is contention free medium access, where, it starts sending the packets whenever it finds free channel from first mini time slot to i-1th mini time slot.

The authors of (Ali, S. & Yu, F.R., 2009) focussed on application layer QoS. For that, they implemented a method of sensing selective channels only and the decision of channel access is done based on it. They used channel state information, while taking decisions, to obtain application layer QoS.

In view of QoS requirement of multimedia services, the authors in (Gunawardena, S. & Zhuang, W., 2010), derived voice capacity of cognitive radio system based on effective bandwidth and effective capacity with proper MAC. This analysis can help call admission control to provide QoS in CR networks.

Most of the times, QoS metrics in these networks are satisfied by giving preference to some devices and traffic types compared to other devices and traffic types. Some of them are listed here. Based on characteristics, SUs traffic can be classified into 4 types as follows (Yang, W. & Zu, Y., 2016):

i. Real-time and fixed rate service: For this type of data, transmission delay should be as small as possible, as it is a real-time data. Ex: VoIP (Voice over Internet Protocol). The transmission rate and packet length are constant in it. During spectrum handoffs, high capacity channels are to be selected for this type of data. This can be treated as the highest priority data.
ii. Real-time and variable rate service: For this type of data, transmission rate and packet length are not constant. Ex: MPEG video. One should ensure high

channel capacity during spectrum handoffs. As this is also real-time, high priority can be assigned.

iii. Non-Real time and variable rate service: The packet length and transmission rate are not constant for this type. Ex: FTP service. As it is non-real time, there is no urgency of data transmission and hence it can be treated as low priority data.

iv. The Best Effort Service: It is non-real time and delay insensitive data like the e-mail and SMS and can be treated as least priority data.

In the above works, researchers concentrated on what channels to be sensed, how much time the channels to be sensed, how to reduce the interference to PUs, how to minimize the number of handoffs, how many SUs can be admitted to reduce the number of handoffs etc.

In this thesis, the focus is on the aspect of reducing the latency values to the real time transmissions, thereby meeting the real time transmission requirements of various devices with different priorities. To meet the objective, SUs are classified into four priorities based on their tolerable latencies. The users with less tolerable latency are given more importance and will be admitted in that priority order. Various methods are proposed and implemented in this work to achieve the objective of supporting real time transmissions.

1.5. Terminology Used in Cognitive Radio Networks

Terminology and basic mechanisms of cognitive radio networks are described here, with reference to Figure 1.6. When an SU wants to use spectrum holes, but if no spectrum holes are available, then it will be blocked. On the other hand, if SU finds a spectrum-hole, then, it will use that spectrum hole, the mechanism of which is known as *Opportunistic Spectrum Use*. The process of vacating the present channel and occupying another spectrum hole, when a primary user returns back is called *Spectrum Handoff*. At the time of handoff, if no free channel is available, it is said to be dropped. In this work, when secondary users with varying priority levels are considered, say 4 different priorities, they are termed as SU1s, SU2s, SU3s and SU4s with decreasing priorities in that order. Here SU1s are treated as hard real-time, i.e. highest priority SUs; SU2s and SU3s can be treated as soft real-time, with priority of SU2s more compared to SU3s.

Finally, SU4s are non-real time SUs, which are least priority SUs. To support real-time SUs, pre-emption is allowed in the order of their priority. When a high priority SU is requesting and no free channel is available at that time, the low priority SU using the channel at that time, is supposed to vacate the channel for the sake of high priority SU.

The availability of spectrum holes changes continuously with respect to both time and geographical location. As license-holders of spectrum, the PUs will maintain QoS, but the QoS maintenance of SUs is difficult due to random nature of spectrum holes. But QoS fulfilment of SUs is important in time-critical applications like factory automation, surveillance, real-time audio/video transmission (Zhao, Y., Mao, S. Neel, J. O. & Reed, J. H., 2009; Devroye, N., Mitran, P. & Tarokh,V., 2006; Luo, H., Ci, S. & Wu, D., 2011; Liang, Z., Feng, S., Zhao, D. & Shen, X. S., 2011). In such situations, planning of guaranteed QoS for time-critical applications is a real challenge through this opportunistic access.

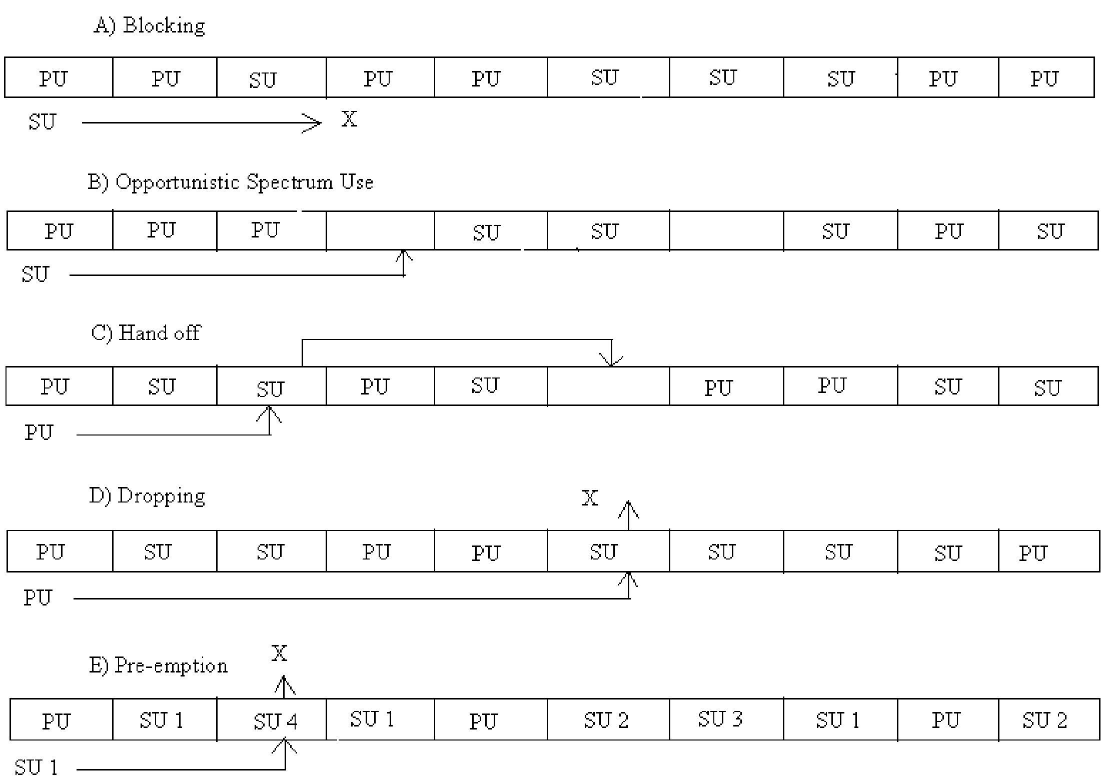


Figure 1.6. Terminology used in Cognitive Radio Networks

1.6. IEEE Standardization of Cognitive Radios

IEEE 802.22 Working group is related to cognitive radio, which includes physical (PHY) and medium access control (MAC) procedures for operating in TV broadcast range to work as wireless regional area network (WRAN). WRAN's are designed to operate in unused bands of VHF/UHF TV channels. (Sturza, M. A. & Ghazvinian, F., 2007).

The inspiration behind the development of IEEE 802.22 standard was to use the spectrum bands of unused terrestrial TV to provide broadband services. The spectrum bands of terrestrial TV selected to use for broadband service are having high quality propagation characteristics covering larger areas. The 802.22 network envisages ensuring appropriate QoS for high quality voice and data services. The IEEE 802.22 standard is designing the mechanisms to operate in frequency ranges from 54 -862 MHz and planning to extend up to 900 MHz (Cordeiro, C., Challapali, K., Birru, D. & Sai Shankar, 2005).

1.7. Objective and Scope of the Thesis

The objective of the thesis is to devise mechanisms for Supporting Real-Time Transmissions in Cognitive Radio Networks with efficient utilization of Bandwidth and Reduced Interference.

Scope of the thesis is:

- Study of Cognitive Radio Spectrum Management issues.
- Investigating the MAC layer designs suitable to transmit Real-time data of Cognitive Radio users.
- Proposing appropriate methods of channel accessing, scheduling, pricing along with spectrum prediction for providing QoS to real-time SUs.
- R2014a version of MATLAB along with Simulink is used to carry out simulations in this work. A desktop computer powered with Core2 duo processor

and 2GB RAM with Windows 7 operating system is the computing hardware used.

- Comparing results with the existing ones.

1.8. Contributions of the Thesis

1. Proposed a channel access mechanism that supports real-time traffic of secondary users by assigning appropriate number of priorities. Further improvement of it is obtained by introducing Timeout-Aware Inter- Queuing concept.

2. Proposed a novel auction mechanism, called Range Bound Bidding, in which predefined bid values are used. The secondary users use the relative predefined bid values based on their urgency of channel requirement. The final channel cost is same for all users, who were allocated channels at that time instant and hence avoids multiple biddings by the same user. In addition to this the final price of channel takes demand and supply into consideration.

3. ANFIS based spectrum prediction is carried out to save the sensing time and energy, because with prediction sensing only the channels which are predicted to be free only are to be sensed instead of all channels. Besides, it helps in proper planning of spectrum handoffs to ensure QoS of both primary and secondary transmissions.

4. Frequency reuse is proposed instead of channel reservation to utilize the bandwidth in an efficient manner and to improve the blocking probability. The problem of co-channel interference with frequency reuse is taken care with the help of co-channel interference simulations in multi-user cognitive radio network.

1.9. Thesis Organization

The contents of the thesis, segregated into five different chapters (from 2-6), are briefly described below chapter-wise.

Chapter 2: Timeout-Aware Inter-Queuing for QoS Provisioning of Real-Time Secondary Users

This chapter provides the methods, which are mainly focussed on classifying the secondary users into multiple priority categories, and using the queuing techniques to achieve QoS of real-time users. Related previous works and the proposed method are presented. In the proposed method, SUs are classified into four priorities to represent various levels of prioritized users. In addition, Timeout-Aware Inter-Queuing is introduced to improve further the QoS of real-time users. The performance of proposed method is compared with existing methods in terms of blocking probability.

Chapter 3: Range Bound Bidding for Bandwidth Optimization

This chapter discusses about various auction techniques from literature and the proposed Range Bound Bidding method for Bandwidth Optimization. Here, priorities are linked to the bids of secondary users. In the proposed method, maximum bid is predefined and all the remaining bid values are sub-multiples of maximum bid. This is aimed at overcoming the ambiguity of secondary users, such as how much bid value would fetch them the spectrum bandwidth. The results of proposed method are compared in terms of revenue and blocking probability with the existing techniques.

Chapter 4: Prediction of Spectrum Availability

This chapter covers various prediction techniques from the literature and the proposed ANFIS based spectrum availability prediction. The performance of prediction is measured in terms of mean square error and regression analysis. The prediction will help in advanced planning of channel assignment which can reduce the number of handoffs of secondary users.

Chapter 5: Frequency Reuse for Optimum Utilization of Bandwidth

This chapter covers the methods that support frequency reuse depending on acceptable mutual interference among secondary users. The frequency reuse technique proposed here not only supports the real-time secondary users but also offers efficient utilization of bandwidth. The proposed technique is compared with the existing channel reservation technique. Better call completion rate and blocking probability are achieved.

Chapter 6: Conclusion and Future Scope

This chapter concludes the work done in the thesis highlighting the main contributions of it. It also includes the directions for future extensions.