# MEDIUM ACCESS CONTROL PROTOCOL FOR SPECTRUM SHARING IN COGNITIVE RADIO COMMUNICATION SYSTEM

**by**

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Date:

## Candidate's Declaration

I hereby certify that the work which is being presented in the thesis entitled "*Medium Access Control Protocol for Spectrum Sharing in Cognitive Radio Communication System*" in fulfillment of the requirement for the award of the degree of *Doctor of Philosophy* in Electronics and Communication Engineering and submitted in the Department of Electronics and Communication Engineering of Jaypee University of Information Technology, Waknaghat (H.P), India is an authentic record of my own work, carried out during the period from July 2012 to May 2015, under the supervision of **Prof. Ghanshyam Singh.**

The matter presented in this thesis has not been submitted by me for the award of any other degree in this Institute or any other Institute/University.

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This is to certify that the above statement made by the candidate is correct to the best of our knowledge.

**Prof. Ghanshyam Singh**
Professor,
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Research is to see what everybody else has seen, and to think what nobody else has thought.

# DEDICATION

I am here because of my father Mr. Sushil Sharma, my mother Mrs. Meena Sharma and my loving brother Harsh.

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# ABSTRACT

The frequency allocation performed by regulatory bodies have allocated spectrum for various services through static/fixed spectrum allocation scheme in order to avoid interference among the users, which reveals that most of the frequency bands have already been assigned. However, the Federal Communications Commission (FCC) spectrum policy task force has reported that the utilization of frequency bands below 3 GHz ranges from 15% to 85% and these are even more poorly utilized for the frequency range above 3 GHz. Therefore, the spectrum is not scarce but the allocated spectrum is underutilized due to the fixed spectrum allocation scheme. Now as the complexities of wireless technology increases, new multidisciplinary approaches for the spectrum sharing/management are required with inputs from technology, economics and regulatory authorities. Recently, the cognitive radio has come into action to handle the spectrum scarcity problem and enhanced the spectral efficiency. The fundamental concept of cognitive radio has been adopted from the software defined radio (SDR) which can operate on multiple frequency bands without any hardware modification, however selection of frequency band and operating parameters are manually controlled by the user through software. The artificial intelligence part for learning and decision making is not available in SDR in contrast to the cognitive radio. Therefore, the cognitive radio is a software defined radio along with the capability of opportunistically identifying the unused portions of the licensed spectrum and making decision such as about modulation scheme, transmission power etc. without the human intervention. This device is based on the dynamic spectrum access (DSA) and opportunistic spectrum access (OSA) schemes for spectrum access/allocation instead of fixed spectrum allocation. These spectrum allocation schemes are the flexible method of assigning spectrum to the cognitive users which defines a set of techniques and models to support the dynamic management of the spectrum and have broader impacts over the society by enabling further growth in the wireless applications and services. The cognitive radio terminal observe, learn, optimize and intelligently adapt to achieve optimal frequency band usage and establish communication, while ensuring that the licensed or primary users of the spectrum are not affected. This device is able to operate in multiple frequency bands and maximizes the utilization of limited radio spectrum while accommodating the increasing number of services and applications in the wireless communication system. The potential decisions on optimal sensing and transmission time with proper coordination among the users (primary/secondary) for spectrum access are important characteristics of spectrum sharing methods.

In this thesis, we have technically overviewed the state-of-the-art of various spectrum sharing techniques and discussed their potential issues with emerging applications of the communication system, especially to enhance the spectral efficiency. The potential advantages, limiting factors, characteristic features of the existing cognitive radio spectrum sharing domains are thoroughly discussed and an overview of the spectrum sharing is provided as it ensures the channel access without interference/collision to the licensed users in the spectrum. The spectrum sharing encompasses several techniques such as the power control, game theory, multiple antennas and medium access control (MAC) protocol. The controlled cognitive user's transmit power permit the sharing of licensed spectrum to avoid interference with the primary user. However, the game theory is most commonly market based method of the spectrum sharing dealing with the spectrum leasing, spectrum trading and revenue of the users. On the other hand, multiple antennas are used for spectrum sharing, which allows the beam steering to the desired user and limit the interference to other users. However, in all the spectrum decision and sharing techniques, the channel is considered as a spectrum unit and the development of a protocol/set of rules is a crucial issue. On this track, we have proposed a novel multichannel MAC protocol for the distributed cognitive radio network and have computed and compared it with the reported literatures. The proposed cooperative MAC protocol is for the distributed cognitive radio network and schedules itself without any central entity. We have implemented the back-off algorithm for contention solving among the competing cognitive users for reserving the idle licensed channels. In the proposed cognitive radio MAC protocol, each channel is divided into cycle time, which consists of four intervals such as idle, sensing–sharing, contention, and data transmission. It is well known that as more and more licensed channels are sensed by the cognitive radio terminal for detecting large number of idle licensed channels, there is significantly increase in the complexity and power consumption of the terminal and it results the tradeoff between the number of sensed channels and complexity or power consumption. However, based on this consideration, we have attempted to limit the number of sensed channels by each terminal and shared the sensing results with other cognitive users so that more number of licensed channels information is available at each cognitive terminal in comparison to the channels which it has sensed. Therefore, the cognitive users are considered to sense the fixed number of licensed channels and they share the sensing results with each other. The back-off algorithm implementation in the proposed scheme during the contention interval for resolving collision among the competing users, has allowed the collided users to become successful by selecting another contention slot from the increased contention window. The increased number of successful users has enhanced the throughput of the cognitive radio network by transmitting their data over the detected idle licensed channels. Moreover, the optimum number of contention slots have been achieved which has maximized the number of successful cognitive users as well as throughput.

Further, for more practical scenario, the effect of imperfect sensing on the proposed distributed cognitive radio MAC protocol is considered. The idle channels detection in cognitive radio MAC protocol is affected by the imperfect sensing which is resulted by the false-alarm. The false-alarm occurs when the cognitive user falsely (imperfectly) detects the licensed channel busy which is actually idle and in this situation the cognitive user cannot utilize the opportunity for data transmission. Further, miss-detection also occur due to imperfect sensing in which busy licensed channels are detected as idle and hence cognitive users interfere with the ongoing primary user's communication. The simulation results are presented for different probabilities of the false-alarm and the throughput degradation is computed for this sensing scenario. However, miss-detection causing interference to the primary users is also presented. Moreover, one of the important parameter to observe the performance of MAC protocol is the energy consumption of the proposed system. Since, a mobile terminal is generally having limited battery power, therefore the proposed system should have high energy efficiency. The energy efficiency in imperfectly sensed environment has also been computed for the proposed distributed multichannel MAC protocol for different false-alarm probabilities. In addition to this, the numerical results are presented to demonstrate the developed theoretical findings such as throughput and energy efficiency of the proposed system in the perfect and imperfect sensing environment. We have also proposed an algorithm for computing the optimum transmit power of the cognitive radio users and maximizes the energy efficiency. The cognitive user energy consumption in the proposed MAC protocol that is the energy consumption in sensing-sharing, contention, and data transmission interval are also computed. The simulation results are presented for the energy efficiency variation with the traffic load of licensed channels as well as for different channel gains.

Since, the spectral bandwidth is one of the scarce resources of the wireless communication, therefore the potential issue of bandwidth wastage which arises in the proposed distributed cognitive radio MAC protocol is also dealt with the significant improvement in the proposed scheme. It is further proposed that the sensing-sharing and contention interval bandwidth is also utilized for the data transmission and it has resulted in the significant throughput enhancement. The number of sensing-sharing and contention slots utilized for the data transmission by the cognitive users have been computed and used for throughput enhancement of the cognitive radio network. In addition to this, the effect of traffic load variation on the proposed system performance is also presented.

We have also proposed a frame structure to eliminate the sensing-throughput trade-off problem and reduction of the data loss rate in the conventional cognitive radio user frame structure. In the conventional frame structure, the cognitive radio user first senses the status (active/idle) of the spectrum and then avoid harmful interference to the primary user by adapting transmit power based on the spectrum sensing decision. It depicts that the cognitive user ceases data transmission at the beginning of each frame for sensing. Since, it is required that the false-alarm probability should be low to provide more opportunities for the cognitive radio users to reuse the spectrum band and it results higher achievable throughput. In addition to this, the higher detection probability provides better primary user transmission protection. Moreover, it is well known that the increase in sensing time results higher probability of detection and lower probability of false-alarm, however it provides less data transmission time and hence limits the throughput of cognitive radio user. Therefore, we have proposed that sensing and data transmission are performed simultaneously to increase the sensing and data transmission time and hence avoids the sensing-throughput tradeoff. Further, it is proposed that instead of sending one long block of data in each frame, we send two or more shorter blocks to minimize the data loss rate in case the primary user becomes active in between the data transmission. The sensing results of the previous frame and current frame that is calculated till a particular data block, are utilized to make the decision of data transmission. Moreover, we have numerically simulated and presented the results which has reduced the data loss rate and has maximized the throughput. Further, we have also computed the effective throughput of the proposed scheme.

For the wireless communication systems, the channel capacity is used as a basic performance measurement tool for the analysis and design of new and more efficient techniques to improve the spectral efficiency. We have numerically computed the channel capacity in fading environment under the average interference power constraint with two different adaptation policies namely, adaptive power and adaptive rate and power adaptation in multilevel-quadrature amplitude modulation (M-QAM) format for spectrum sharing in the cognitive radio communication systems. In addition to this, the small scale fading effect over the transmit power of the secondary transmitter is also explored. The rate and power of secondary transmitter is varied based on the sensing information and channel state information of the secondary and primary links. The channel capacity is maximized for aforementioned two policies (adaptive power and adaptive rate and power) by considering the Lagrange optimization problem for average interference power constraint.

Finally, we have concluded the thesis and have presented the future direction in cognitive radio technology. In this thesis, a distributed cognitive radio MAC protocol has been proposed and the proposed system throughput maximization has been achieved. The proposed MAC protocol has also been studied for the imperfect sensing scenario and its effect on the performance of cognitive radio system is illustrated. Moreover, the wasted bandwidth of the proposed MAC protocol has been utilized for further throughput enhancement. Further, the energy efficiency has been maximized for the proposed system by applying the simple algorithm for optimizing the transmit power of the cognitive user. The novel frame structure of the cognitive user is also proposed which has reduces the data loss rate of the cognitive user and has maximized the throughput of the cognitive user. Moreover, the fading environment effect over the cognitive radio users has been studied for rate and power adaptation policies. However, the cognitive radio for green communication and its security issues are the potential research problems in this field. Besides a long-term, interdisciplinary effort to tackle the problem of building and deploying large-scale cognitive radio networks that meet the future growing demands of spectrum by our society, we believe that there is a need for an immediate research effort in the area of cognitive radio testbeds and its infrastructure.

# CHAPTER 1

# Introduction

## 1.1 Introduction

Recently, the spectrum resource demand has been greatly increased due to the emerging wireless services and products in the market. The frequency allocation performed by regulatory bodies of different countries have allocated spectrum for various services through static/fixed spectrum allocation scheme in order to avoid the interference among users, which reveals that most of the frequency bands have already been assigned [1, 2]. However, the FCC spectrum policy task force has reported that the utilization of frequency bands below 3GHz ranges from 15% to 85% and these are even more poorly utilized for the frequency range above 3 GHz [3]. Therefore, the spectrum is not scarce but the allocated spectrum is underutilized due to the fixed spectrum allocation scheme. This unutilized spectrum of certain service provider/licensed user is called spectrum white space or spectrum hole as shown in Fig. 1.1 in which the spectrum utilization measurement between the 9kHz-1GHz is shown [4].

Due to the spectrum scarcity created by fixed spectrum allocation, some new services wanted to enter the communication world might not get enough spectrum for their functioning. The limitations of aforementioned fixed spectrum allocation based scheme have been discussed in detail in [5] and to mitigate this challenging problem, the cognitive radio evolution has occurred which uses dynamic spectrum access (DSA) [6] and opportunistic spectrum access (OSA) [7] schemes for spectrum allocation instead of fixed spectrum allocation. DSA and OSA are the flexible methods of assigning spectrum to the users which define a set of techniques and models to support the dynamic management of the spectrum and have broader impact over the society by enabling further growth in the wireless applications and services. Therefore, the cognitive radio is a promising wireless communication technology geared to solve the spectrum scarcity problem by opportunistically identifying the unused portions of the spectrum, which observe, learn, optimize, intelligently adapt to achieve optimal frequency band usage and establish communication, while ensuring that the licensed or primary users of the spectrum are not affected [5]. It is able to operate in multiple frequency bands and maximizes the utilization of limited radio spectrum while accommodating the increasing number of services and applications in the wireless communication systems. The driving force behind this cognitive radio technology is the new spectrum licensing methods initiated by the FCC, which are more flexible to allow the unlicensed (or secondary/cognitive) users to access the spectrum as long as the licensed (primary) users are not interfered by the unlicensed users.

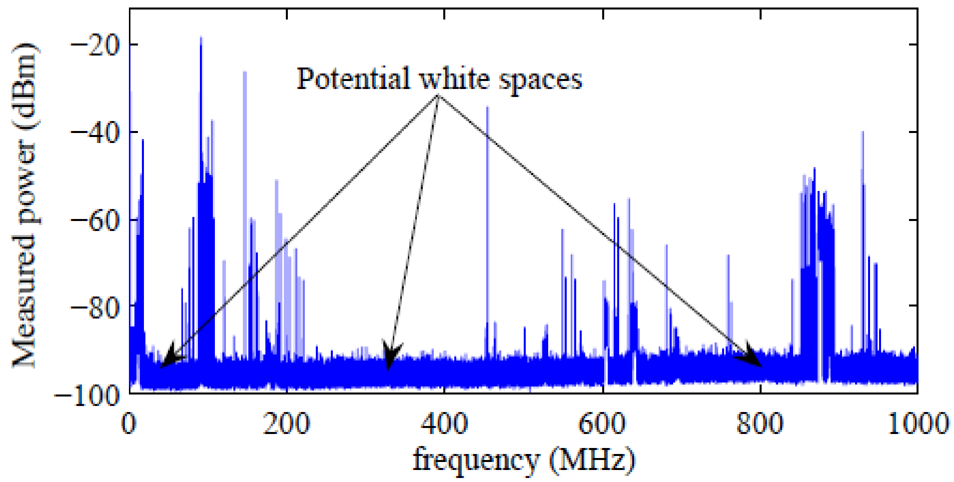



**Fig. 1.1** Spectrum utilization measurements in 9 kHz-1 GHz band [4].

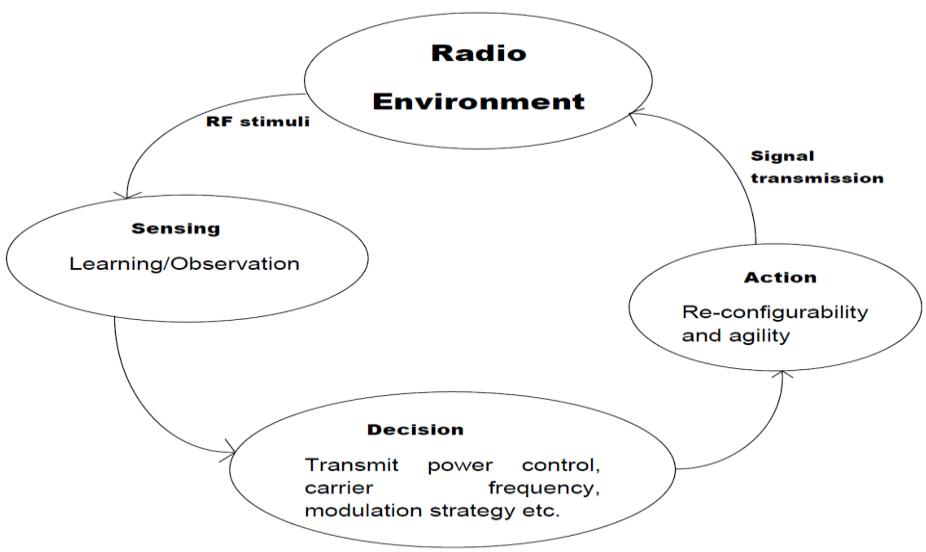



**Fig. 1.2** The cognitive radio cycle.

Fig. 1.2 illustrates the cognitive radio cycle describing the functioning of cognitive radio. Cognitive radio observes the radio environment and makes the decision on control parameters that is transmit power, carrier frequency, and modulation etc. of the device. Based on the decision, cognitive radio reconfigures itself for data transmission. Various research communities have different definitions of the cognitive radio and each community has unique view as the defining features of cognitive radio. According to the communication theorists view, the cognitive radio is primarily about dynamic spectrum sharing, while networking/information technology researchers interpret cognitive radio as a device capable of cross-layer optimization, the computer scientists picture it as a device capable of learning and adapting with assumed capabilities, while the hardware/radio frequency community often views it as an evolutionary step from Software Defined Radio (SDR) [8-12]. Basically, the fundamental concept of cognitive radio has been adopted from the SDR, which can operate on multiple frequency bands without any hardware modification, however the selection of frequency band and operating parameters are manually controlled by the user through software. The artificial intelligence part for learning and decision making is not available in SDR in contrast to the cognitive radio. The cognitive radio is the software defined radio along with the capability of sensing their environment and making decision such as about modulation scheme, transmission power etc. without human intervention. A primary network is not aware of the cognitive network behavior and it does not need any specific functionality to coexist with it. When a primary user transmission is detected, the secondary users should immediately react by changing their radio frequency power, rate, codebook, used channel, etc. because their transmissions should not degrade primary users' quality-of-service (QoS). The main functions of cognitive radio are classified into following three steps [13]:

A) Spectrum sensing,

B) Spectrum sharing/management, and

C) Spectrum mobility.

**A) Spectrum sensing**

In [5], the authors have explored three potential approaches such as database registry, beacon signals, and spectrum sensing to identify the spectrum opportunities. The database registry method requires the global positioning system (GPS) mounted on unlicensed devices to determine its location and accesses the database of primary network to detect the licensed channels that are vacant at that location. However, there are some potential challenges associated with the database registry method to detect the spectrum opportunities, which are as follows:

1. New commercial entity to be built and maintained for database,
2. Cognitive devices need to know their location with prescribed accuracy which is difficult for indoor GPS enabled devices, and

3. Devices need additional connectivity in a different frequency band for its ability to access the database prior to any transmission in the licensed frequency band.

Further, for detecting the spectrum holes with beacon signals, the main challenge is that an unlicensed device transmits if it has received a beacon (control) signal and has identified unutilized channels within the service area. Moreover, without reception of the beacon signal, the unlicensed user transmission is not permitted which keeps unlicensed users waiting even when the licensed spectrum is not occupied in case of hidden terminal problem. Further, the beacon infrastructure should be maintained either by a licensed operator or by some other operator adding extra cost factor. However, in spectrum sensing, a hypothesis model is followed for detection of primary users signal. When cognitive users are sensing the spectrum of primary user in a cognitive radio network, there are two hypotheses for the received signal $y(t)$: absent or present, that are denoted by $H_0$ and $H_1$, respectively [14].

$$y(t) = \begin{cases} h\, s(t) + w(t) & H_1 \\ w(t) & H_0 \end{cases}$$

where $h$ is the channel gain, $w(t)$ is the additive white Gaussian noise with mean zero and variance $E[|w(t)|^2] = \sigma_{\mathrm{w}}^2$, $s(t)$ is the primary user signal which is assumed to be random process with mean zero and variance $E[|s(t)|^2] = \sigma_s^2$. $w(t)$ and $s(t)$ are assumed to be mutually independent. $H_1$ hypothesis depicts primary user signal presence in a certain frequency band and $H_0$ is null hypothesis representing no primary user signal in the spectrum. The spectrum sensing approach is best among aforementioned approaches to yield the unused channel because unlicensed users autonomously detect the licensed spectrum and no modification to the existing infrastructure of the licensed system is required. Therefore, the dynamic spectrum access through the spectrum sensing is compatible with legacy wireless communications systems. However, the spectrum sensing approach is used in various cases along with database registry method to know the utilization pattern of the licensed channels. The spectrum sensing is defined as the capability of the cognitive radio to detect the available channels, within the pre-existing systems (licensed bands/primary user's band) and various dimensions of the sensing such as time, space, angle-of-arrival, code along with frequency have been explored for full awareness about the spectrum. For example, 1) in time dimension: an opportunity of particular spectrum to be unused in specific time has to be sensed, 2) in space dimension: particular band to be unused in specific geographical area has to be sensed, and 3) in code dimension: even if a band is occupied in time, frequency and space dimension, it can still be used by the cognitive radio users by using free spreading code or hopping sequence. There are two spectrum sensing methods as shown in Fig. 1.3, namely:

(i) Non-cooperative/transmitter detection.

(ii) Cooperative detection.

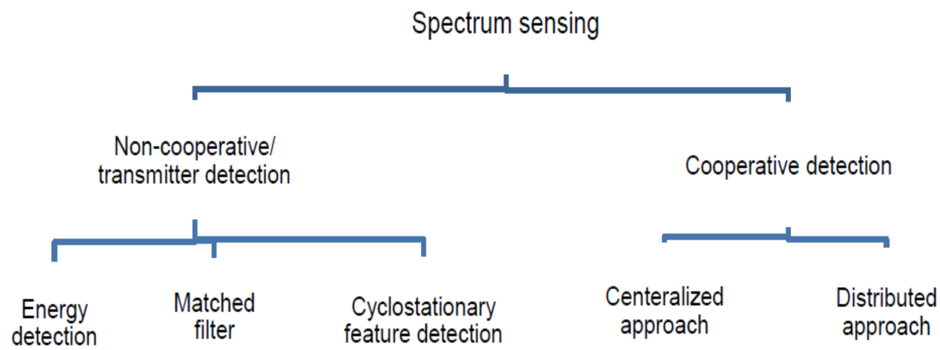



**Fig. 1.3** The spectrum sensing techniques.

### (i) Non-cooperative/transmitter detection

The non-cooperative/transmitter detection is so called because cognitive radio sensing is based on the detection of only transmitted signal from primary user transmitter [13]. Transmitter detection has been classified into three detection methods as described below:

*a) Energy detection*

It is the most commonly used spectrum sensing method, because it detects the presence or absence of primary user signal without requiring any information about nature of primary user signal. In the energy detection technique as shown in Fig. 1.4, the energy of received signal is used for the detection of primary user signal and the presence of signal in the channel is detected if there is significantly more energy present than that of only noise [15]. To compute the energy of the received signal, the signal after passing through band-pass filter is squared and integrated over the observation time interval *T*. Finally, the output of integrator is compared with that of the threshold to know the presence or absence of primary user signal as shown in Fig. 1.4. Therefore, the threshold is set to differentiate between the signal and noise and setting up proper threshold is challenging task.

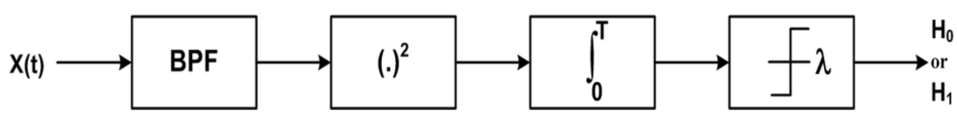



**Fig. 1.4** The energy detection technique [16].

The energy detection technique cannot differentiate between the type of the signal, that is between noise and primary user signal [17, 18]. Moreover, it can result false alarm by falsely detecting the noise as signal and miss the presence of primary user signal by detecting signal as noise if threshold is not set properly. Also, it has poor performance in low SNR and cannot detect spread-spectrum signal.

*b) Matched filter*

The matched filter detection requires the knowledge of primary user signal such as modulation type, operating frequency, bandwidth, and frame format to detect the primary user signal and maximizes the received signal-to-noise ratio. The main advantage of matched filtering is minimum sensing time for accurate detection of signal in comparison to the other methods of sensing however, this detection method has more complexity and large power consumption [13]. Matched filter detection is also capable to differentiate between the primary user signal and noise because of the primary user signal information availability.

*c) Cyclostationary feature detection*

The cyclostationary feature detection relies upon periodic redundancy introduced into the signal by modulation and sampling because modulated signals are in general coupled with sine wave carriers, pulse trains, spreading sequences or cyclic prefixes causing periodicity in the transmitted signal [19]. Cyclostationary detector uses these non-random periodic statistics of signals for detection by observing the mean and autocorrelation of received signal. If the mean and autocorrelation vary periodically in time, then the received signal is of primary user otherwise it is noise which does not have any periodicity. As a result, cyclostationary detectors can successfully operate in extremely low SNR environments and can differentiate between the primary user signal and noise [20].

**(ii) Cooperative detection**

Due to the lack of interaction between primary and cognitive radio users, transmitter detection techniques rely only on weak signals from the primary transmitters. In transmitter detection method, cognitive radio user (transmitter) may have a good line of sight to a cognitive receiver but is not able to detect the primary transmitter due to shadowing. Thus, hidden terminal problem is there in the non-cooperative/transmitter detection and transmitter detection technique alone cannot avoid interference to primary receivers because of the lack of primary receiver information [13]. Therefore, cooperative sensing method [21] allows the collaboration of sensing information from other users for more accurate primary transmitter detection. In cooperative sensing, accurate sensing is performed due to the collaboration of multiple cognitive users sensing results in comparison to the single cognitive user in non-cooperative detection [22]. Further, shadowing and multipath fading effects can be mitigated in cooperative detection so that the detection probability is improved. However, cooperative detection method has more overhead traffic and requires more resources than non-cooperative detection. Cooperative detection has been classified into three schemes:

*a) Centralized approach*

The centralized method uses a base station or fusion center for the cognitive radio network that collects the sensing results of all cognitive users and executes the data fusion [23, 24] or decision rules [25] to reach the final decision of sensing about the availability of primary user spectrum band.

*b) Distributed approach*

In the distributed approach, all cognitive users exchange their sensing results and then each user combines the sensing results of its neighbors to make the final decision individually about the primary user presence/absence on the channel [23, 26]. Moreover, Fig. 1.5 shows the comparison of various sensing methods according to their accuracy and complexity.

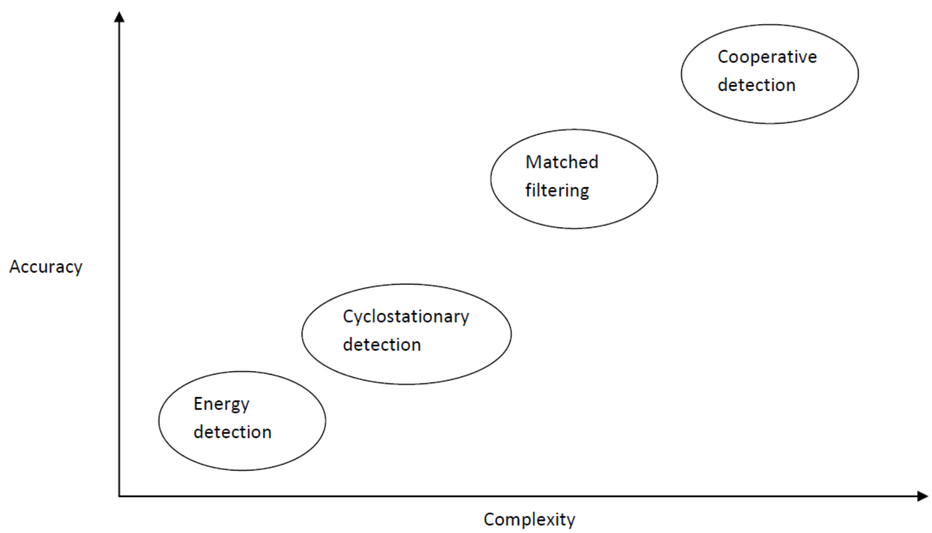



**Fig. 1.5** Various sensing methods comparison in terms of their complexity and accuracy [17].

**B) Spectrum sharing/management**

The dynamic spectrum access method significantly improves the utilization of frequency band and enhances the performance of communication systems. The key component of dynamic spectrum access in cognitive radio technology is spectrum sharing, which is responsible for an efficient and fair spectrum allocation or scheduling solutions among the licensed and cognitive users. In the spectrum sharing model, the radio spectrum can be shared between the primary user network and a cognitive user network, simultaneously. However, the unlicensed or cognitive users can opportunistically access the radio spectrum if it is not occupied or fully utilized by the primary users. Furthermore, as long as the unlicensed user does not interrupt the primary user ongoing communication by maintaining the interference level at the primary receiver below the defined tolerable interference threshold, the spectrum access by an unlicensed user is allowed and it remains transparent to the primary user. Such type of sharing takes place without the primary user being aware of cognitive user that is the transmission of cognitive user is having minimal impact on the operating conditions for which primary user devices are designed. This model of spectrum sharing is attractive as it increases spectrum access and spectrum utilization and also, promises coexistence with existing legacy systems. By considering different parameters of the cognitive radio network, several system models for spectrum sharing are defined as shown in Fig. 1.6 and are discussed as follows:

**(i) Cognitive network architecture**

The architecture of cognitive radio network is an important aspect for sharing the licensed spectrum with multiple cognitive users. There are mainly two types of cognitive radio network architecture described in detail as follows [5]:

*a) Centralized cognitive radio network*

In the centralized cognitive radio network, the control of spectrum allocation and access to a particular regime of the spectrum by cognitive users is performed by a central controller, for example, a base station [23, 27]. In addition to this, all the cognitive users communication are followed through this central controller and the spectrum access decisions like duration of spectrum allocation and transmit power by the cognitive users are controlled through this central base station. For this purpose, the central controller needs to collect information about the spectrum usage of the licensed users as well as information about the spectrum requirements of the cognitive users. An optimal solution based on this information can be obtained which maximizes the total network throughput, provides QoS and reduces latency etc. The decisions of central controller are broadcasted to all the cognitive users in the network. However, the information collection and exchange to and from the central controller and the cognitive users incur a considerable overhead [5].

*b) Distributed cognitive radio network*

In the distributed cognitive radio network, unlicensed users communicate with each other directly that is in a peer-to-peer manner without requiring any base station or central controller [5, 27]. Moreover, an unlicensed user can make a decision on spectrum access independently and autonomously. Since each unlicensed user has to collect information about the ambient radio environment and make its decision locally, the cognitive radio transceiver of each unlicensed user requires greater computational resources than that required in the centralized network. However, the communication overhead in this case would be smaller. In the multi-hop communication, the unlicensed users sometimes may be assumed as relay stations [5].

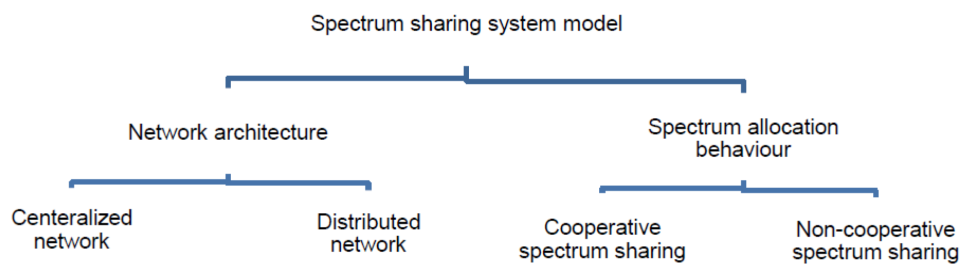



**Fig. 1.6** The spectrum sharing system model for cognitive radio communication system.

**(ii) Spectrum allocation behavior**

*a) Cooperative spectrum sharing*

In the cooperative sharing scheme [28], all the cognitive users cooperate with each other either through a centralized base station or through a common control channel in the centralized or distributed cognitive radio networks, respectively. The cooperation between cognitive users is performed to share the spectrum with maximum efficiency by exchanging the sensing information with each other and thus the cooperative spectrum sensing [29] reduces the sensing time while improving the spectrum sensing accuracy, incurs good degree of fairness, higher complexity, and overhead with an increase in the energy consumption [30]. However, in order to reduce the communication overhead, complexity and power consumption in the cooperative spectrum sensing, only those sensing information are used which are useful in determining the primary user's presence [31]. The communication overhead is further minimized in the cognitive radio spectrum sharing system through clustering [32] in which the spectrum sensing results are combined and processed locally by a cluster head. The cluster head of each cluster, reports the result to a central controller to make a final decision regarding the channel access. However, some other techniques have been proposed for sharing the spectrum by combining the spectrum sensing results of different unlicensed users and making decision of spectrum sharing based on cooperative sensing and the simplest technique is to use an OR operation among the received sensing results [33], and weighted data based fusion [34]. The sensing and combining techniques based on maximal ratio combining (MRC) and equal gain combining (EGC) with the help of multiple antennas and under different fading channels are investigated in [35] and demonstrate that this method improves detection probability of the primary users.

*b) Non-cooperative spectrum sharing*

In comparison to the cooperative spectrum sharing, in this spectrum sharing method the cognitive users do not exchange any kind of information with each other [5]. However, this method of sharing is advantageous for few users network and provides less communication overhead, but in the large user network it will cause severe degradation of spectrum efficiency because of the selfish nature of each cognitive user. Since the spectrum sensing information of single user is utilized to make decision for sharing the primary licensed channel, therefore the probability of false alarm is significantly more in the non-cooperative spectrum sharing in comparison to that of the cooperative spectrum sharing method and results into the performance degradation of either primary or secondary user.

**C) Spectrum mobility**

The spectrum mobility allows the cognitive radio users to switch to other unutilized frequency band in case of primary user appearance during the cognitive radio ongoing communication. However, the primary and secondary user's mobility have incorporated complexity in the cognitive radio network spectrum design. The presence or absence of licensed channel for a stationary or pedestrian cognitive user in a particular location will be ambiguous when licensed user is moving very fast. In addition to this, the sensing decision of a particular channel in a scenario may not be accurate for the fast moving cognitive user because at the current location of cognitive user that channel availability status might be different and it would be recommended for fast cognitive users to do spectrum sensing frequently to minimize false alarm and increase detection probability of licensed channel. Moreover, efficient spectrum handoff techniques should be developed for cognitive users so that cognitive user will preempt the channel when the primary user transmission starts on that channel. Markov process has been utilized by authors to predict the behavior of primary users from its past behavior so that cognitive user will vacate the channel before primary user resumes its transmission and has avoided the forced termination of cognitive users transmission [36]. This method of vacating the licensed channel is called proactive handoff however in reactive spectrum handoff, immediately spectrum is vacated without prior knowledge to cognitive users. Moreover, cognitive users should have reserved some of the idle channels otherwise their ongoing communication will be disrupted. This reallocation of spectrum band to cognitive user can either be done by central coordinator or control channel in distributed MAC protocol. In [37], inter-cell and intra-cell spectrum handoff techniques for cognitive users have been proposed by the authors. Further, in [38], the cognitive radio spectrum mobility is discussed with the help of Poisson distribution and protocol has been proposed with inbuilt spectrum mobility feature.

### 1.1.1 Spectrum access techniques

In a shared-use model, the spectrum can be accessed by an unlicensed user or cognitive user in three different modes [5], namely spectrum interweave/opportunistic spectrum access, spectrum underlay and spectrum overlay and are discussed in detail as follows:

*a) Spectrum interweave/opportunistic spectrum access (OSA)*

At a particular time, frequency or space, if the spectrum is not utilized by a primary user, it can be opportunistically accessed by the cognitive users with the help of spectrum interweave access method [39, 40] as shown in Fig. 1.7(a). Therefore, in order to access a spectrum band using spectrum interweave technique, a cognitive user has to perform spectrum sensing to detect the activity of a primary user in that regime. If a spectrum hole that is inactive primary user is detected, the cognitive user may access that unutilized spectrum as is clear from Fig. 1.7(a). Once the primary user resumes its transmission, the cognitive user must have to vacate the spectrum. The spectrum interweave method can be used by the cognitive radio in frequency division multiple access (FDMA), time division multiple access (TDMA), or orthogonal frequency division multiplexing (OFDM) wireless systems.

*b) Spectrum underlay*

In spectrum underlay access method, the cognitive user can transmit concurrently with a primary user as shown in Fig. 1.7(b). However, the transmit power of the cognitive user should be limited so that the interference caused by the cognitive user to the primary user remain below the interference temperature [39]. The interference temperature is defined as the interference limit set at primary user's receiver up to which it can tolerate interference without affecting its operation. The spectrum underlay can be used for cognitive radio systems using code division multiple access (CDMA) or ultra-wide band (UWB) technology [5]. Therefore, in the spectrum underlay access technique, the spectrum sensing to detect spectrum hole for cognitive user transmission is not needed however, threshold level for interference avoidance should not be crossed by the cognitive user's transmission.

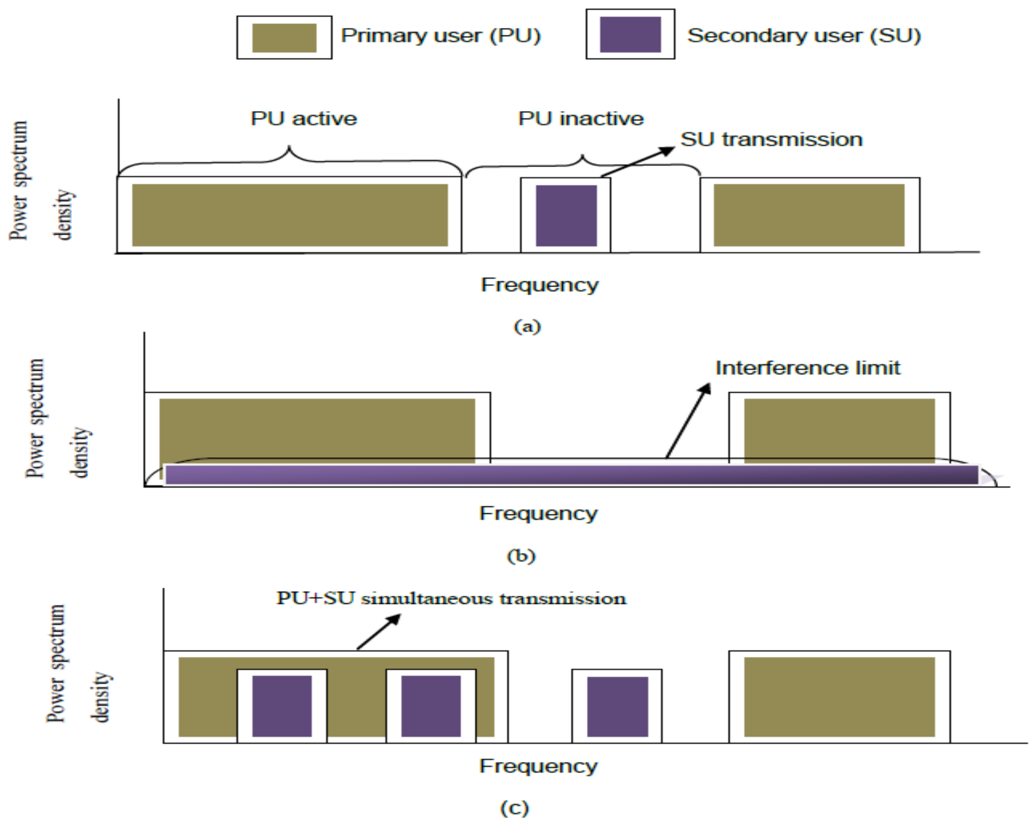



**Fig. 1.7** Spectrum access techniques (a) Spectrum interweave (b) Spectrum underlay, and (c) Spectrum overlay.

*c) Spectrum overlay*

In the spectrum overlay mode of spectrum access method, concurrent primary and cognitive user's transmission is allowed as shown in Fig. 1.7(c). However, the interference at the cognitive and primary receiver is mitigated by advanced pre-coding and interference cancellation techniques [41-43]. Although, spectrum overlay is a promising spectrum sharing technique, it requires a great degree of cooperation with primary user and knowledge of the primary user's message signal. Moreover in this technique, the cognitive user help to relay the primary user's information by utilizing some part of its power and remaining power for transmitting its own data [44, 45]. Therefore, the increase in the primary user's SNR due to relaying is balanced by the decrease in its SNR due to secondary user's interference, resulting in same SNR at primary receiver without cognitive user. Hence, primary user is unaware of the cognitive user's presence.

Moreover, the dirty paper coding [46] is used by cognitive transmitter to mitigate interference at the cognitive receiver.

### 1.2 Related Work

The spectrum sharing plays a major role in the cognitive radio communication systems and it can be performed by using various techniques. However, the implementation of a particular spectrum sharing technique depends on the QoS requirements. In this section, different sharing techniques are presented as follows [47]:

#### 1.2.1 Power control

The cognitive radios must follow the rules/restrictions to access the spectrum [5] and a management protocol as well as a reliable and scalable mechanism to allow a cognitive radio user to follow the rules, is required. However in case, the protocols are violated then proactive and reactive techniques of power control can be used to avoid this misbehavior. A proactive technique includes the rule (for example, maximum power limit) and an enforcement mechanism (power allocation). However, this proactive technique is applied before the cognitive radio users start misbehaving that is before violating spectrum access rules. On the other hand, a reactive technique is required to punish the misbehaving cognitive radio user. Since, the cognitive users coexist with the primary users in an operating spectrum, mere consideration of transmission power limits on a channel may not be sufficient [48]. The presence of primary users in the adjacent channels forces to reduce the demand for signal power transmission on an available channel for minimum adjacent channel interference. Hence, the occupancy of the neighboring channels is also a critical parameter for the improved spectrum sharing in transmit power mode. Furthermore, in opportunistic spectrum access transmission model, the cognitive user can transmit only when it detects the spectrum hole, which is the time duration that primary user is not transmitting over the band. However, in [49], the authors proposed a new spectrum sharing transmission model in which the secondary user can transmit at any time without detecting the primary user, which is active or not, but it has to restrict its transmission power so that harmful interference at the primary user is avoided. This consideration is good for the case when the perfect channel state information is not available and it operates similarly as that of Ultra-Wide Band (UWB).  However, the restriction on the transmit power decreases the transmission range of the cognitive radio user data and could not take full advantage of unutilized licensed spectrum in which it can transmit with maximum power. Therefore, the authors in [50] have proposed that the sensing is performed to vary the transmission power of the secondary user, so that when the primary user is active, the secondary user transmits with low power to avoid the interference at primary user and vice versa. In addition to this, the wrong channel information results into the degradation of cognitive radio system performance [51]. Further, the variations in transmission power and rate according to the fading conditions are discussed in [52, 53]. Kang in [54] has determined the optimal power allocation to cognitive users under Rayleigh fading environment with the assumption of channel state information (CSI) availability at cognitive users and have calculated ergodic and outage capacities closed form expressions.

Further, OFDM based cognitive radio network is also exploited by researchers/scientist and the several authors have described different methods for the allocation of optimal power to the subcarriers of cognitive radio user because of the side-by-side coexistence of cognitive and primary users. Initially, the power loading method [55] has been developed for the OFDM cognitive radio network to allocate the optimal power to the subcarriers by keeping the interference constraint satisfied and using the location information of secondary with respect to the primary users. The comparison of various power allocation methods in OFDM based cognitive radio networks are illustrated in Table 1.1. Since, fairness is one of the important parameter considered for the network performance, therefore, Wang et al. in [56] have considered the fairness of the cognitive users in the OFDM based cognitive radio network and have proposed fast optimal power and simple power distribution algorithm with complexities of $O(L^2N)$ and $O(L+N)$, respectively. Moreover, the cognitive user's capacity optimization problem has been solved in [56] with interference, fairness and total power constraints taking into account. Further, in [57], joint rate and power optimization problem has been considered in max-min and proportional fairness scenario.

Recently, a new power domain spectrum sharing method called non-orthogonal multiple access (NOMA) [58] has been explored by the researchers/scientists. Various advantages of NOMA like higher throughput due to wide bandwidth, exploitation of channel gain for optimal power allocation, has outperformed OFDM scheme [59] and is beneficial for the spectrum sharing in cognitive radio. All the users of NOMA utilize whole available bandwidth in comparison to the OFDMA where available bandwidth is divided into subcarriers which results in enhanced throughput [60] and the power allocation to cognitive users considers the channel conditions, with more transmit power allocated to the user with good channel conditions in comparison to the user with more severe environment. However, since the same frequency is utilized for all user's transmission in NOMA, therefore receiver should have capability to decode its own signal carefully and should minimize the co-channel interference. Therefore, this system is somehow complex than OFDM in terms of receiver decoding scheme. The NOMA is an efficient scheme of spectrum sharing in cognitive radio because it avoids the competition among the cognitive users of getting the specific channels out of all available channels and there is need of only power control according to the environment. The base station or central coordinator, controls the power allocation to different users, however for distributed environment NOMA concept is still open for research.

**Table 1.1** Comparison of power allocation methods in OFDM based cognitive radio networks.

| **Power allocation method** | **Description** | **Complexity** | **No. of iterations** |
|---|---|---|---|
| Gradient based approach [61] | Power allocation to the cognitive users in time varying channel with adaptive step size while transmitting in only unutilized licensed frequency band and considering adjacent channel interference. Multiple primary and cognitive users are considered. | $O(N)$ | *3* |
| Power loading scheme [62] | Consider both co-channel and adjacent channel interference due to transmission by cognitive user in active and inactive licensed frequency bands, power allocation is performed in time varying channel. | $O(NlogN)+$ $O(LM)$ | $L+1$ |
| Geometrical programming approach [63] | Considering coexistence of a primary user and multiple cognitive users in same frequency band and allocating power to cognitive users with aim of power saving. | Depends on the number of iterations. | fixed |
| Iteration minimum algorithm [64] | Single cognitive user pair and multiple primary users are considered and cognitive users transmit only in unutilized licensed channels. | $O(Tf_s logN+N)$ | *2* |

### 1.2.2 Game theory

The game theory in cognitive radio network is developed basically for the spectrum sharing through trading and fairness rules and main objective is to fulfill the cognitive network demand while maximizing revenue of the primary network. Therefore, employing game theory could effectively guarantee the fairness and rationality or the spectrum management among the cognitive radio network [65, 66]. Further, in [65] the authors have proposed the OODA (orient-observe-decide and act) method to share the primary network's spectrum among multiple heterogeneous cognitive networks with different QoS requirements and this method takes into account the behavior modeling of the cognitive users. Further, the authors in [67] have considered the varying bandwidth subcarriers of multicarrier communication network allocated to cognitive users and the utility function with aim to maximize the data rate of cognitive users with constraints on resources such as power, spectrum and bandwidth are defined. The main contribution of this work lies on the definition of utility function which is based on proportional fairness, harmonic mean fairness and maximum/minimum fairness with allocation problems. In [67, 68], the authors have considered the assumption on a node that it cannot transmit and receive on the same channel, simultaneously and have allocated the resources to competing users in ad-hoc network, however [67] solves the convex optimization problem and in [68], the resource allocation by connectivity graph coloring method is performed. The advantage of technique [67] over connectivity graph is the less iteration requirement and significantly higher throughput. However, in both schemes [67, 68] there is only one homogeneous primary user network which is utilized by the cognitive users without considering the heterogeneity of the primary user system. Further, the authors in [69] have maximized the cognitive radio links capacities by using the incremental sub-gradient optimization approach for both with and without fairness constraints and assumed that each cognitive radio user is half-duplex. In the aforementioned references [65, 67-69], the entire available spectrum from the spectrum pool is divided into orthogonal subcarriers for OFDM access scheme in order to minimize the interference and enhance the spectrum efficiency. However, through the game theoretical spectrum sharing using OFDM access scheme in ad-hoc cognitive network, Niyato and Hossain in [70] have performed sharing of licensed spectrum using TDMA mode in centralized cognitive network where all the available bandwidth is accessed by multiple cognitive users at different times. Moreover, this technique is simpler than multicarrier communication but it results the throughput degradation in comparison to the multicarrier OFDM access scheme. The article [70] emphasized on the various factors of the spectrum trading between the primary and secondary users. The spectrum trading is the process which is needed after spectrum sensing to share the sensed idle channels. In the literature, three kinds of trading markets are defined viz monopoly, oligopoly and exchange market [71]. In

[72], Nie and Comaniciu have investigated the design of channel sharing etiquette for the cognitive radio networks for both the cooperative and non-cooperative scenarios. The performances of different components of game theoretical framework for radio resource management, namely, network-level bandwidth allocation, connection-level bandwidth allocation, capacity reservation, and admission control have been analyzed in detail in [73]**.**

In addition to this, the method of spectrum sharing between various primary and secondary users based on the cost and amount of required bandwidth is explored in [74]. Further, in [75, 76] the most common application of game theory that is auction theory in cognitive radio spectrum sharing through interaction procedure between the cognitive users and primary users is discussed. The optimality solution for obtaining the equilibrium in demand and supply of the auctioned spectrum is discussed in [77]. Moreover, it has been presented that the Nash equilibrium [78] is used for non-cooperative game theory for allocating the spectrum to multiple cognitive users and Nash bargaining solution for cooperative game among cognitive and licensed users [77]. However, the static game spectrum sharing method employed for spectrum allocation in [78] has deteriorated the efficiency of wireless network because of the inefficient Nash equilibrium outcomes due to the user's selfishness of achieving its own benefit discarding overall and fair spectrum sharing. Moreover, the spectrum sharing through cooperative game theory gives single objective function of all the cognitive users and provides optimal solution by considering each user's interest called linear proportional fairness method of spectrum sharing. In multiple cognitive user's competing environment, the most common auction schemes are sequential auction or Vickrey auctions [79], however the time definite assignment of spectrum [75] makes Vickrey auction more advantageous than sequential auction for the cognitive users spectrum sharing. Moreover, single and double auction methods are also defined as the classification of auction methods [80-82]. In single auction trading method there is one seller and many buyers, and the buyer which bid highest wins the item. However, in case the number of sellers and buyers grow large, double auction is efficient method for spectrum trading. In double auction [80, 83], the sellers/buyers submit their selling/buying prices to the auctioneer (spectrum broker) and the auctioneer decides to allocate the spectrum to the specific buyer at the price higher than asked by specific seller to make profit for itself [84]. In [85], the authors have discussed the double auction in primary and cognitive radio networks with the primary and secondary users being the bidders of the available channels. Furthermore, the author's in [85] have considered that the broker will allocate the single channel to only one primary user network and to single/multiple cognitive user networks with primary network having higher priority than the cognitive user networks. Moreover, the benefit primary user network will get after trading the spectrum to cognitive network depends upon amount of spectrum and the amount of time the allocation is performed. However, in order to get more benefit, the primary network should not deteriorate its own user's services. Therefore, Chang and Chen in [75] have considered the QoS of primary users through its blocking rate to ensure proper allocation. In [75], the benefits of primary users, cognitive users, regulatory system and service provider have been considered and a super-frame structure of cognitive users for competing with each other is explored. Vickrey auction scheme based on SINR and power is discussed in [75] and the min-max fair SINR allocation is performed for cognitive game spectrum allocation. Instead of pricing and auction theory, revenue based sharing is proposed in [86] in which revenue shared by primary user network depends on the resources allocation among the primary and cognitive users.

### 1.2.3 Multiple antennas

The concept of multiple antennas has also been exploited as a potential method for spectrum sharing in the cognitive radio communication system due to throughput enhancement and interference cancellation. A system model for the cognitive radio network, where multiple antennas are implemented at cognitive user transmitter is presented in [87], which provides the significant enhancement in the channel capacity as compared to the single antenna at cognitive user transmitter. In addition to this, it is also able to transmit on the same spectrum which primary user is currently using due to the multiple antennas beam-forming [88]. Moreover, the multiple antennas are used to allocate the transmit dimensions in space and hence provides the cognitive transmitter more degrees of freedom in space in addition to the time and frequency to balance between maximizing its own transmit rate and minimizing the interference powers at the primary receivers. Two algorithms direct- channel singular value decomposition (D-SVD) and projected-channel SVD (P-SVD), which enhance the cognitive radio user capacity and avoid the interference at primary receiver by projecting null to the primary receiver through beam-forming, respectively, are proposed in [87]. Bakr et al. [89] have used the antenna weights to place nulls at the primary receivers whereas the secondary radio receivers use adaptive techniques to decode in the presence of interference from the primary users. To obtain the antenna weights, the channel estimation is performed through feedback from the primary receivers and uses these estimates to compute the appropriate antenna weights. The antenna weights are then adapted by the cognitive radio transmitter antennas to form the radiation pattern which nullify the interference at primary receiver and provide efficient communication to its respective cognitive radio receiver.

Further, in [90, 91] the authors have discussed about the characteristic function and its application in computation of the channel capacity under fading environment with multiple antennas. Moreover in [92], MGF (moment generating function) and characteristic function (CF) is used to compute the error rate as well as channel capacity. The fading channel capacity using the MGF approach [93-96] in multiple antennas scenario with different correlation coefficient in the fading environments has been formulated in [97]. Moreover, the authors of [98] have considered the cognitive radio spectrum sharing scenario without conventional constraint in the sharing environment that is on the cognitive users transmit power and primary user received interference power, and have interpreted that this results without degradation of the cognitive or primary services due to the linear processing of the channel gains in multiple antennas spatial domain. The authors have also considered the imperfect CSI effect on the system performance, however the proposed method is not suitable for the cognitive users sharing full-duplex primary user spectrum. In addition to this, the authors of [99] have calculated the single cognitive user system capacity by considering the interference constraint at primary receiver and hence need to limit it's transmit power. Moreover, the multiple antennas are considered at both cognitive and primary users. However, the pre-whitening instead of post-whitening multi-antenna spectrum sharing technique is considered for cognitive users which have reduced the amount of interference at primary receiver in comparison to the post-whitening scheme. Further, the underlay multicast method of spectrum sharing in cognitive radio has been proposed in [100] using multiple antennas only at cognitive access point, then broadcast the same information to all cognitive receivers with beam-steering and limit the side-lobe power to the primary receiver. However, the perfect CSI is needed in [100], otherwise, coexistence of cognitive and primary users in the same spectrum might degrade both primary and cognitive user performance. In addition to this, Sridharan and Vishwanath in [101] have derived the multiple input multiple output (MIMO) cognitive channel (MCC) capacity with CSI knowledge at cognitive user. However, there is transmit power limit at both primary and secondary transmitter and MCC capacity is maximized by considering these two transmit power constraints at both transmitters, with the help of Lagrange's optimization. Since the cognitive user system does not want to change the primary user network and should not impose any restriction on the primary network, therefore the primary user transmit power constraint [101] is not the feasible solution to enhance the cognitive radio system performance. In [102], Adian, and Aghaeinia have jointly considered the transmission time and power allocation to the heterogeneous cognitive users in centralized and distributed cognitive network. In addition to this, the authors also have considered multiple antennas advantage with constraint of resource allocation fairness in heterogeneous cognitive user network. Recently, a new multiple antenna channel model called cognitive interference channel instead of classical interference channel has been considered in [103] where the cognitive transmitter is provided with the knowledge of the primary user data. This extra information at cognitive transmitter helps to know about the neighboring nodes.

### 1.2.4 Medium access control (MAC) protocol

Traditionally, in the spectrum sharing, the users get access to the channel through medium access control (MAC) protocol. The difference in MAC protocol of traditional wireless communication and cognitive radio system is that multiple channels have to be shared by the multiple cognitive users instead of the single channel sharing by multiple users in conventional MAC protocols. In addition to this, the cognitive users have to differentiate between the primary user and cognitive user transmission so that it has to decide whether to stop transmission to protect primary user or to retransmit in case of interference with other cognitive user. The available licensed channels for communication vary with time and location, due to this reason each cognitive user does not have fixed number of channels for transmission. All these functioning have to be incorporated into MAC protocol of the cognitive radio communication system. Since, the cognitive user has intelligence capability and is able to switch among multiple channels and therefore, it is necessary in the cognitive radio MAC protocol spectrum sharing technique that the sensing and switching features have to be incorporated. In addition to this, there may be multiple cognitive radio users trying to access the spectrum, therefore the cognitive radio network MAC protocol access should be coordinated to prevent multiple users colliding in overlapping portions of the spectrum. The cross-layer design and optimization methods [104, 105] for the cognitive radio have been provided to mitigate the layered protocol and structure limitations. The physical layer directly deals with the physical environment/channel that is followed by the MAC layer, which needs great attention for the design of communication system, and various parameters of this layer are frame type, frame size, data rate, channel/time slot allocation, scheduling scheme, retransmission probability etc. All these parameters of MAC layer are the part of MAC protocol and are responsible for the spectrum sensing and spectrum access decisions [106]. The major objectives of cognitive MAC protocol design are:

a) To optimize the spectrum sensing and spectrum access decision,

b) To control the multiuser access in the multichannel network, and

c) To allocate the radio spectrum and schedule traffic transmission.

For DSA-based cognitive radio networks, MAC protocols which have been designed for traditional wireless networks need to be modified to include the spectrum sensing and spectrum access. The design of MAC protocol for cognitive radio is a very challenging task due to the requirement for the coexistence of cognitive users with licensed users [106] and such a protocol needs to achieve the highest spectrum utilization by detecting all the spectrum opportunities accurately to access the spectrum so that the collision with the other cognitive users has to be minimized. However depending on the channel quality, the transmission parameters such as modulation and coding level can be adapted at the MAC layer. Various ideas have been discussed to use some optimization model [106-108] for optimizing the spectrum sensing and spectrum access decisions. In [106], Kim and Shin have discussed the mechanism for sensing period optimization and idle channel discovery delay reduction by the cognitive users. However in [107], POMDP (partially observable Markov decision process) is employed for accessing the licensed channels by cognitive users. The MAC protocol has to select the best available channels to sense and based upon different channels sensing results, the cognitive radio user decides which channel has to access for the data transmission. This decision is based on the objective to maximize the transmission rate, and the constraints like the interference with a licensed user must be lower than the threshold. Considering the hardware constraints such as single radio, partial spectrum sensing and spectrum aggregation limit, the hardware constraint-MAC (HC-MAC) [108] has been proposed for an efficient spectrum sensing and access decision. The model is applicable for single or multiple channels/single or multiple users however it suffers from multichannel hidden terminal problem [108]. Further, MAC protocols for multichannel and multiuser cognitive radio system have been discussed in [109-114]. Moreover, the main objectives of these protocols are to perform negotiation among the cognitive users for spectrum access in the multichannel environment and to avoid collisions due to the simultaneous transmissions. In [109], the cognitive MAC (C-MAC) protocol is proposed for the distributed cognitive radio network in which there is no central entity like base station available for the coordination among the cognitive radio terminals. In C-MAC, each available licensed channel is scheduled, which is divided into super-frames that consist of consecutive beacon and data transmission period. A rendezvous channel (RC) is assumed to be available throughout the network operation, which provides the synchronization and coordination among the cognitive users through non-overlapping beacon periods. There is backup channel also, which is detected during the sensing and is used to immediately provide choice of alternate spectrum band in case of the appearance of primary user. However, each cognitive radio user periodically visits RC for sharing of load information of each band for: 1) synchronization, 2) to gather the information about primary and secondary user's discovery, 3) to avoid the hidden node problem and, 4) to exchange the schedules for beacon periods so that beacons are not simultaneously sent over all the spectrum bands. Further, each cognitive terminal that wants to send data to its intended receiver will first send beacon signal during its designated beacon slot, coordinate with other users and once synchronized then can transmit over assigned channel. However, any spectrum change by the cognitive terminal that occurs in C-MAC must first be announced over the RC so that other cognitive users will also know about this change. Therefore, to set up an RC which is available throughout the cognitive network is a very important issue. However, this protocol has some technical issues such as to setup non-overlapping beacon, quiet periods without any central entity and RC availability [109]. In addition to this, the network synchronization must needed in C-MAC and requirement for beacon control infrastructure makes it more complex. However, it is free from the hidden terminal problem as in the case with HC-MAC [108]. The cognitive radio enabled multi-channel (CREAM) MAC protocol has also been discussed in [110], which is free from hidden-terminal problem and network synchronization however there is large communication overhead in this MAC protocol.

Further, the opportunistic spectrum access – MAC (OSA –MAC) for distributed cognitive radio network is proposed in [111] which is somehow similar to the architecture of IEEE 802.11 ad-hoc MAC protocol however, the functioning is different than WLAN IEEE 802.11 MAC [115] as further explained. In the OSA-MAC, there is one dedicated control channel for cognitive users to exchange the control information, which is owned by the cognitive user service provider. The time of each channel is also divided into beacon intervals and all the cognitive users are synchronized with periodic beacon transmission. Each beacon interval consists of three phases namely, the channel selection phase, sensing phase and data transmission phase [111]. The cognitive user transmitter first sends ad-hoc traffic indication message (ATIM) over the control channel to its receiver which contains the licensed idle channels list that it wants to use for data transmission. With the agreement on the selected channel, the cognitive receiver fed back ATIM-ACK (acknowledgment) to the transmitter over control channel, after that cognitive user switches to the selected channel and start sensing it continuously during the sensing phase. However, if there is no primary user detected on the selected channel then data is transmitted during data transmission phase otherwise with the detection of primary user, the cognitive radio switches back to the control channel. The major limitation of OSA- MAC is large overhead before the actual data transmission in which the data of cognitive user is transmitted after request-to-send (RTS) and clear-to-send (CTS) message exchange with respective receiver which is preceded by the amount of time at which the back-off timer has expired. There is bandwidth wastage also during ATIM window in OSA-MAC.

In addition to this, an error adaptive MAC protocol [112] has been proposed with switching of error recovery and dual transmission modes according to the channel status of cognitive radio network. Moreover, the additional channels detected during the sensing are utilized for error recovery in poor channel conditions and for increasing the throughput in good channel states. However, this protocol makes the receiver systems more complex due to precise channel estimators and need more than one transceiver for utilizing large number of idle channels. Recently, a self-scheduling multi-channel cognitive radio-MAC (SMC-MAC) [116] protocol for the distributed cognitive radio network has been proposed, in which the cooperation among the cognitive users has minimized the sensing time and has enhanced the throughput. However, the technical issues needed to be handled in this protocol are the collisions of cognitive users in contention interval and the bandwidth wastage over the licensed channels during sensing-sharing and contention period [117]. Furthermore, a dynamic common control channel (DCCC) based MAC protocol has also been proposed in [118] for cellular cognitive radio network. In addition to this, an opportunistic matched filter based MAC [119], the prioritized cognitive radio MAC (PCR-MAC) [120], cooperate and access spectrum sharing protocol [121], distributed sequential access MAC (DSA-MAC) [122] and cognitive adaptive MAC (CAMAC) [123] have been proposed recently and comparison of various MAC protocols are shown in Table 1.2. Further, the impact of selfish users on the MAC protocol fairness has been considered in [124] using Jain’s fairness index [125].

There is significant scope for devising protocols that adapt the cognitive radio transmissions based on the type of the interferer. The newer performance metrics that capture the cognitive radio specific improvements should be devised and used for evaluating different MAC protocols. However, we believe that MAC protocol design for cognitive radio is an open area of research and will be of interest to both the industry and the academia as this technology matures in the next few years.

**Table 1.2** Performance comparisons of various cognitive radio MAC protocols.

| Protocol | MAC technique | Spectrum access technique | No. of transceivers | Dedicated control channel | Synchronization needed | Hidden terminal problem |
|---|---|---|---|---|---|---|
| HC-MAC [108] | Contention based | Interweave/OSA | 1 | Yes | No | Yes |
| C-MAC [109] | Polling based | Interweave/OSA | 1 | Yes | Yes | No |
| CREAM-MAC [110] | Contention based | Interweave/OSA | 1 with multiple sensors | Yes | No | No |
| OSA-MAC [111] | Contention based | Interweave/OSA | 1 | No | Yes | No |
| Error adaptive MAC [112] | Contention based | Interweave/OSA | More than one | No | No | Yes |
| SMC-MAC[116] | Contention based | Interweave/OSA | 1 | Yes | No | No |
| PCR-MAC [120] | Contention based | Interweave/OSA | 2 | Yes | No | No |
| Cooperate and access spectrum sharing protocol [121] | TDMA based | Overlay | 1 | No | Yes | Yes |
| DSA-MAC [122] | Polling based | Interweave/OSA | 1 | No | Yes | No |
| CAMAC [123] | Contention based | Interweave/OSA | 1 | Yes | No | No |
| MMAC-CR [126] | Contention based | Interweave/OSA | 2 | Yes | Yes | No |

### 1.3 Problem Formulation

The potential challenge in spectrum sharing is to have significantly improved spectrum efficiency without losing the advantages associated with static spectrum allocation. Spectrum policy domain should develop policies for spectrum sharing that leads to efficient spectrum use, protect the rights of license holders and maintains the quality-of-service. There are also significant economic considerations such as the policies must protect the interests of primary users, who have made significant investments in the infrastructure. However, in all the spectrum decision and sharing techniques, channel is considered as a spectrum unit and the development of a protocol/ set of rules is crucial issue. Generally, the common control channel facilitates many spectrum sharing functionalities, however channel must be vacated when a primary user returns, and then implementation of a fixed common control channel is not feasible. Moreover, in cognitive radio networks a channel common to all users is highly dependent on topology and varies over time. Therefore, the solution of this issue is also very crucial in cognitive radio communication systems.

Further, the spectrum sharing in the cognitive radio network is highly dependent on the number of users in the system. More cognitive users increases competition and may decrease the cognitive radio network performance. Therefore, it is necessary to have highly scalable spectrum sharing cognitive system. Moreover, the energy efficient cognitive radio terminal is the need of cognitive communication network and to have an energy efficient cognitive radio network is a challenging task. Since, the user's terminal has limited battery life and the cognitive radio user's sensing also consumes energy in addition to its data transmission therefore, the spectrum sharing techniques should enhance the performance with minimum energy consumption. In addition to this, as we know that the cognitive radio works on unutilized licensed channels and has lower priority than licensed users, therefore the blocking probability of cognitive radio communication is high which creates severe problem, particularly for the real time cognitive radio user's traffic. The sharing methods should be designed carefully in cognitive radio network which will fulfill QoS requirements of the cognitive users.

The main problem addressed in this thesis is how to efficiently share the spectrum of licensed users with cognitive users. Since, the potential scope of the methods of sharing the spectrum is very broad and is also discussed in the previous section of this chapter, however the scope of this thesis is limited to the second layer of the OSI (open systems interconnection) model for spectrum sharing. More specifically, the objective of this research work has been to deploy the

MAC protocol for the multichannel distributed cognitive radio network. The motivation of this research work is from the work proposed by Stevenson et al. in [127] which have standardized the cognitive MAC protocol (IEEE 802.22) for centralized cognitive radio network, however, for the distributed cognitive network, MAC protocol is not yet been standardized. Another important goal is to design the suitable frame structure for the cognitive radio system in the primary user interfering environment. The key performance indicators of the system are the throughput and energy efficiency and have been computed for the proposed system. Moreover, since the sensing errors result the severe effect on the performance of cognitive radio and primary user's communication system, therefore it is another important parameter to be discussed for the design of cognitive radio MAC protocol. Furthermore, the cognitive users are unlicensed users and should not cause any interference to the licensed users, therefore, transmit power control algorithm should be there for avoiding the degradation in the primary user network and also to enhance the energy efficiency of the cognitive users. Since the channel has fading phenomenon and fading consideration is very important for designing a communication system. Therefore, the spectrum sharing in the fading environment of cognitive radio system is also an important issue to be discussed.

## 1.4 Thesis Organization

The remainder of this thesis is organised as follows. In Chapter 2, we have proposed a novel multichannel cooperative MAC protocol for the distributed cognitive radio network which has back-off algorithm for contention solving among the competing cognitive users. The back-off algorithm for resolving collision among the competing users has allowed the collided cognitive users to become successful by selecting another contention slot from the increased contention window. The increased number of successful users has enhanced the throughput of the cognitive radio network by transmitting their data over the detected idle licensed channels. Moreover, the optimum number of contention slots have been achieved which has maximized the number of successful cognitive users as well as throughput. Furthermore in Chapter 3, the effect of imperfect sensing on the proposed distributed cognitive radio MAC protocol is considered. Imperfect sensing by the cognitive radio results in the false alarm and miss detection which affects the idle channels availability to cognitive users and primary user's degradation due to interference, respectively. False alarm probability has resulted in the less number of idle channels detection in comparison to the perfect sensing scenario and hence has degraded the throughput of the cognitive radio network. Moreover, Chapter 3 has also computed the energy efficiency of the proposed MAC protocol in perfect and imperfect sensing scenario. Furthermore in Chapter 4, the potential issue of bandwidth wastage which arises in the proposed distributed cognitive radio MAC protocol is also dealt with the significant improvement in the proposed scheme. In Chapter 4, it is proposed that significant enhancement in the throughput occurs in the proposed MAC protocol, if sensing-sharing and contention interval bandwidth is also utilized for the data transmission.

In addition to this, in Chapter 5 we have proposed an algorithm for computing the optimum transmit power of the cognitive radio users and maximizes the energy efficiency. The cognitive user energy consumption in the proposed MAC protocol that is the energy consumption in sensing-sharing, contention, and data transmission interval are also computed in the Chapter 5. We have also proposed a frame structure in Chapter 6 to reduce the data loss rate and eliminate the sensing-throughput trade-off problem of the earlier proposed frame formats of cognitive radio user.

Moreover in Chapter 7, we have numerically computed channel capacity of the cognitive user in fading environment under the average interference power constraint with two different adaptation policies namely, adaptive power and adaptive rate and power adaptation in multilevel quadrature amplitude modulation (M-QAM) format. Finally, Chapter 8 concludes the thesis and has presented the future direction in cognitive radio technology.

# CHAPTER 2

## Proposed MAC Protocol for Distributed Cognitive Radio Network

### 2.1 Introduction

Recently, the spectrum scarcity has become bottleneck for the development of wireless communication. In addition to this, the growing numbers of unlicensed wireless devices have overcrowded the Industrial-Scientific-Medical (ISM) band of the radio frequency spectrum. Therefore to alleviate the spectrum utilization pressure on the affected spectrum bands, the cognitive radio constantly senses and accesses the spectrum opportunities in the whole radio spectrum. A key challenge in the cognitive radio network is to have an efficient sensing and non-interfering spectrum access decision, which enable the cognitive users to reserve chunks of the spectrum for certain periods of time. However, the modeling of variable bandwidth communication in the cognitive radio is very complicated and the channel accessing policies have to be defined for the cognitive radio users. In this chapter, we have proposed a novel medium access protocol that is MAC protocol for the distributed cognitive radio network which defines the cognitive radio access policies for the unutilized spectrum.

Various MAC protocols for the distributed cognitive radio network have been proposed by different researchers/scientists [108-114, 116, 118-122], which have been discussed in detail in Chapter 1. However, the technical issues of some of the protocols proposed in [108-110, 116] for distributed cognitive radio network are described as: 1) hidden terminal problem in the hardware constrained-MAC (HC-MAC) protocol [108], 2) the synchronization requirement among the cognitive users in cognitive MAC protocol (C-MAC) [109], 3) large communication overhead before data transmission in the cognitive radio enabled multi-channel (CREAM) MAC protocol [110], and 4) contention interval access scheme and its severe effect on the throughput of SMC-MAC protocol [116]. These technical problems are rectified in the proposed MAC protocol in this chapter and have provided significant enhancement of the throughput in comparison to that of the SMC-MAC protocol. We have implemented back-off algorithm for contention solving among the cognitive users and hence reserve the idle licensed channels for the data transmission. In the proposed multichannel cooperative MAC protocol for the distributed cognitive radio network, the cognitive users share the sensing results with each other over control channel and available licensed channels along with control channel are divided into cycle-time consisting four intervals that are: 1) idle interval, 2) sensing–sharing interval, 3) contention interval, and 4) data transmission interval. However, in the reported SMC-MAC [116] protocol, the less number of contention slots during the contention interval result significantly more collisions and the large contention slots increases successful cognitive users while decreasing the data transmission interval, since the total cycle time is fixed. Hence, less data transmission time results the less amount of throughput which is the major limitation of SMC-MAC protocol [116]. In addition to this, in SMC-MAC protocol it has not been possible that the collided cognitive users in the contention interval can once again select other contention slot to be successful in the current cycle-time and therefore they have to wait for the next cycle-time to become successful for data transmission. However, the proposed method in this chapter has applied the back-off mechanism to resolve the aforementioned problem by allowing the collided cognitive users to again select the contention slot in the same cycle-time to become successful. Also, we have optimized the number of contention slots to make all users successful in comparison to that of SMC-MAC protocol. Therefore, more number of cognitive users became successful and significantly more data is transmitted in the proposed method in comparison to that of the SMC-MAC protocol.

The remainder of chapter is organized as follows. In Section 2.2, the system model of the proposed MAC protocol has been described. Section 2.3 has shown proposed algorithm for contention solving among users in the cognitive radio network. Moreover, performance analysis of the proposed MAC protocol has also done in Section 2.3. Further in Section 2.3, numerical simulation results of the proposed MAC protocol have been presented and finally, Section 2.4 concludes the chapter.

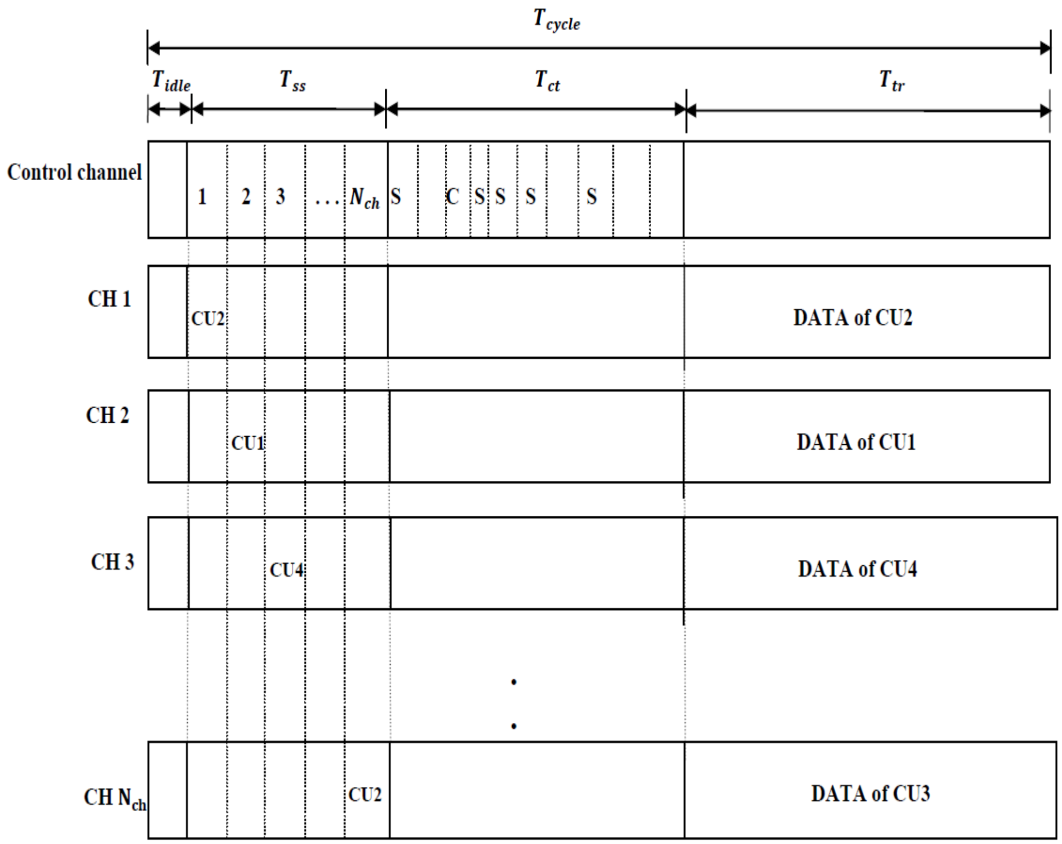
## 2.2 MAC Protocol and System Design

### 2.2.1 System model

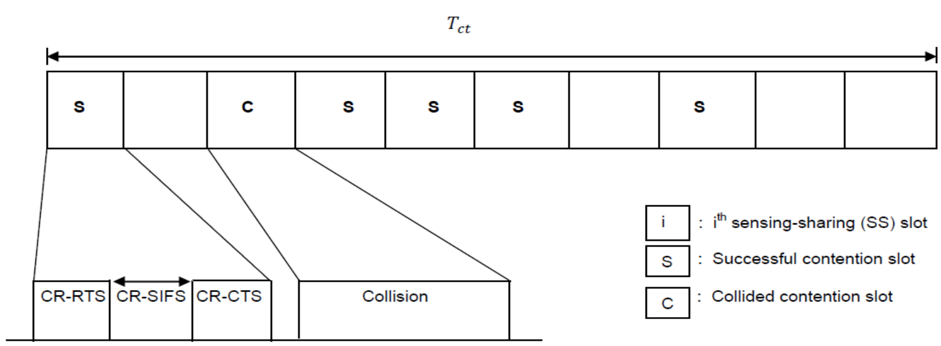
In the proposed system model, we have considered a primary user network having $N_{\mathrm{ch}}$ number of licensed channels and a cognitive radio network comprising of $N_{\mathrm{CU}}$ number of cognitive users. The primary user network is assumed to be cellular network and the traffic of cellular network is based on Poisson distribution which has been reported by researchers in [128]. Cognitive users utilize licensed channels of the primary network for communication applications at the time when they (licensed channels of the primary network) are idle. It is also assumed that the sensing performed by a cognitive user is perfect so that there are no probabilities of false alarm and miss detection [13] in the sensing results. In addition to this, control channel is assumed to be always available to the cognitive network and the cognitive user terminal is equipped with single transceiver (full-duplex mode) which can change frequency to switch among multiple channels. However, if a cognitive user wants to transmit/receive its data on/from different idle channels simultaneously, it should have multiple transceivers. Furthermore, to increase the performance of cognitive radio system, it is desirable that a cognitive radio user should sense as many licensed channels as possible. Since, we know that there are different sensing techniques in cognitive radio system and each technique requires some mathematical computation [129] of the received signals to detect the presence or absence of primary user, therefore as more and more licensed channels are sensed by a cognitive radio terminal there is increase in the complexity and power consumption of the terminal. This results into the tradeoff between number of sensed channels and complexity or power consumption. However, based on this consideration, we have attempted to limit the number of channels sensed by each terminal and allowed the sharing of sensing results with other cognitive users so that more number of licensed channels information is available at each cognitive terminal in comparison to the channels which it has sensed.

### 2.2.2 Proposed MAC protocol

The proposed MAC protocol consists of a control channel on which cognitive users cooperate with each other and $N_{\mathrm{ch}}$ licensed channels as shown in Fig. 2.1(a). The control channel cooperation among the cognitive users is performed by presenting all the sensing results of cognitive users on the control channel and then the idle channel/channels from the pool of total available idle channels, whose information are available on the control channel, have been selected by the cognitive users. Each channel is divided into cycle time, $T_{\mathrm{cycle}}$ as has been discussed in introduction of this chapter, which is further divided into four intervals: idle interval ($T_{\mathrm{idle}}$), sensing–sharing interval ($T_{\mathrm{ss}}$), contention interval ($T_{\mathrm{ct}}$), and data transmission interval ($T_{\mathrm{tr}}$) as shown in Fig. 2.1(a). Moreover, it is assumed that for idle and sensing-sharing interval, all cognitive users are tuned to the control channel. In addition to this, the cognitive users compete in contention interval to reserve the idle licensed channels and then tuned to the selected idle channels. The sensing-sharing and contention intervals are further divided into number of slots [116] as shown in Fig. 2.1 and Fig. 2.2. The sensing-sharing interval has number of slots equal to the number of licensed channels and each cognitive user randomly selects sensing-sharing slots in order to sense the selected slot number licensed channel during that slot period.



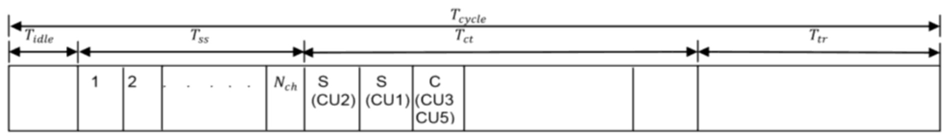

(a)



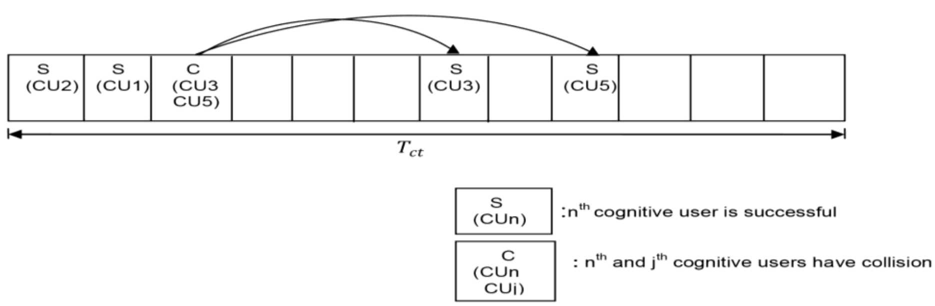

(b)

**Fig. 2.1** The proposed distributed cognitive radio MAC protocol (a) system model consisting of multiple licensed channels and control channel for cooperation among cognitive users (b) contention interval expansion of control channel.

Let us consider there are 20 licensed channels in the network and each cognitive user can sense two licensed channels therefore, the number of sensing-sharing slots are 20 and out of these 20 slots whichever slots the cognitive users randomly select, they start sensing to the selected slot number channel. For example, as shown in Fig. 2.1 second cognitive user has selected the first and last slots randomly, therefore this user senses first licensed channel during first sub-slot and sensing information is broadcasted in second and third sub-slot of first slot as described in Fig. 2.3. Since, all the other cognitive users are tuned to the control channel which hears the broadcasted sensing information in first slot and therefore stores the channel status information of first licensed channel. Similarly, in the last sensing-sharing slot, again second cognitive user senses last licensed channel that is twentieth licensed channel and shares the sensing information about the availability of this channel with other cognitive users.




(a)




(b)

**Fig. 2.2** The control channel structure of (a) the SMC-MAC protocol [116] without the back-off algorithm during the contention interval and (b) the proposed scheme with the back-off algorithm during contention interval.

Moreover, other cognitive users also randomly pick two slots for sensing the respective licensed channels and hence, cognitive users cooperate by sharing the sensing results with each other in sensing-sharing interval. Furthermore, it is also possible that more than one user senses the same licensed channel by selecting same slot during the sensing-sharing interval, however sensing of the same licensed channel by two or more cognitive users is not a problem but broadcasting the same information by the users on the same channel simultaneously causes corrupted sensing information. Therefore, to avoid this problem, we have considered that the cognitive user, after sensing a channel during first sub-slot of the selected sensing-sharing slot, will randomly wait for some time during second sub-slot in order to broadcast sensing information. During this random waiting time of second sub-slot, if the cognitive user hears any transmission, it would know that another user has also selected the same channel for sensing and is broadcasting the sensing information over the control channel, therefore the cognitive user will not transmit its own sensing information to avoid collision and get that channel sensing results from the already broadcasted information. However, it is out of the scope of our proposed work that how each user select the random waiting time during second sub-slot to avoid collision. This procedure of sensing and sharing is performed by all the cognitive users during their selected slot and hence each cognitive user has sensing information of the channels sensed by it and also by the other users, which resulted the reduced sensing time.

Further, the cognitive users compete for reserving the idle licensed channels, detected by cognitive users in sensing-sharing interval, by selecting a contention slot from the contention interval. A cognitive user is able to send a frame successfully in the transmission interval of the idle licensed channel only if that cognitive user is not having a collision with other cognitive users in the contention slot, which is possible only if each transmitting cognitive user has selected different contention slot in the contention interval. The collision by a cognitive user is detected by listening to the cognitive radio Clear-to-Send (CR-CTS) frame which has been sent by the destination cognitive user in response to the cognitive radio Ready-to-Send (CR-RTS) frame transmitted by the source cognitive user. These CR-RTS and CR-CTS frames have been sent over the selected contention slot in the control channel, and it is obvious that if more than one source cognitive user has selected the same contention slot they will not receive CR-CTS frame correctly, and hence detect collision. This probability of collision is significantly high if the number of contention slots is limited and the cognitive users are significantly more. However, the large number of contention slots although increases the success rate of cognitive users in the cognitive radio network but simultaneously decreases the data transmission interval and hence throughput of the cognitive network. Hence, there is contention slots-throughput tradeoff problem in the SMC-MAC protocol [116]. Since, a cognitive user during its selected contention slot knows the already reserved idle channels by other users because of the exchange of CR-RTS and CR-CTS frames on the control channel and will not request to utilize those idle channels on its own CR-RTS frame. Hence, the possibility of reserving same idle channel by more than single user is avoided due to the cooperation over control channel during contention interval. On the CR-RTS frame, the source cognitive user send list of available idle channels to the destination cognitive user. However, it might be possible that at the destination cognitive user location all those channels are not idle due to hidden terminal, therefore the destination user sends CR-CTS frame with selected idle channel which is available at both the transmitter and receiver on which they will transmit data during the data transmission interval. The CR-RTS and CR-CTS frame's structure with different fields have been discussed in detail in [116]. In the proposed MAC, the cooperation of cognitive users is shown in Fig. 2.1(a) where the data of third cognitive user (CU3) is transmitted on channel $N_{ch}$ which is sensed idle by the second cognitive user (CU2) in sensing-sharing interval. This is because channels sensed by third cognitive user during sensing-sharing interval are not detected idle as that by the second cognitive user which has detected both channel 1 (CH 1) and channel $N_{ch}$ (CH $N_{ch}$) idle and therefore third cognitive user utilized the extra idle channel of second cognitive user for data transmission.

Further, Fig. 2.1(b) shows the detailed description of contention interval. The inter-frame spacing between CR-RTS and CR-CTS frame is given by CR-SIFS as that in IEEE 802.11 [115]. In SMC-MAC [116], it has been proposed that each cognitive user randomly chooses a contention slot which makes it more vulnerable to collision among the cognitive users. So in order to reduce the number of collisions, we have modified the control channel's contention interval as shown in Fig. 2.2(b) by using the back-off algorithm in the contention interval. By taking an example, it has been shown in Fig. 2.2(a) that the cognitive user 3 (CU3) and cognitive user 5 (CU5) are having collision during $T_{\text{ct}}$ in SMC-MAC and hence cannot reserve the licensed channels during the current $T_{\text{cycle}}$. However, in the proposed method, the performance can be improved by modifying the control channel as shown in Fig. 2.2(b) which allows collided cognitive users to select another contention slot in the same $T_{\text{cycle}}$. In Fig. 2.2(b), the cognitive user 3 (CU3) and cognitive user 5 (CU5) after collision again selects a contention slot from the contention window with the help of back-off algorithm and if the selected contention slots are different, both the cognitive users become successful and transmits its data in data transmission interval. However, if again there is collision due to selection of same slot from the increased contention window, then the contention window size is further increased and same procedure is followed. This whole procedure has been presented with the help of flow diagram shown in Fig. 2.3. Since, we have considered that the cognitive user is having full-duplex capability, so a cognitive node can simultaneously transmit and receive. The selection of licensed idle channel by the cognitive user during the contention interval switches the cognitive node to the selected channel.

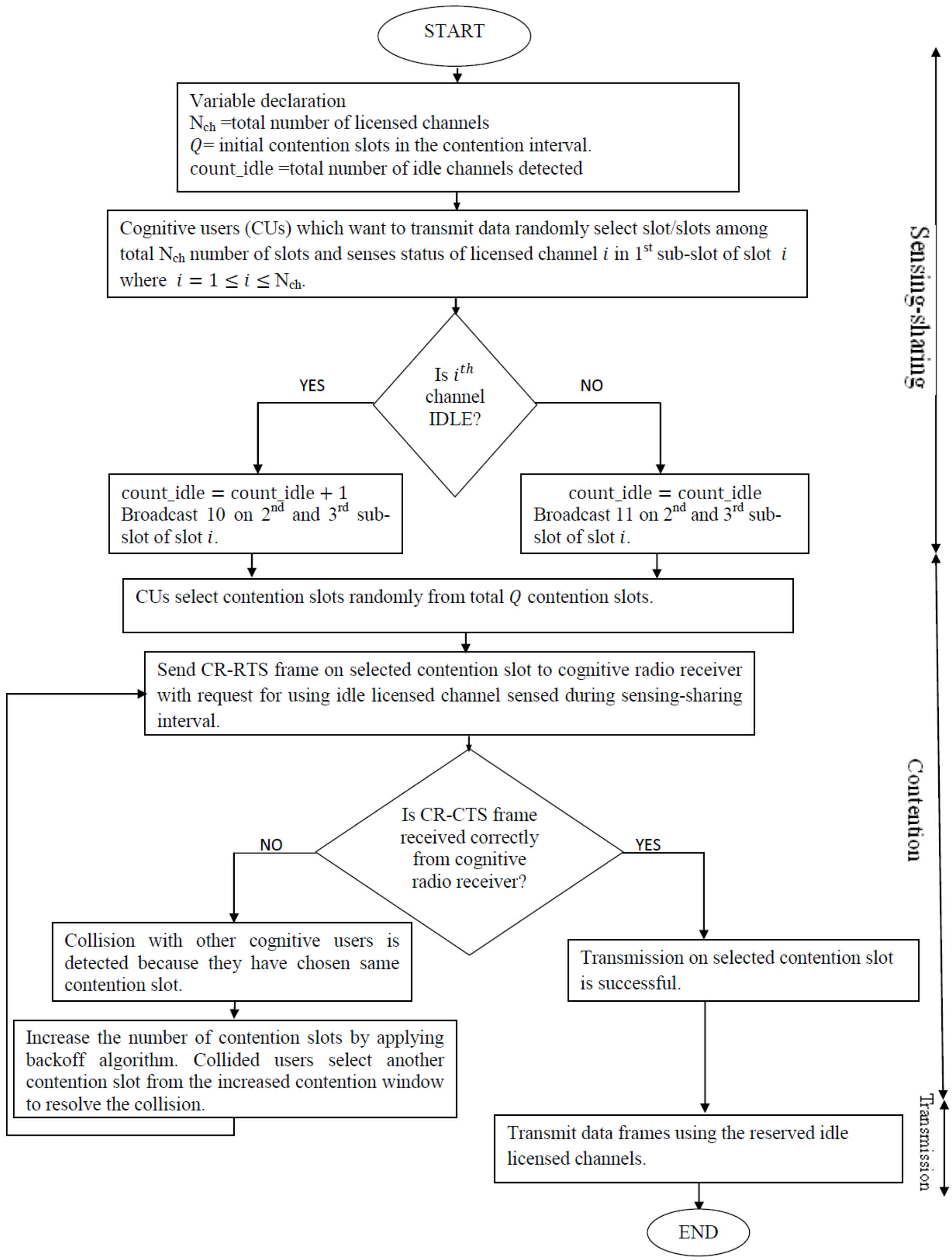



**Fig. 2.3** The flow diagram of the proposed MAC protocol.

Further, if the primary user signal has been sensed by the cognitive node on the selected licensed channel in the data transmission interval, the node stops transmission of its own signal to protect the primary user on that channel. Since the sensing is performed almost throughout the cycle time by cognitive node, however, during the sensing- sharing interval the sensing results are also shared with other users to incorporate cooperation and enhance performance of the cognitive network.

### 2.3 Performance Analysis

In this section, the numerical analysis of the proposed MAC protocol is performed and different parameters of the cognitive network are discussed. For fixed number of channels sensed by each cognitive user, idle channels detected by cognitive users are computed in sensing-sharing interval. Moreover, the successful users after contention in the contention interval are computed and throughput of the cognitive users which have successfully reserve the idle channels for data transmission is computed.

#### 2.3.1 Sensing-sharing analysis

In [128], the behavior of cellular communication system subscribers, which follows the Poisson distribution and exponentially distributed arrival time between two calls, is discussed. The Poisson process is a Markov process with state transitions limited to the next higher state or to the same state and having a constant transition rate. Therefore, for the given Poisson distribution of primary network cellular calls, with inter-arrival time T and average rate $\lambda$, the distribution of waiting times between successive calls is computed using the cumulative distribution function (CDF) [128]:

$$p_{\mathrm{i}} = P\left(T \leq T_{\mathrm{cycle}}\right) = 1 - P\left(T > T_{\mathrm{cycle}}\right) = 1 - exp\left(-\lambda\, T_{\mathrm{cycle}}\right)$$

where $p_{\mathrm{i}}$ is the given probability of cognitive user interfering with the primary user and $T_{\mathrm{cycle}}$ is the maximum interference time that a cognitive user is allowed to interfere with the primary user. Hence, the $T_{\mathrm{cycle}}$ is computed as:

$$T_{\mathrm{cycle}} = -\frac{ln\,(1-p_{\mathrm{i}})}{\lambda}$$

Further, the $i^{\mathrm{th}}$ licensed channel utilization is represented by the probability $\alpha_{\mathrm{i}}$, where $1 \leq i \leq N_{\mathrm{ch}}$ and we have assumed that on average the total utilization probability of each channel is:

$\alpha = \frac{\sum_{i=1}^{N_{\mathrm{ch}}} \alpha_{\mathrm{i}}}{N_{\mathrm{ch}}}$. Therefore, the probability of $l$ idle channels in the system follows the binomial distribution as given by [116]:

$$p(l) = \binom{N_{\mathrm{ch}}}{l} (1-\alpha)^{l} \alpha^{N_{\mathrm{ch}}-l}, \qquad 0 \leq l \leq N_{\mathrm{ch}} \tag{2.1}$$

where $N_{\mathrm{ch}}$ is the total number of licensed channels and the average number of idle licensed channels present in the primary network are [116]:

$$E[L] = \sum_{l=0}^{N_{ch}} l\, p(l) \tag{2.2}$$

where $p(l)$ is obtained from (2.1). Let us assume that the cognitive user senses limited $Ch_{\mathrm{max}}$ channels randomly among the total $N_{\mathrm{ch}}$ licensed channels. Then the probability distribution of the number of sensed idle channels $m$ among the sensed licensed channel $Ch_{\mathrm{max}}$ , by the single cognitive user is [116]:

$$p(m) = \binom{Ch_{\mathrm{max}}}{m} (1-\alpha)^{m} \alpha^{Ch_{\mathrm{max}}-m}, \qquad 0 \leq m \leq Ch_{\mathrm{max}} \tag{2.3}$$

Thus, the average number of sensed idle channels by a cognitive user are:

$$E[M] = \sum_{m=0}^{Ch_{\mathrm{max}}} m\, p(m) \tag{2.4}$$

where $p(m)$ is achieved from (2.3). Then, the probability of a cognitive user sensing a licensed channel is given by:

$$\mu = \frac{\text{Number of channels each cognitive user sense}}{\text{Total number of licensed channels}}$$

or

$$\mu = \frac{Ch_{\mathrm{max}}}{N_{\mathrm{ch}}} \tag{2.5}$$

Since, cognitive users choose and sense licensed channels independently therefore from (2.5) we can obtain the probability that a channel is not sensed by any $N_{\mathrm{CU}}$ number of cognitive users, which is given by:

$$p_{\mathrm{nosensed}} = (1-\mu)^{N_{\mathrm{CU}}} \tag{2.6}$$

However, from (2.6), the probability that a channel is sensed by at least one cognitive user is:

$$p_{\mathrm{sensed}} = 1 - p_{\mathrm{nosense\ d}} \tag{2.7}$$

The probability distribution of $n$ detected idle channels among $E[L]$ idle licensed channels, by $N_{CU}$ cognitive users is determined by using (2.2) and (2.7) as:

$$p(n) = \binom{E[L]}{n} p_{\text{sensed}}{}^{n} \, (1 - p_{\text{sensed}})^{E[L]-n}, \qquad 0 \le n \le E[L] \tag{2.8}$$

From (2.8), the average number of sensed idle channels by $N_{\text{CU}}$ cognitive users are computed as:

$$E[N] = \sum_{n=0}^{E[L]} n \, p(n) \tag{2.9}$$

where $p(n)$ is achieved from (2.8).

### 2.3.2 Contention analysis

After sensing the licensed channels and sharing the results of sensing among $N_{CU}$ cognitive users during the sensing-sharing interval, the cognitive users compete with each other for reserving the idle licensed channels in the contention interval. However each cognitive user, which has data to send to its intended receiver, randomly selects a contention slot among total number of contention slots, $Q$, in the contention interval. Now, following two cases are considered, one in which without any contention resolving method, the number of successful cognitive users are computed and in the other case back-off algorithm is applied. The case, without back-off algorithm is for the existing SMC-MAC protocol, which has already been discussed in [116].

- Case-1: Without back-off algorithm

Since the contention slot selection by each cognitive user is random, therefore it is possible that two or more cognitive users have selected the same contention slot, which results the collision and collided cognitive users cannot reserve idle licensed channels for data transmission in the data transmission interval. However, the successful contention slot results when the single cognitive user selects a contention slot and can transmit its data over the reserved idle licensed channel during the transmission interval. Since, we have $Q$ number of contention slots, therefore the probability of selecting each contention slot is:

$$r = \frac{1}{Q}$$

The number of cognitive users which select a given contention slot is denoted by random variable $s$, and follows the binomial distribution as:

$$p(s) = \binom{N_{CU}}{s} r^{s} (1 - r)^{N_{\text{CU}} - s}, \qquad 0 \le s \le N_{\text{CU}} \tag{2.10}$$

The probability of a contention slot being successful is determined from (2.10), when $s$ = 1 that is when the single cognitive user has selected a given contention slot. Therefore, the probability of success from (2.10) is [116]:

$$p_{\text{success}} = p(1) = \binom{N_{\text{CU}}}{1} r^1 (1-r)^{N_{\text{CU}}-1}$$
$$= N_{\text{CU}}\, r\, (1-r)^{N_{\text{CU}}-1} \tag{2.11}$$

Consider $t$ be the random variable, which denotes the number of successful cognitive users and the probability of $t$ cognitive users being successful is [116]:

$$p(t) = \binom{Q}{t} (p_{\text{success}})^t (1 - p_{\text{success}})^{Q-t}, \qquad 0 \leq t \leq Q \tag{2.12}$$

The average number of successful cognitive users is computed from (2.12) and is defined as:

$$E[T] = \sum_{t=0}^{Q} t\, p(t) \tag{2.13}$$

From (2.13), the average number of collided cognitive users are:

$$E[C] = N_{CU} - \sum_{t=0}^{Q} t\, p(t) \tag{2.14}$$

where $p(t)$ is achieved from (2.12).

- Case-2: With back-off algorithm

In the proposed scheme, after first time detecting the collision during contention interval, contention window size increases according to the back-off algorithm and then the cognitive user again selects another contention slot from the increased contention window, now if again there is collision, we further increase the contention window size. In this case, the contention interval is made flexible and when there are more collided cognitive users, the contention slots are increased in order to increase the number of successful cognitive users. Therefore, it is evident that with the increase in the number of cognitive users, the congestion problem arises and in order to solve this problem, we have to increase the contention window size and hence number of contention slots in the contention interval will increases significantly. Therefore in the proposed scheme, contention interval is made flexible according to the number of cognitive users in the network. The algorithm for the proposed scheme is described as follows:

**Algorithm:**

**Step1:** Variable declaration

**$N_{CU}$**=*Number of cognitive users*

**CW**= *Number of contention slots initially*

= $2 \times N_{CU}$

**$CW_{new}$**= *$CW+2^4$, which is selected initially by cognitive users which undergoes collision for the first time during contention interval*

**Count**= *number of collided cognitive users*

**Z**= *Number of successful cognitive users*

**Step 2:** Count the number of collided cognitive users in the contention interval

$N_{CU}$ *cognitive users randomly select contention slots between 1 and* CW

**IF** $N_{CU}$ *cognitive users have selected different contention slots*

$N_{CU}$ *cognitive users are successful*

**ELSE**

*Count=count the number of cognitive users which have selected the same contention slots*

Z= $N_{CU}$ - *Count*

**END**

**Step 3**: Solve contention among collided cognitive users with the help of back-off algorithm

**FOR** i *=1:10 //taken by default*

Count *number of cognitive users randomly select contention slot between* CW *and* $CW_{new}$

**IF** *Count number of cognitive users have selected different contention slots*

*All* $N_{CU}$ *cognitive users are successful*

*break;*

**ELSE**

X=*the number of cognitive users which have selected the same contention slot*

*Z=Z + (Count-X)*

*Count=X*

*CW=CW<sub>new</sub>*

$CW_{new}=CW+2^{i}$

***IF*** $Z=\mathrm{N_{CU}}$

*All cognitive users have become successful by selecting different contention slots.*

*break;*

**END**

**END**

---

### 2.3.3 Data transmission and throughput analysis

The successful cognitive users transmit their data in the data transmission interval on the idle channels selected during the contention interval. The data transmission interval $T_{\mathrm{tr}}$ is defined by subtracting the idle time $T_{\mathrm{idle}}$, the sensing-sharing time $T_{\mathrm{ss}}$, and the contention time $T_{\mathrm{ct}}$ from the cycle time $T_{\mathrm{cycle}}$ [116]. This transmission interval is utilized for the computation of throughput of cognitive users. However, the maximum achievable throughput is the throughput when all detected licensed idle channels are utilized for data transmission in data transmission interval. Therefore, the maximum achievable throughput is defined as the product of the average number of sensed idle channels $E[N]$, the amount of time available for the data transmission per cycle interval ($T_{\mathrm{tr}}/T_{\mathrm{cycle}}$), and data rate per sensed idle channels $R$. Hence, the maximum achievable throughput is given as [116]:

$$Th_{\max} = \frac{E[N]\times T_{\mathrm{tr}} \times R}{T_{\mathrm{cycle}}} \tag{2.15}$$

where $E[N]$ is achieved from (2.9). However, the throughput of successful users in the SMC-MAC protocol is minimum of the $(Ch_{\mathrm{idle}} \times T)$ and the average number of sensed idle channels from (2.9) where $Ch_{idle}$ is the number of idle channels that a cognitive user is allowed to use. Therefore, the throughput of cognitive users in SMC-MAC is given as [116]:

$$Th_{\mathrm{SMC-MAC}} = \frac{E[\min\ (Ch_{\mathrm{idle}} \times T\ ,\ N)] \times T_{\mathrm{tr}} \times R}{T_{\mathrm{cycle}}} \tag{2.16}$$

where $T$ is the number of successful cognitive users during the contention interval. Therefore, $(Ch_{\text{idle}} \times T)$ defines the total number of idle channels on which all $T$ successful cognitive users can transmit. Moreover, the throughput of the successful cognitive users in the proposed scheme is given as:

$$Th_{\text{prop.}} = \frac{E[\min(\text{Ch}_{\text{idle}} \times Z, \text{N})] \times T_{\text{tr}} \times R}{\text{T}_{\text{cycle}}} \tag{2.17}$$

where $Z$ is the number of successful users after the back-off algorithm in the contention interval.

**2.4 Simulation Results**

The proposed distributed MAC protocol parameters for cognitive user network are employed from IEEE 802.11a [115]. The simulation parameters are as follows: idle interval ($T_{\text{idle}}$) is 34 µs, single slot time is 9µs, CR-RTS, CR-CTS and CR-SIFS frame time are 24µs, 24 µs and 16 µs, respectively. The data rate of each channel is 54 Mbps.

$$T_{\text{idle}} = CR - SIFS + 2 \times single\ slot\ time,$$

$$T_{\text{ss}} = 3 \times N_{\text{ch}} \times single\ slot\ time, \text{ and}$$

$$T_{\text{ct}} = number\ of\ contention\ slots \times \big((CR - RTS) + (CR - SIFS) + (CR - CTS)\big).$$

The simulation results of the sensing-sharing analysis, which is discussed in Section 2.3.1, have been presented in Fig. 2.4 and Fig. 2.5. The total number of licensed channels are assumed to be $N_{\text{ch}} = 20$ and $Ch_{\text{idle}} = 1$. In, Fig. 2.4 the numerical results are presented from (2.9) for the case when the total number of cognitive users are $N_{CU} = 5$, $N_{CU} = 10$ and the traffic load $\alpha$ is assumed 0.5. Since a cognitive user is able to sense only the fixed number of channels given by $Ch_{max}$, therefore Fig. 2.4 shows that as the number of channels sensed by each cognitive user increases, the number of idle channels detected by $N_{CU}$ (number of cognitive users) users also increases. However for higher value of $Ch_{\text{max}}$, more mathematical computations are required and it makes the cognitive radio terminal less energy efficient. Further, Fig. 2.5 demonstrates the actual number of idle channels and the number of idle channels sensed by 10 cognitive users for different values of traffic load $\alpha$ and $Ch_{\text{max}}$. Moreover, Fig. 2.5 reveals that there is gap between the actual number of idle channels present and the number of idle channels detected for different $\text{Ch}_{\text{max}}$ values which is due to the less number of channels sensed by the individual cognitive user in particular defined $\text{Ch}_{\text{max}}$. However, it has been demonstrated in Fig. 2.5 that as the cognitive user's ability to sense the licensed channels increases that is as the value of the parameter $\text{Ch}_{\text{max}}$ increases, the total number of idle channels sensed by all the cognitive users approaches to the total number of available idle channels. Moreover, there are some limitations of the SMC-MAC protocol [116, 130] which are discussed through the numerical simulation results and the proposed scheme has avoided these limitations as demonstrated in Fig. 2.6 and Fig. 2.7.

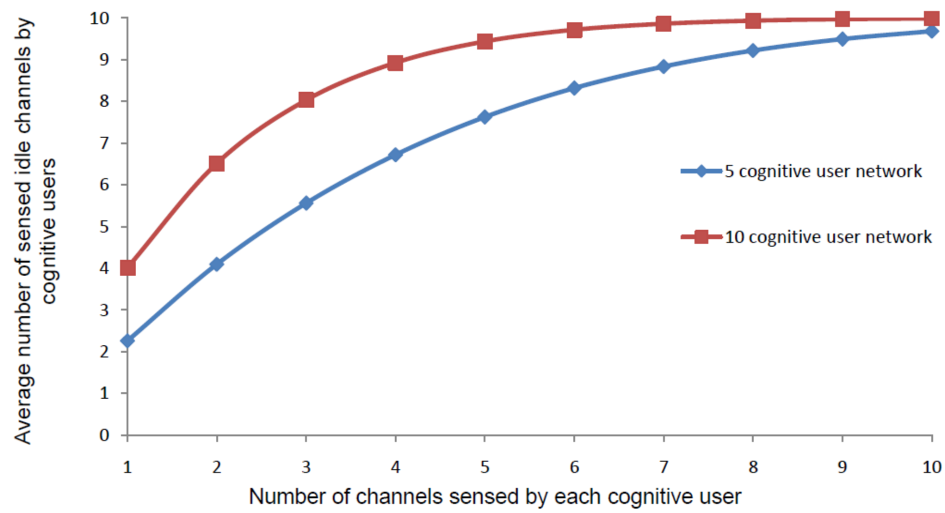



**Fig. 2.4** The response of the number of channels sensed by each cognitive user over the average number of sensed idle channels by 5 and 10 cognitive user network.

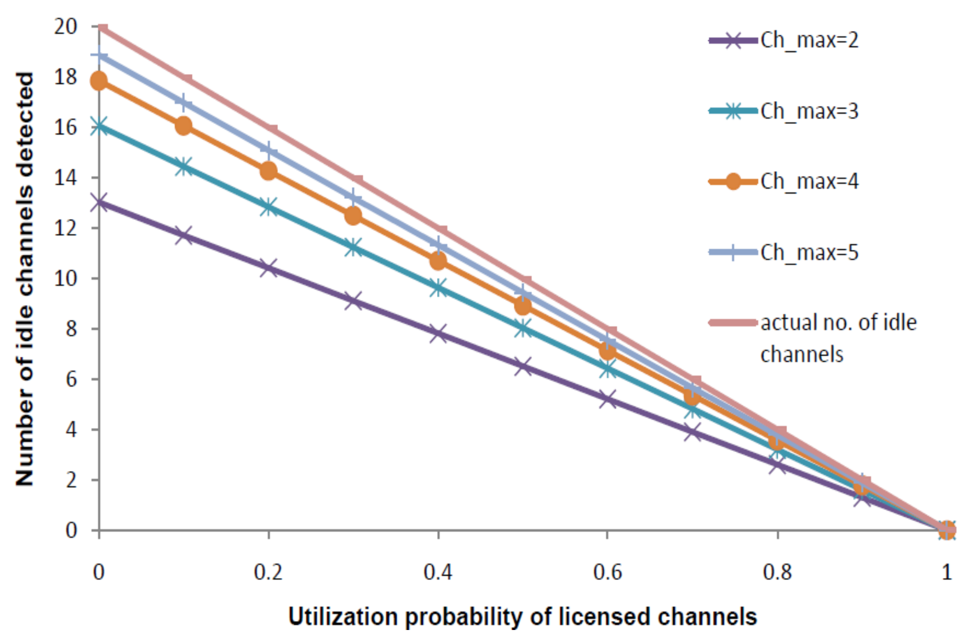



**Fig. 2.5** The response of the utilization probability of licensed channel over the number of sensed idle channels with for 10 cognitive user's network.

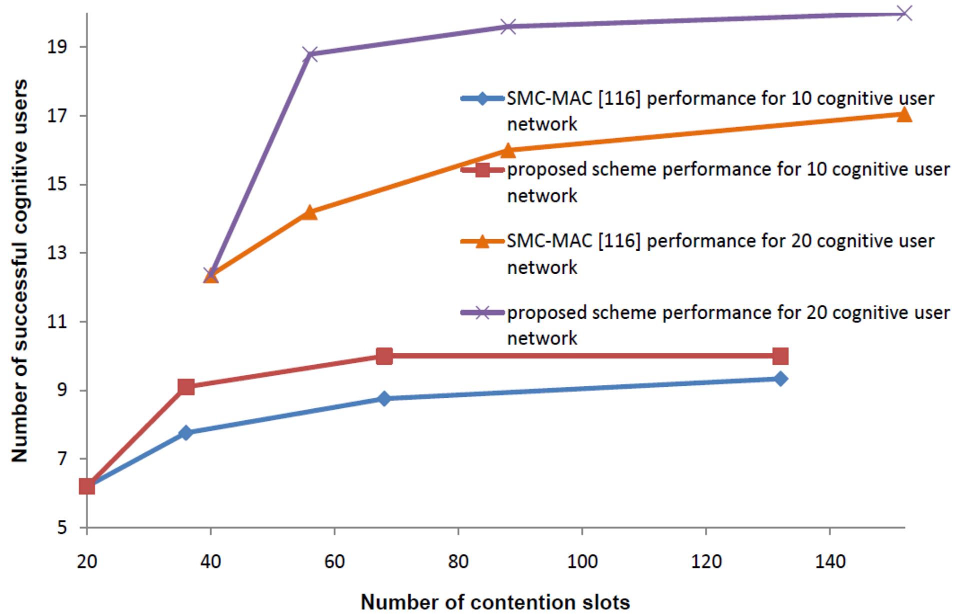



**Fig 2.6** The number of successful cognitive user's variation with the number of contention slots for the proposed and SMC-MAC [116] protocol in different number of cognitive user network on average 10 runs.

In the proposed method as discussed earlier, the binary exponential back-off mechanism is applied to resolve the contention among the collided users, and significantly more number of the users become successful as illustrated from Fig. 2.6 when compared with the SMC-MAC protocol for the same number of contention slots. The SMC-MAC protocol is without the contention resolving algorithm as discussed in [116, 130] and it is clearly illustrated in Fig. 2.6 that the total number of successful cognitive users are significantly more in case when the back-off algorithm is applied in the proposed scheme. Since, in SMC-MAC it has not been possible that the collided cognitive users in the contention interval can once again select the contention slot in that cycle time which resulted the less number of successful cognitive users as shown in Fig. 2.6 and hence the data transmission could not be possible in the same cycle for the collided cognitive users in SMC-MAC protocol.

Further in Fig. 2.7, the throughput is plotted with the number contention slots in 10 and 20 cognitive user network, when channel utilization probability is 0.1. From the Fig. 2.6 and Fig. 2.7, it is illustrated that there is some optimum value of contention slots depending on the number of cognitive users for which the number of successful users and throughput is maximum and if we further increase the contention slots from this value, the throughput decreases due to the decrease in the data transmission interval. Since in the wireless communication system, the number of transmitting cognitive users is randomly changing, therefore to have a fixed number of contention slots is not practical as is done in SMC-MAC protocol [116]. However, in the proposed scheme the optimum number of contention slots varies according to the number of cognitive users to enhance the performance as shown in Fig. 2.7. Further, the throughput is more in 20 user network as compare to the 10 user network because more successful users have get idle channels in former case than later. In addition to this, the throughput of the proposed scheme and SMC-MAC protocol in 20 cognitive user's network scenario is same at optimum contention slots as shown in Fig. 2.7. This is because although the number of successful cognitive users in the proposed scheme is higher at optimum contention slots than in SMC-MAC protocol as is clear from Fig. 2.6, however the number of successful users getting idle channels for data transmission in 20 cognitive users network is same as that in SMC-MAC protocol due to the selected $Ch_{max}$ parameter in this case. Hence, the throughput of proposed scheme in 20 cognitive users network could be more than SMC-MAC protocol throughput at optimum contention slots if all the successful cognitive users in the proposed scheme have got the idle channels as has been the case of 10 user's network shown in Fig. 2.7. However, the results presented for computing the optimum contention slots are simulated results, and the detailed analysis along with analytical results for the proposed scheme are discussed in next chapter.

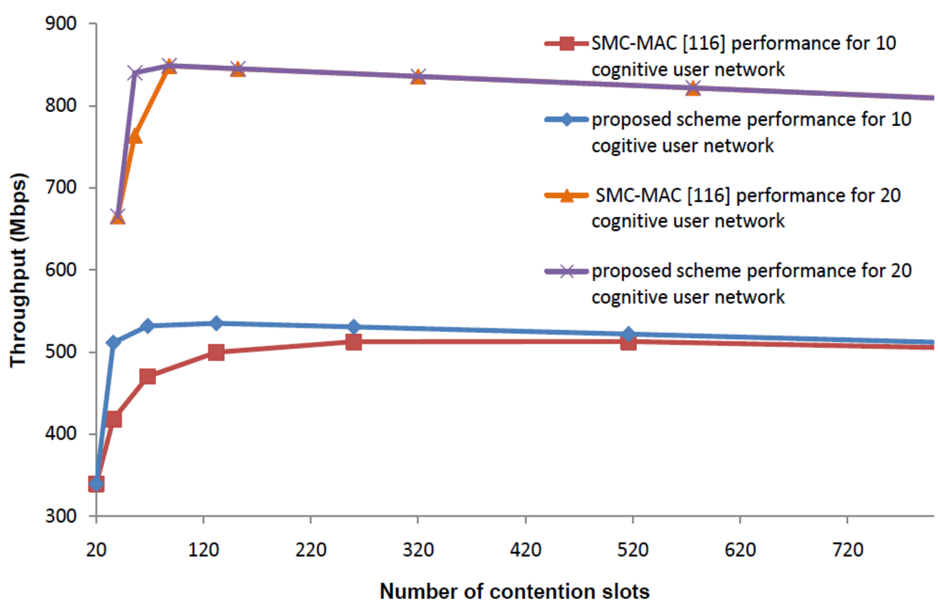



**Fig. 2.7** The throughput comparison among proposed and SMC-MAC protocol [116] with varying contention slots having average utilization probability (α) 0.1 of licensed channels and data rate of 54Mbps of each channel.

## 2.5 Conclusion

In this chapter, a cooperative MAC protocol for the distributed cognitive radio communication system with back-off algorithm for contention solving has been proposed. The proposed method has significantly enhanced the performance of cognitive radio communication system by increasing the number of successful cognitive users for the data transmission. Hence the proposed method has enhanced the throughput in comparison to that of the existing SMC-MAC protocol reported in [116] for the distributed cognitive network, and have been demonstrated by the numerical simulation results. The proposed MAC protocol has optimized the number of contention slots depending on the number of cognitive users in comparison to the fixed number of slots in SMC-MAC protocol.

# CHAPTER 3

## Distributed Cognitive Radio MAC Protocol in Perfect and Imperfect Channel Sensing Scenario

### 3.1 Introduction

In the previous chapter, it is assumed that the sensing of licensed channels by cognitive users is perfect, which is practically very difficult to yield. Therefore in this chapter, the practical scenario of imperfect sensing/sensing errors is considered in the proposed distributed cognitive radio MAC protocol. The idle channel detection in the cognitive radio MAC protocol is affected by the false alarm probability occurred due to imperfect sensing. The false-alarm [13, 131] occurs when the cognitive user falsely (imperfectly) detects a licensed channel busy which is actually idle, and in this situation the cognitive user cannot utilize the opportunity of data transmission. Miss detection also results into the imperfect sensing of licensed channel, due to which cognitive user transmits its data on the already occupied licensed channel by the primary user and hence causes interference to the primary user. In this chapter, a potential scheme has been proposed to depict the effect of perfect and imperfect sensing on the performance of the proposed distributed cognitive radio MAC protocol. The simulation results are presented for different false alarm probabilities and the throughput is computed in this environment. Moreover, the amount of interference occurred on the primary user network due to miss detection probability is also seen. Further, as we have discussed in the previous chapter and [132], the number of collisions are significantly high if the number of contention slots are limited and cognitive users are significantly more. However, the large number of contention slots although increases the success rate of cognitive users in the cognitive network but simultaneously decrease the data transmission interval and hence throughput of the cognitive radio network. Therefore, mathematical formulation of the optimum number of contention slots is obtained for the proposed MAC protocol so that the throughput of cognitive radio network enhances with the minimum number of contention slots which has been discussed in Section 3.3.2 of this chapter. In the results and discussion section of this chapter, we have obtained the optimized number of the contention slots using the proposed MAC protocol with the back-off algorithm at which all the users become successful.

Further, one of the important parameter to observe the performance of MAC protocol is energy consumption [133, 134] of the proposed system. Since a mobile terminal is, generally, having limited battery power, therefore the proposed system should have high energy efficiency. Recently, several researchers/scientists have presented significant work in the field of energy consumption and energy efficiency of the cognitive radio system [134-136]. Wang et al. [134] have optimized the spectrum sensing and access time to reduce the energy consumption of the cognitive radio user. However, the tradeoff between energy consumption in data transmission and energy overhead is discussed in [135]. Therefore, we have numerically computed the energy efficiency [136] of the proposed distributed multichannel cognitive MAC protocol for different false-alarm probabilities. The energy consumed for sensing the licensed channels, sharing the sensing information, reserving the idle channels and for data transmission is computed. Moreover, the throughput and energy efficiency of the proposed MAC protocol are also compared with that of the perfect sensing scenario.

The remainder of chapter is organized as follows. In Section 3.2, the problem formulation is explained in detail. The mathematical modeling for the perfect and imperfect sensing along with the contention interval analysis is performed in Section 3.3. In addition to this, the throughput for perfect and imperfect sensed environment is also computed. Further, in Section 3.4, the energy efficiency of proposed MAC protocol is numerically computed and Section 3.5 explores the numerical simulation results. Finally, Section 3.6 concludes the work.

## 3.2 Problem Formulation

Due to the false alarm probability, the number of idle channels detected by the cognitive users in the sensing-sharing interval of the cognitive radio MAC protocol is less than the actual number of idle channels detected in perfect sensing. Since in the contention interval, cognitive users compete for reserving the idle licensed channels detected in the sensing-sharing interval, therefore less data will be transmitted over the licensed channels in case of the false alarm due to the less detected idle channels which results lesser throughput in comparison to that of the perfectly sensed environment. In addition to this, miss-detection can also happen in which the busy licensed channels will be detected as being idle, and although cognitive users transmits its data on the miss detected licensed channels but will not increase the throughput when compared with the perfect sensing environment. This is because, the data of cognitive users transmitted on the miss detected licensed channels undergoes collision with the primary users data and hence does not contribute to the cognitive users throughput. However, the miss-detection causes interference to the primary user. Hence, we have seen the false alarm effect on the throughput and energy efficiency of the proposed MAC protocol and miss detection effect on the interference to the primary network.

Moreover, once the channel is detected busy, either due to the perfect or imperfect sensing (false alarm), in the sensing-sharing interval by a cognitive user, this channel will not be utilized or sensed again in the current cycle interval. Hence, only the false alarm has affected the throughput of proposed MAC protocol due to the detection of less number of idle channels compared to the actual idle channels present. Moreover in the MAC protocol, the cognitive users data is only transmitted in the data transmission interval, therefore the cognitive user can easily know about the primary user signal in sensing-sharing and contention interval and the situation of both the primary and cognitive users transmitting, simultaneously will never occur, hence no need to differentiate between the primary and secondary user's signal. However, in case the primary user activated during the data transmission interval, its presence is detected immediately by the cognitive user which is currently using this channel and the cognitive user stops the data transmission to protect primary user.

### 3.3 Mathematical Modeling

In this section, the mathematical modeling of the perfect and imperfect channel sensing for the distributed cognitive radio MAC protocol is performed and different parameters of the cognitive radio network are analyzed.

#### 3.3.1 Sensing-sharing interval analysis

Since it is obvious that false alarm results in less number of idle channels detection by the cognitive users and it has affected the system performance. Therefore, this subsection computes the total number of idle channels detected by the cognitive users for both perfect and imperfect sensing scenario and interference probability to the primary network due to miss detection as follows:

##### *3.3.1.1 Perfect sensing*

Firstly, we find out the number of cognitive users needed for a particular number of the licensed channels sensing at a given $Ch_{\max}$ . The probability distribution that *x* number of slots out of $N_{\mathrm{ch}}$ slots in the sensing-sharing interval is not selected by any cognitive user is given by:

$$p(x) = \binom{N_{\mathrm{ch}}}{x} p_{\mathrm{nosensed}}{}^{x} \left(1 - p_{\mathrm{nosensed}}\right)^{N_{\mathrm{ch}} - x}, \qquad 0 \le x \le N_{\mathrm{ch}} \tag{3.1}$$

where $p_{\text{nosensed}}$ is achieved from (2.6). The average number of sensing-sharing slots not selected by any cognitive user is:

$$E[X] = \sum_{x=0}^{N_{\text{ch}}} x\, p(x) \tag{3.2}$$

Therefore, the average number of sensing-sharing slots selected or number of licensed channels sensed by $N_{\text{CU}}$ cognitive users is:

$$E[Y] = N_{\text{ch}} - E[X] \tag{3.3}$$

The equation (3.3) provides the total number of channels selected for sensing from the total licensed channels by all the cognitive users for the given $Ch_{\max}$ value. The number of idle channels detected among the selected licensed channels in (3.3) by $N_{CU}$ cognitive users for the given utilization probability α of each channel is:

$$p(u) = \binom{E[Y]}{u} (1-\alpha)^{u}\, \alpha^{E[Y]-u}, \qquad 0 \le u \le E[Y] \tag{3.4}$$

From (3.4), the average number of idle channels detected by $N_{\text{CU}}$ cognitive users is computed as:

$$E[U] = \sum_{u=0}^{E[Y]} u\, p(u) \tag{3.5}$$

*3.3.1.2 Imperfect sensing*

As it has been discussed earlier that false alarm and miss detection are the two parameters to be considered in imperfect sensing, therefore in this sub-section these parameters effect on the proposed MAC protocol have been shown.

(a) False alarm

For the given probability of the false alarm and idle channels detected by $N_{CU}$ cognitive users, the probability of $g$ channels that are falsely detected busy out of $E[U]$ licensed idle channels by $N_{CU}$ cognitive users is:

$$p(g) = \binom{E[U]}{g} {p_{\text{f}}}^{g} (1-p_{\text{f}})^{E[U]-g}, \qquad 0 \le g \le E[U] \tag{3.6}$$

Therefore, the average number of falsely detected licensed channels that is the number of channels detected busy contrary to being idle is:

$$E[G] = \sum_{g=0}^{E[U]} g\, p(g) \tag{3.7}$$

The average number of idle channels detected after certain false alarm probability by $N_{CU}$ cognitive users is:

$$E[H] = E[U] - E[G] \tag{3.8}$$

(b) Miss detection

Moreover, the average number of busy channels detected for the particular value of $Ch_{max}$ and α is:

$$E[I] = E[Y] - E[U]$$

Therefore, out of the busy channels defined in the above equation, some busy channels will be detected idle due to miss-detection. The probability of z channels being miss detected out of E[I] channels for the given miss detection probability $p_m$ is:

$$p(z) = \binom{E[I]}{z} {p_m}^z (1-p_m)^{E[I]-z}, \; 0 \le z \le E[I]$$

The average number of miss detected licensed channels are:

$$E[Z] = \sum_{z=0}^{E[I]} z\, p(z)$$

Therefore, average number of idle channels detected by total $N_{CU}$ cognitive users after certain miss detection probability is:

$$E[J] = E[U] + E[Z]$$

Therefore, the average number of idle channels detected after certain miss detection probability by $N_{\mathrm{CU}}$ cognitive users will be more than $E[U]$, however it does not contribute to the cognitive user's throughput as discussed earlier. In addition to this, due to miss detection, the primary user's presence will not be detected on the licensed channel by the cognitive users and therefore the interference to the primary user will occur if the miss detected licensed channel has also been utilized by the cognitive user along with the primary user. Therefore, the probability of interference to the primary user due to miss detection is computed as follows [137]:

$$P_{int} = p_m \times Prob(p \ge (T_{idle} + T_{ss} + T_{ct})) \times P_{CU} \tag{3.9}$$

where $p_m$ is the probability of miss detection. $Prob(p \geq (T_{idle} + T_{ss} + T_{ct}))$ defines the probability that primary user transmits in the data transmission interval and where $T_{idle}$, $T_{ss}$, $T_{ct}$ defines idle, sensing-sharing, and contention interval, respectively of a cycle time.

$Prob(p \geq (T_{idle} + T_{ss} + T_{ct})) = \exp(-\lambda_p(T_{idle} + T_{ss} + T_{ct}))$

$\lambda_p$ is the average primary user ON-rate as is discussed in [137]. Further, $P_{CU}$ gives the probability of cognitive user grabbing a channel after successful contention slot and is given as:

and,
$$P_{CU} = \begin{cases} \frac{\binom{N_{CU}-1}{E[J]-1}}{\binom{N_{CU}}{E[J]}}, & E[J] \leq N_{CU} \\ 1, & otherwise \end{cases} \tag{3.10}$$

### 3.3.2 Contention interval analysis

The cognitive users compete with each other for reserving the idle licensed channels during the contention interval after sensing-sharing interval as is described in the previous chapter. However each cognitive user, which has data to send to its intended receiver, randomly selects a contention slot among the total number of contention slots. As already discussed in Chapter 2, the comparison has revealed that the application of back-off algorithm in the contention interval has enhanced the cognitive radio network performance.

The analysis of the contention interval with back-off algorithm is described in detail in this section. Let the number of contention slots initially be $CW_1$ and each cognitive user randomly selects a contention slot with probability $r_1$. $CW_1$ is given as: $CW_1 = 2 \times N_{\mathrm{CU}}$. Therefore the relation between the contention slots $CW_1$ and $r_1$ is given as:

$$r_1 = \frac{1}{CW_1}$$

Let $s_1$ be the number of cognitive users, which select a contention slot with probability $r_1$ and its probability distribution is given as:

$$p(s_1) = \binom{N_{\mathrm{CU}}}{s_1}(r_1)^{s_1}(1 - r_1)^{N_{\mathrm{CU}} - s_1}, \quad 0 \leq s_1 \leq N_{\mathrm{CU}} \tag{3.11}$$

Moreover, in (3.11), $s_1 = 0$ represents that a slot is not selected by any cognitive user, $s_1 = 1$ represents that a slot is selected by single cognitive user and $s_1 \geq 2$ indicates that a slot is selected by two or more cognitive users causing collision in that slot. Further, from (3.11) we can find the probability that a contention slot is selected by only single cognitive user and is given as:

$$p_{\text{success (1)}} = p(1) = \binom{N_{\text{CU}}}{1} (r_1)^1 (1 - r_1)^{N_{\text{CU}} - 1} \tag{3.12}$$

$$= N_{\text{CU}}\, r_1 \,(1 - r_1)^{N_{\text{CU}} - 1} \tag{3.13}$$

Equation (3.13) also represents the probability of success of a contention slot since it is selected by only single cognitive user. Since selection of a slot by cognitive users is independent in each trial, and the probability of success of a slot in each trial is $\text{p}_{\text{success (1)}}$, therefore from the binomial distribution, we can find the average number of successful contention slots or average number of successful cognitive users as:

$$E[T_1] = CW_1 \times \text{p}_{\text{success (1)}} \tag{3.14}$$

From (3.14), the average number of collided cognitive users is:

$$E[C_1] = N_{\text{CU}} - E[T_1] \tag{3.15}$$

Further, to increase the contention interval size in order to make all the cognitive users successful, we follow the procedure as:

$$r_{\text{i}} = \frac{1}{CW_{\text{i}}}, \text{ where i=2,3,4,…, and } CW_2 = 2^4,\ CW_3 = 2 \times CW_2, CW_4 = 2 \times CW_3\ , \ldots\ldots \tag{3.16}$$

Therefore, the contention interval is increased according to the binary exponential back-off algorithm. The number of cognitive users, which have collided in the former contention interval are competing for the individual contention slot during the incresed contention interval, which is described as:

$$p(s_{\text{i}}) = \binom{E[C_{\text{i}-1}]}{s_{\text{i}}} (r_{\text{i}})^{s_{\text{i}}} (1 - r_{\text{i}})^{N_{\text{CU}} - s_{\text{i}}}, \qquad 0 \le s_{\text{i}} \le E[C_{\text{i}-1}], i = 2, 3, 4, \ldots \tag{3.17}$$

$$p_{\text{success (i)}} = E[C_{\text{i}-1}] \times r_{\text{i}} \times (1 - r_{\text{i}})^{E[C_{\text{i}-1}]-1} \tag{3.18}$$

The average number of successful cognitive users is computed from (3.18) and is defined as:

$$E[T_{\text{i}}] = CW_i \times p_{success\ (i)} \tag{3.19}$$

and the average number of collided cognitive users are:

$$E[C_i] = E[C_{\text{i}-1}] - E[T_{\text{i}}] \tag{3.20}$$

Further, the total number of contention slots $CW_{total}$ are:

$$CW_{\text{total}} = \sum_{i=1}^{i} CW_{\text{i}} \tag{3.21}$$

Hence, the total number of successful cognitive users till $CW_{total}$ contention slots, are:

$$E[T_{\text{total}}] = E[T_{\text{i}-1}] + E[T_{\text{i}}] \tag{3.22}$$

We have assumed the maximum contention window size $CW_{\max}$ of 1024. However, in case the maximum contention window is reached that is: $CW_{\text{total}} = CW_{\max}$ and all the cognitive users in the network have not become successful, then contention interval will not increase further and the cognitive users became successful till maximum contention interval will enter into the data transmission period.

### 3.3.3 Data transmission interval analysis

The data transmission interval $T_{\text{tr}}$ is defined as:

$$\begin{aligned} T_{\text{tr}} &= T_{\text{cycle}} - (T_{\text{idle}} + T_{\text{ss}} + T_{\text{ct}}) \\ &= T_{cycle} - \left(\mathrm{T}_{\text{idle}} + 3 \times \mathrm{T}_{\text{slot}} \times \mathrm{N}_{\text{ch}} + \mathrm{CW}_{\text{total}} \times (\mathrm{CR} - \mathrm{RTS} + \mathrm{CR} - \mathrm{SIFS} + \mathrm{CR} - \mathrm{CTS})\right) \end{aligned} \tag{3.23}$$

where $T_{\text{cycle}}$ is the total cycle time, $T_{\text{idle}}$, $T_{\text{ss}}$ and $T_{\text{ct}}$ are idle interval, sensing-sharing interval and contention interval duration, respectively. Since sensing-sharing interval contains $N_{\text{ch}}$ number of slots and each sensing-sharing slot have three sub-slots, therefore $3 \times T_{\text{slot}} \times N_{\text{ch}}$ denotes whole sensing-sharing interval duration. Similarly, $CW_{\text{total}} \times (CR - RTS + CR - SIFS + CR - CTS)$ is the whole contention interval duration.

As discussed in the previous chapter, only those successful cognitive users transmit their data in the data transmission interval which have got the idle licensed channels. Further, the throughputs for following two cases are considered: 1) for the perfectly sensed licensed channels and 2) for the licensed channels imperfectly detected busy or for false alarm case. These two cases are discussed below:

#### *3.3.3.1 Throughput for perfect sensing*

The throughput $T$ is the product of the minimum of the $E(\text{Ch}_{\text{idle}} \times T_{\text{total}})$ and the average number of sensed idle channels from (3.5), the amount of time available for the data transmission per cycle interval ($T_{\text{tr}}/T_{\text{cycle}}$), and the data rate per sensed idle channels $R$. Further, the throughput $T$ for the proposed MAC protocol is given as:

$$T = \frac{E[\min(\mathrm{Ch}_{\mathrm{idle}} \times T_{\mathrm{total}}, U)] \times T_{\mathrm{tr}} \times R}{T_{\mathrm{cycle}}} \tag{3.24}$$

where $Ch_{\mathrm{idle}}$ is the number of idle channels that a cognitive user is allowed to use, simultaneously. $E[T_{\mathrm{total}}]$ is the number of successful users after the use of back-off algorithm in the contention interval which is obtained from (3.22), and the number of idle channels detected $E[U]$ is obtained from (3.5).

#### *3.3.3.2 Throughput for imperfect sensing*

The throughput for imperfect sensing scenario (false alarm), $\mathrm{T_I}$ is computed from (3.8) since the less idle channels are detected in the false detection and is given as:

$$T_I = \frac{E[\min(\mathrm{Ch}_{\mathrm{idle}} \times T_{\mathrm{total}}, \mathrm{H})] \times T_{\mathrm{tr}} \times R}{T_{\mathrm{cycle}}} \tag{3.25}$$

$E[H]$ is obtained from (3.8), which is the total number of idle channels detected in the false alarm scenario. However, the throughput for the miss detection scenario is same as that for perfect sensed scenario as discussed earlier in this chapter because data of cognitive users transmitted over the miss detected channels undergo collision with primary user's data and hence does not contribute to the cognitive radio user throughput.

## 3.4 Energy Efficiency

Since it is known that, the cognitive radio before accessing a licensed channel perform spectrum sensing on the channel, which consumes energy due to the radio frequency (RF) circuit operation and baseband signal processing as discussed in [135, 138]. In addition to this, in the proposed MAC protocol, there are energy overheads due to the sensing, competing and idling [135] before the data transmission. Therefore, it is clear that the energy consumption is not only in the data transmission interval for information transfer but also in the sensing-sharing and contention interval in which even idling of users also consume energy. The performance of proposed MAC protocol in terms of the energy consumption is further computed in this section and the energy efficiency parameter is defined for this purpose as:

$$\mathrm{EE} = \frac{\text{Total amount of useful data delivered (bits)}}{\text{Total energy consumed (Joule)}}$$

where EE is the energy efficiency and the total amount of useful data delivered is given by the throughput per cycle time. The total energy consumed is computed by the data transmitted during each interval of total cycle time. We have used three parameters, namely, 1) the transmission power ($P_{\mathrm{T}}$) that is required by a cognitive node for transmitting data, 2) reception power ($P_{\mathrm{R}}$) that is consumed by a cognitive user terminal while receiving data, and 3) idle mode power ($P_{\mathrm{I}}$) is the power consumed by the cognitive terminal when it is neither transmitting nor receiving data and is only tuned to a particular channel [139]. Therefore, the energy consumption in different intervals is as follows.

### 3.4.1 Energy consumed in sensing-sharing interval

Since, in the sensing-sharing interval, each cognitive user sense $Ch_{\max}$ number of channels by randomly selecting the sensing-sharing slot and in first sub-slot of the selected sensing-sharing slot, licensed channel is sensed and in second and third sub-slot sensing results are broadcasted for the sharing with other cognitive users. Therefore, the total energy consumed by $N_{CU}$ cognitive users for the sensing and broadcasting the sensing results is:

$$(P_{\mathrm{R}} \times T_{\mathrm{slot}} + P_{\mathrm{T}} \times 2 \times T_{\mathrm{slot}}) \times N_{\mathrm{CU}} \times Ch_{\max},$$

where $T_{\mathrm{slot}}$ is the single slot duration. The cognitive users remain idle for the number of slots which are not selected by any cognitive user and the energy consumption for these slots is:

$$E[X] \times P_{\mathrm{I}} \times 3 \times T_{\mathrm{slot}}.$$

where $E[X]$ is from (3.2). Therefore, the total energy consumed in the sensing-sharing interval is:

$$\mathrm{E}_{\mathrm{T}_{\mathrm{ss}}} = (\mathrm{P}_{\mathrm{R}} \times \mathrm{T}_{\mathrm{slot}} + \mathrm{P}_{\mathrm{T}} \times 2 \times \mathrm{T}_{\mathrm{slot}}) \times \mathrm{N}_{\mathrm{CU}} \times \mathrm{Ch}_{\max} + \mathrm{E}[\mathrm{X}] \times \mathrm{P}_{\mathrm{I}} \times 3 \times \mathrm{T}_{\mathrm{slot}} \tag{3.26}$$

### 3.4.2 Energy consumed in contention interval

In the contention interval, the collision by a cognitive user is detected by hearing the cognitive radio Clear-to-Send (CR-CTS) frame. CR- CTS frame has been sent by the destination cognitive user in response to the cognitive radio Ready-to-Send (CR-RTS) frame transmitted by the source cognitive user on the selected contention slot in the control channel, and it is well understood that if more than one source cognitive user has selected the same contention slot they will not receive CR-CTS frame correctly, hence detect collision. The time interval of CR-RTS and CR-CTS frame is $T_{\mathrm{RTS}}$ and $T_{\mathrm{CTS}}$, respectively and the interval of CR-SIFS (cognitive radio Short-Inter Frame Spacing) between CR-RTS and CR-CTS frame is $T_{\mathrm{SIFS}}$. Therefore, in the contention interval, the cognitive user's energy consumption due to the collisions, the successes and for being in idle state in the non-selected contention slots, is given as:

$$E_{\mathrm{T}_{\mathrm{ct}}} =$$

$$P_{\mathrm{T}} \times T_{\mathrm{RTS}} \times \text{total number of collided users} + P_{\mathrm{I}} \times T_{\mathrm{SIFS}} \times \text{total number of collided users} +$$

$P_{\mathrm{I}} \times T_{\mathrm{CTS}} \times \text{total number of collided users} + P_{\mathrm{T}} \times T_{\mathrm{RTS}} \times E[T_{\mathrm{total}}] + P_{\mathrm{I}} \times T_{\mathrm{SIFS}} \times E[T_{\mathrm{total}}] + P_{\mathrm{R}} \times T_{\mathrm{CTS}} \times E[T_{\mathrm{total}}] + [CW_{\mathrm{total}} - (\text{total number of collided users} + E[T_{\mathrm{total}}])] \times P_{\mathrm{I}} \times T_{\mathrm{slot}}$ (3.27)

where the total number of collided users is taken from (3.15) and (3.20) and $E[T_{total}]$ is from (3.22).

### 3.4.3 Energy consumed in data transmission interval

The information/data is transmitted by the cognitive users over the detected idle licensed channels. The number of channels utilized for the data transmission is the minimum of $(Ch_{\mathrm{idle}} \times E(T_1), E\ (U))$ and $(Ch_{\mathrm{idle}} \times E(T_{\mathrm{total}}), E\ (H))$ for the perfect and imperfect sensing, respectively. Therefore, the energy consumption over the information/data transmission interval for the perfect and imperfect sensing is:

$$E_{\mathrm{T_{tr}}} = P_{\mathrm{T}} \times T_{\mathrm{tr}} \times E[min(Ch_{\mathrm{idle}} \times T_1, U)] \tag{3.28}$$

and

$$E_{\mathrm{T_{tr}\,I}} = P_{\mathrm{T}} \times T_{\mathrm{tr}} \times E[min(Ch_{\mathrm{idle}} \times T_{\mathrm{total}}, H)] \tag{3.29}$$

respectively, $E_{\mathrm{T_{tr}}}$ and $E_{\mathrm{T_{tr}\,I}}$ are the consumed energy for the perfect and imperfect sensing, respectively in the transmission time and $E[U]$ and $E[H]$ which are obtained from (3.5) and (3.8). With the above defined energy consumption in different intervals, the energy efficiency of the proposed cognitive MAC protocol is:

$$EE = \frac{T}{E_{\mathrm{total}}} \tag{3.30}$$

$$EE_I = \frac{T_{\mathrm{I}}}{E_{\mathrm{I\_total}}} \tag{3.31}$$

where $EE$ and $EE_I$ are the energy efficiency in the perfect and imperfect sensing, respectively. Moreover,

$E_{\mathrm{total}} = E_{\mathrm{T_{ss}}} + E_{\mathrm{T_{ct}}} + E_{\mathrm{T_{tr}}}$, and

$E_{\mathrm{I\_total}} = E_{\mathrm{T_{ss}}} + E_{\mathrm{T_{ct}}} + E_{\mathrm{T_{tr}\,I}}$, are the total energy consumption over a cycle-time for the perfect and imperfect sensing, respectively.

## 3.5 Results and Discussion

For the proposed MAC protocol, the simulations parameters are shown in Table 3.1 and are employed from IEEE 802.11a [115]. The numerically simulated results of the cognitive MAC protocol for the energy efficiency as well as the perfect and imperfect sensed licensed channels are presented in this section. Fig. 3.1 shows the number of imperfectly (falsely) detected licensed channels that is the number of channels being detected as busy, however those are idle with 10 cognitive users for different probabilities of the false alarm and is computed from (3.7). It is also illustrated from Fig. 3.1 that as the false alarm probability increases for an arbitrary chosen value of $Ch_{\max}$, the number of imperfect/falsely detected licensed channels increases linearly. It should be noted that we have simulated the results when it is assumed that all sensed channels actually are idle for different $Ch_{\max}$. Moreover, with the increase of $Ch_{\max}$ for the chosen value of the probability of false alarm, the number of imperfectly detected licensed channels is more for the higher value of $Ch_{max}$ due to the more number of sensed licensed channels. Further, the simulation results of the sensing-sharing analysis which is discussed in Section 3.3.1, have been presented in Fig. 3.2. The utilization probability of licensed channels with the number of idle channels detected for different $Ch_{\max}$ value is shown by Fig. 3.2(a) and it reveals that for perfect sensing, the number of sensed idle channels are significantly more in comparison to that of the false alarm scenario for a particular value of $Ch_{\max}$. This behavior is well understood from (3.5) which have computed the idle channels detected for a chosen α in the perfectly sensed environment and from (3.7) and (3.8) that reveals the effect of false alarm on the idle channels detection.

**Table 3.1** The simulation parameters of the proposed MAC protocol for the distributed cognitive radio network.

| Simulation Parameters | Numerical Values |
|---|---|
| Number of licensed channels ($N_{\text{ch}}$) | 20 |
| Utilization probability of licensed channels (α) | 0-1 |
| Number of sensed channel by each cognitive user ($Ch_{\max}$) | 2-5 |
| Number of cognitive users ($N_{\text{CU}}$) | 10-30 |
| Probability of false detection ($P_{\text{m}}$) | 0-1 |
| Cycle time ($T_{\text{cycle}}$) | 1s |
| Single slot time ($T_{\text{slot}}$) | 9µs |
| CR-RTS frame duration | 24µs |
| CR-CTS frame duration | 24µs |

| | |
|---|---|
| CR-SIFS frame duration | 16μs |
| Transmit power | 916mW |
| Reception power | 550mW |
| Idle mode power | 550mW |
| Channel bandwidth | 20MHz, 6MHz, 5MHz, 1.25MHz |
| Data rate | 54Mbps, 16.197Mbps, 13.49Mbps, 3.37Mbps |
| Modulation | 64QAM |
| $Ch_{\mathrm{idle}}$ | 1 |

Moreover as the $Ch_{\max}$ value increases, significantly more number of licensed channels are sensed and hence detected idle, which is illustrated from Fig. 3.2(a). Since, each cognitive user can utilize only the single idle channel, therefore for 10 cognitive user's network, maximum number of the idle channels utilized for the data transmission is 10. However, Fig. 3.2(a) has illustrated that for some value of $Ch_{\max}$ and α, the number of idle channels detected is more than 10 for 10 cognitive user's network. Therefore, it is proposed that after detecting the required number of idle channels by particular cognitive users in the sensing-sharing interval's slots, further licensed channels are not sensed by the assigned cognitive users, which has resulted the adaptation of number of channels sensed and also adaptation in the number of cognitive users being used for sensing.

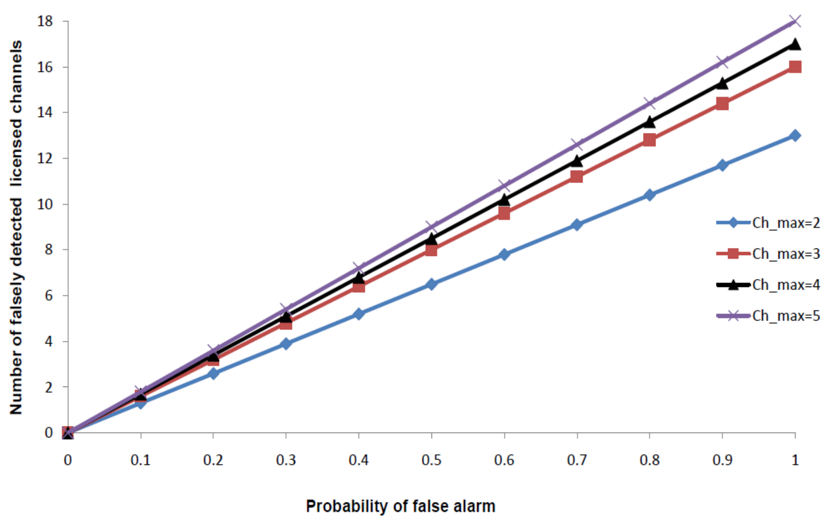
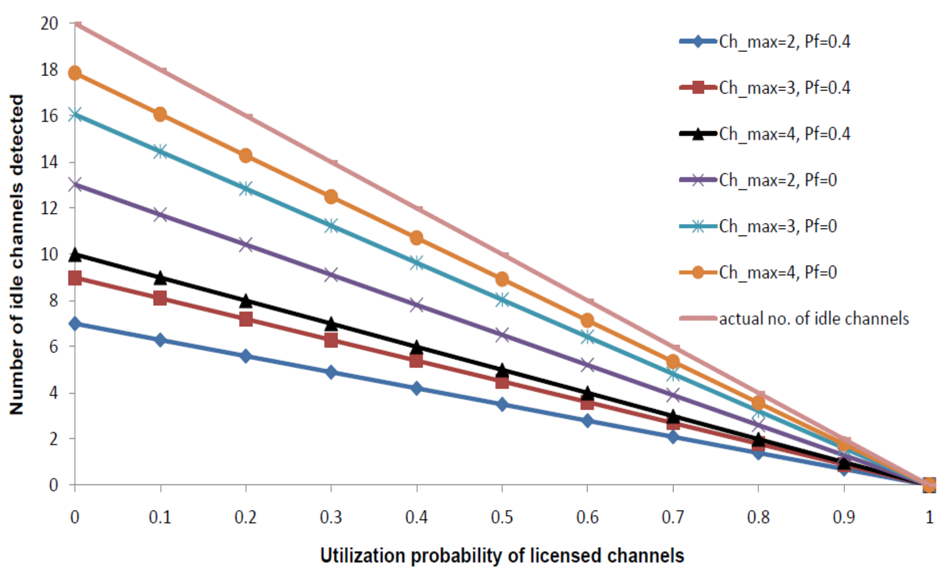
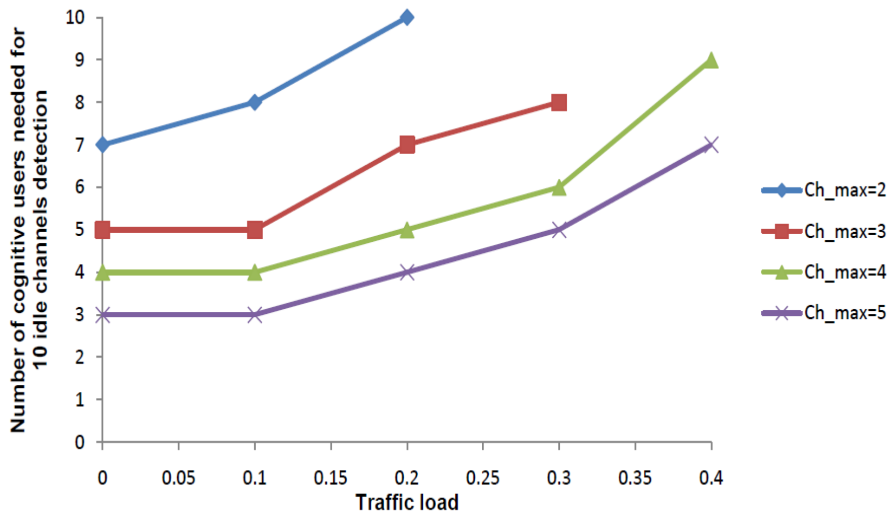



**Fig. 3.1** The number of imperfect/falsely detected licensed channels for different probabilities of false alarm and $\mathrm{Ch}_{\max} = 2, 3, 4,$ and 5, in 20 licensed channels and 10 cognitive user network when it is assumed that all sensed channels actually are idle.

Thus, Fig. 3.2(b) has depicted the number of cognitive users required for the 10 idle channels detection for different utilization probability and for different value of $Ch_{\max}$ in the perfect sensing environment. As the utilization probability of licensed channel increases for particular $Ch_{\max}$ shown in Fig. 3.2(b), even 10 users can not sense 10 idle channels. For example, with $Ch_{\max} = 2$ and for $\alpha \geq 0.3$, all 10 cognitive users cannot find required 10 idle channels and this is also verified from Fig 3.2(a) where the number of idle channels detected by 10 cognitive users is less than 10 for $\alpha \geq 0.3$. In addition to this, the number of cognitive users needed is less for higher value of $Ch_{\max}$ at a particular value of α. Thus, after detecting the required number of idle channels, further users do not have need to sense any other licensed channel and hence can minimize the energy consumed in the sensing and broadcasting the sensed information. Moreover, all the cognitive users cannot detect 10 idle channels for $\alpha \geq 0.4$ with $Ch_{\max} = 2, 3, 4, 5$ which is shown in Fig. 3.2(a) and therefore these values of α are not plotted in Fig. 3.2(b) and all 10 cognitive users sense the licensed channels for these values. Further, the contention interval analysis presented in the Section 3.3.2 of this chapter is simulated and demonstrated in Fig. 3.3, which shows the average number of successful cognitive users in the various number of contention slots for different number of cognitive users network. Fig. 3.3 have also illustrated the comparison between the existing SMC-MAC protocol [116] and the proposed method, which reveals that with the less number of contention slots, more users are successful in proposed scheme in comparison to that of the existing SMC-MAC.




(a)




(b)

**Fig. 3.2** The effects of variation of the utilization probability/traffic load of the licensed channels on the (a) number of idle channels detected for perfect ($P_f = 0$) and imperfect sensing/false alarm ($P_f = 0.4$) with $Ch_{\max} = 2, 3, 4,$ and (b) number of cognitive users required for all needed idle channels detection with different $Ch_{\max} = 2, 3, 4{,}5$ , in 10 cognitive users and 20 licensed channel network.

Moreover, it is clear from Fig. 3.3 that the optimum number of contention slots in the proposed scheme is: $\sum_{i=1}^{3} CW$ at which all the cognitive users become successful. For example, with $N_{CU} = 10$ only 68 slots are required to make all cognitive users successful in the proposed scheme however, in the SMC-MAC approximately 200 slots are needed for this purpose which reduces the data transmission time of the cognitive users. Further, the results presented in the previous chapter are simulated results of the proposed scheme, however the comparison with the analytical results whose mathematical modeling is discussed in section 3.3.2 of this chapter, is shown in Fig. 3.4. It is illustrated from Fig. 3.4 that there is small difference among the analytical and simulated results when we have applied the back-off algorithm for contention solving in contention interval and therefore the throughput is assumed to be same for both cases. Further, Fig. 3.5 shows the throughput of MAC protocol for perfect and imperfect sensing due to false alarm with 10 and 20 cognitive users. Due to the limited number of idle channels detected in the false alarm/imperfect sensing scenario, the cognitive users are unable to utilize other idle channels present and it has limited its throughput when compared with that of the perfectly sensed scenario as shown in Fig. 3.5. According to the Fig. 3.2(a), the number idle channels detected for $Ch_{\max} = 2$ and $P_f = 0$ is more than 10 for $\alpha$= *0, 0.1 ,0.2.* However, since the cognitive radio network can utilize maximum 10 idle channels because of 10 cognitive users in the network, therefore the maximum throughput is of 10 users and not more than that which is the reason that for *α=0, 0.1, 0.2* the throughput is same. However, as α is increasing further from 0.2, the number of idle channels detection decreases from 10 and all the 10 cognitive users cannot get 10 idle channels therefore some of the cognitive users cannot transmit their data due to the lack of idle channels present and hence the throughput is linearly decreasing for all other values of α as shown in Fig. 3.5. The mathematical description of this simulation is also discussed in the analysis section.

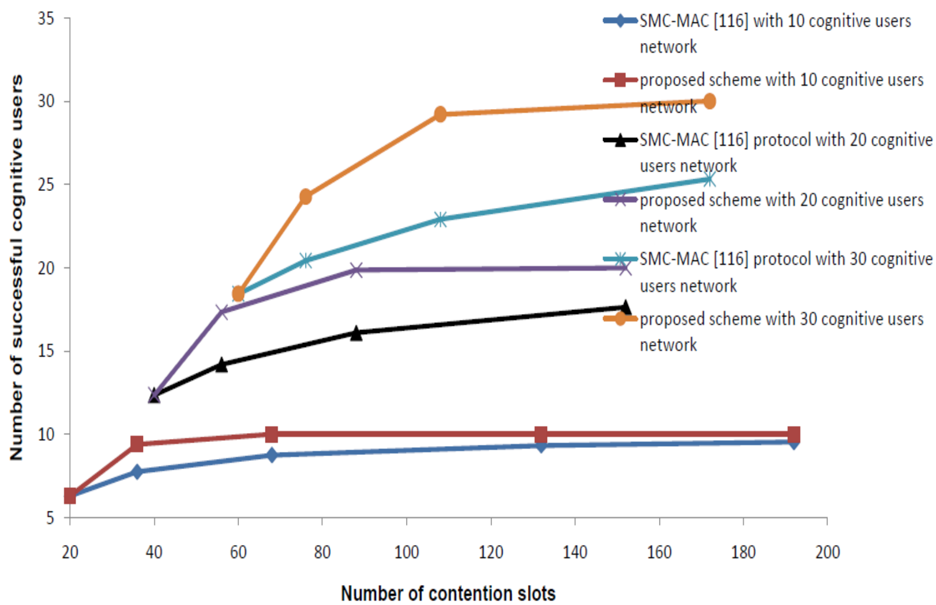



**Fig. 3.3** The number of successful cognitive user's variation with the number of contention slots for the proposed and SMC-MAC [116] protocol in 10, 20 and 30 cognitive user's network.

Further, Fig. 3.6 shows the throughput of cognitive network utilizing varying channel bandwidth of different licensed networks because of the cognitive user terminal's heterogeneous network support, for example TV broadcast network, WCDMA 3G cellular network, and CDMA network of 6 MHz, 5 MHz and 1.25 MHz channel bandwidths. Moreover, Fig. 3.7 has represented the energy efficiency of MAC protocol as computed using (3.30) for different values of $Ch_{\max}$ and perfect sensing scenario in 10, 20 and 30 cognitive user network. The energy efficiency of the 10 user's network is higher than that of 20 and 30 user's network because the total number of licensed channels are fixed that is 20 and more cognitive users have increased the sensing-sharing and contention interval which results decreased data transmission time. In addition to this, more cognitive users resulted more collisions, and successful slots in the contention interval which causes more energy consumption. Therefore, the combined effect of above two factors that are less data transmission time and more number of collisions, has resulted less useful data transmission with more energy consumption for increased cognitive users network and has decreased the energy efficiency of the system.

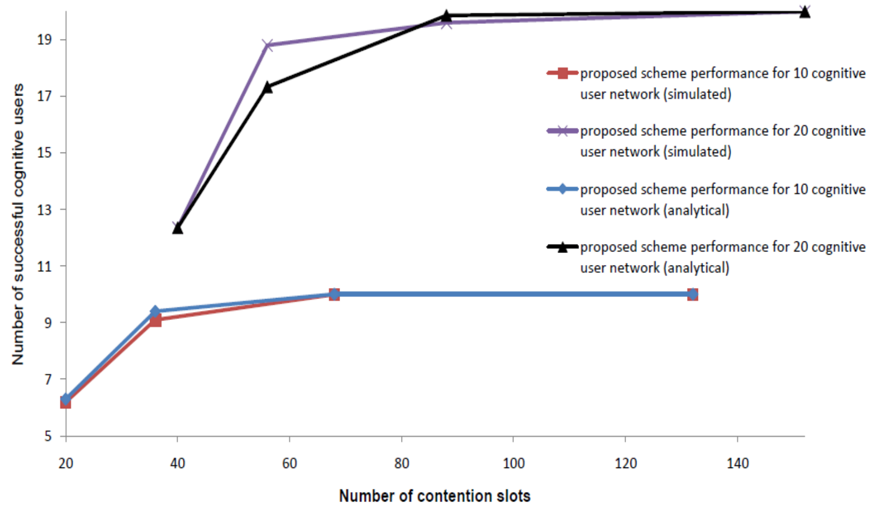



**Fig. 3.4** The comparison of the analytical and simulated results of the proposed MAC protocol.

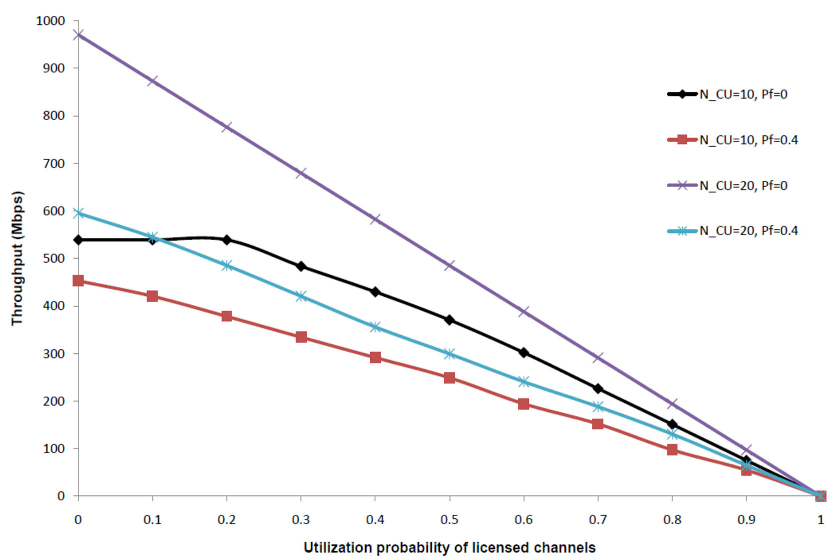



**Fig. 3.5** The throughput of cognitive network with different licensed channels utilization probability for $Ch_{\max} = 2$, $N_{ch} = 20$, $N_{\mathrm{CU}} = 10,\ 20$, data rate of 54 Mbps, and $P_f = 0, 0.4$.

Further, in Fig. 3.8 the energy efficiency is depicted with the traffic load utilization (α) for 10, 20 and 30 cognitive user's network with perfect and imperfect/falsely sensed licensed channels. Since, more is the false alarm probability then less number of idle channels is utilized for transmitting data, consequently less number of information bits is transmitted with less energy efficiency.

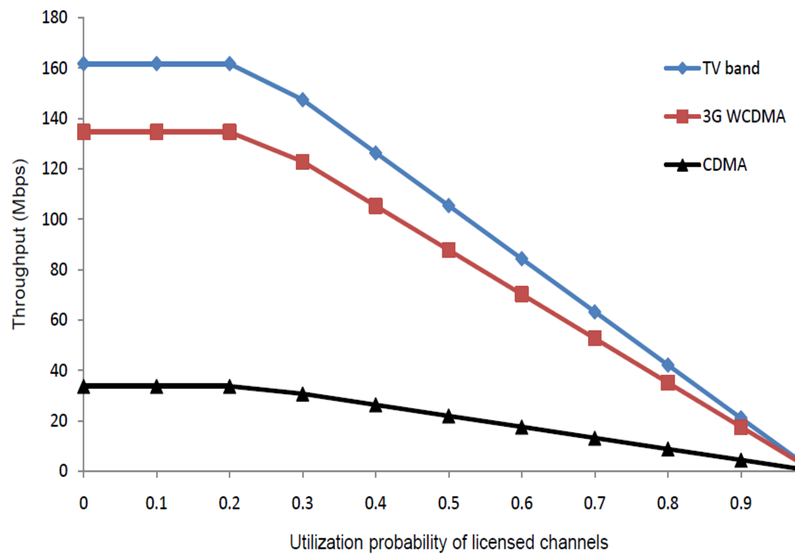



**Fig. 3.6** The throughput variation of cognitive network in different primary user network with licensed channels traffic load for $Ch_{\max} = 2$, $N_{\text{ch}} = 20$, $N_{CU} = 10$ and $R$= 16.197 Mbps (TV band),13.49 Mbps (3G WCDMA), 3.37 Mbps (CDMA).

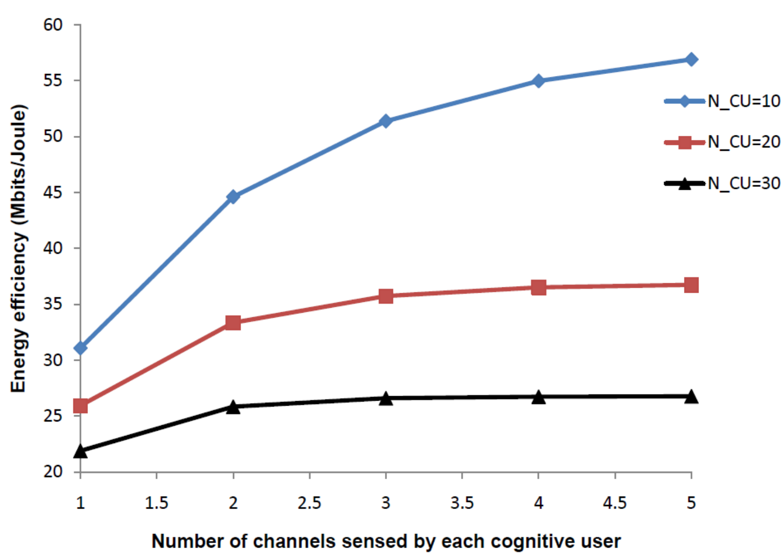



**Fig. 3.7** The energy efficiency of the proposed protocol with different values of $Ch_{\max}$ where the simulation parameters are $\alpha = 0.5$, $R = 54$ Mbps, $N_{\text{ch}} = 20$, $N_{\text{CU}} = 10, 20, 30$ and $Ch_{\max} = 2$.

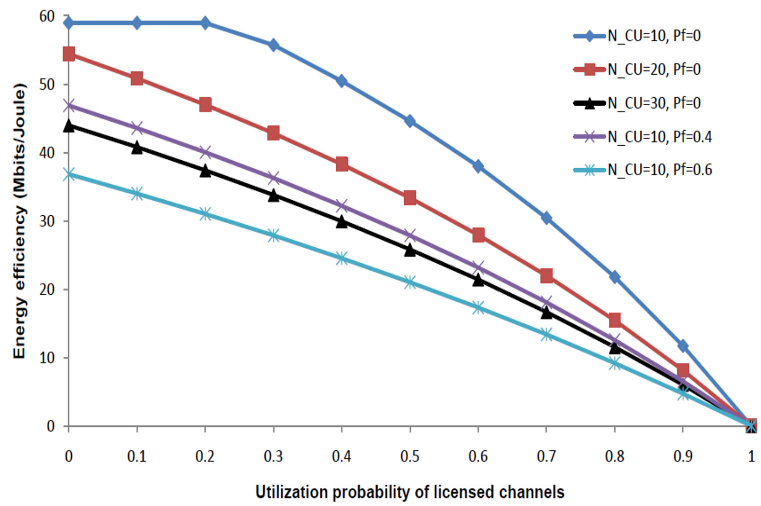



**Fig. 3.8** The energy efficiency variation with the traffic load for various number of cognitive users and different false alarm probabilities, where $R = 54$Mbps, $N_{\mathrm{ch}} = 20$, and $Ch_{\mathrm{max}} = 2$.

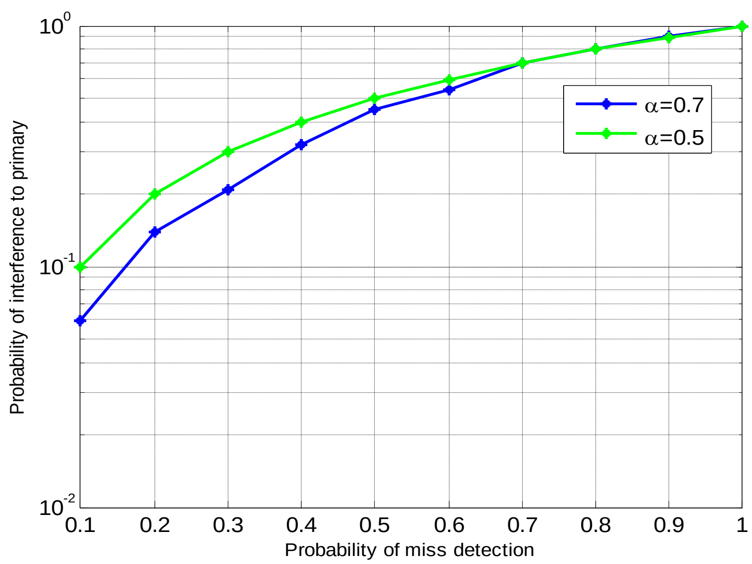



**Fig. 3.9** The probability of interference to the primary user due to different miss detection probability for optimized contention slots in 10 cognitive user's network with $N_{\mathrm{ch}} = 20$.

Moreover, the probability of interference to the primary users due to different miss detection probability for optimized contention slots in 10 cognitive user's network with 20 licensed channels has been shown in Fig. 3.9. It is illustrated from Fig. 3.9 that in the proposed scheme, the interference probability is less for the lower values of miss detection probability. Further, Fig. 3.10 compares the average idle channel utilization with the number of cognitive users in the proposed scheme in this chapter and the one presented in [137]. It is clear from Fig. 3.10 that the idle channel utilization decreases rapidly with the number of cognitive users in the contention based multichannel protocol presented in [137] due to the fixed number of contention slots, however in the proposed scheme we have flexible contention window which vary its size according to the number of cognitive users and hence has resulted in the maximum idle channel utilization even for higher number of cognitive users.

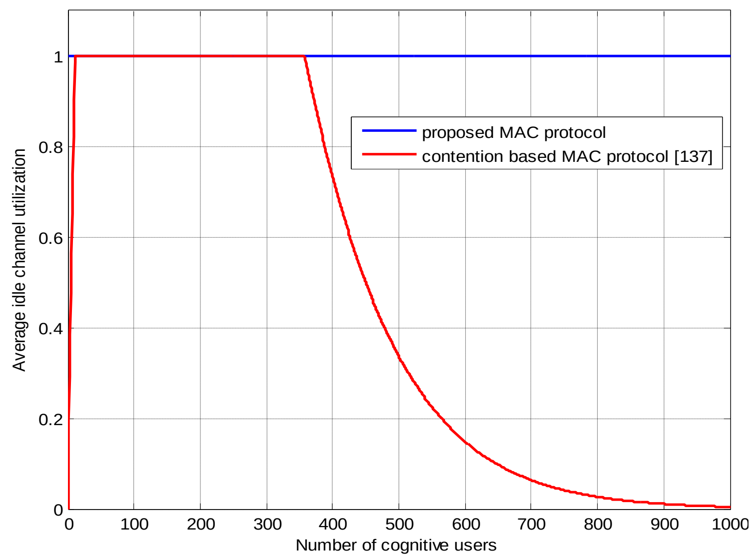



**Fig. 3.10** The average idle channel utilization with the number of cognitive users for $N_{\text{ch}} = 20$ and α=0.5 for the proposed scheme and contention based MAC protocol [137].

### 3.6 Conclusion

In this chapter, the cognitive radio MAC protocol in practical scenario is considered and the perfect and imperfect sensing effect on the performance of throughput and energy efficiency of the cognitive radio network is presented. The imperfect sensing resulted due to false alarm has affected the system performance of cognitive radio network by missing the opportunities of spectrum use in comparison to the perfect sensing, as demonstrated in the simulation results. In addition to this, the optimum number of contention slots has been obtained for the proposed MAC protocol which has avoided contention slots throughput tradeoff problem. Moreover, the performance of MAC protocol for different licensed channels utilization probability has been simulated. The simulation results have illustrated that throughput and energy efficiency of the MAC protocol for imperfectly sensed environment is less as compared to that of the perfect sensing scenario and the interference to the primary user is less in the proposed protocol for lower values of miss detection probability.

# CHAPTER 4

# Throughput Enhancement using Bandwidth Wastage in MAC Protocol of the Distributed Cognitive Radio Network

## 4.1 Introduction

As it has been proposed in the previous chapters that the back-off algorithm in SMC-MAC protocol has enhanced the cognitive radio system performance, however in the proposed scheme licensed channels are not utilized by the cognitive users in the sensing-sharing and contention interval. Since, it is known that only control channel is utilized in sensing-sharing and contention interval, which is the wastage of bandwidth over these intervals on idle licensed channels as shown in Fig. 4.1.

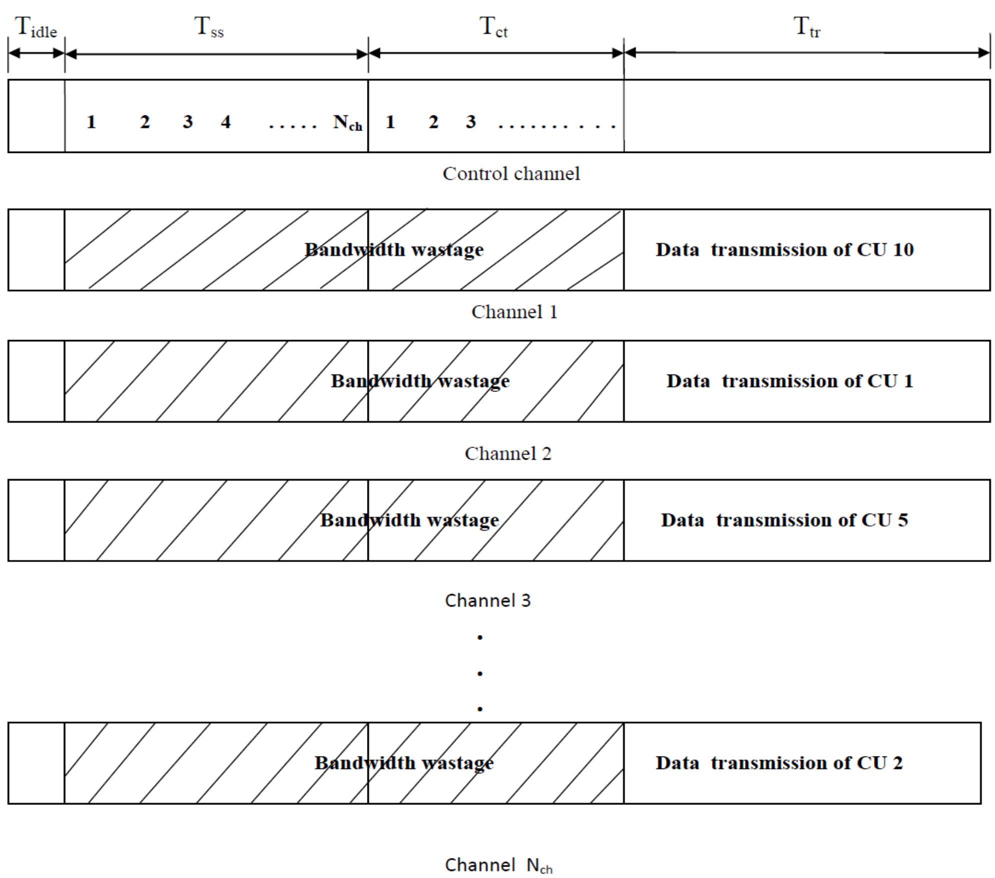



**Fig. 4.1** The bandwidth wastage of licensed channels in the cognitive radio medium access control protocol for the cooperative distributed network.

Moreover, it is clear that idle channel detected by the cognitive user in a sensing-sharing slot is utilized only in data transmission interval and therefore, all the remaining sensing-sharing slots after idle channel detection and contention interval of that licensed channel remains unutilized causing waste of bandwidth. Since, the bandwidth is one of the scarce resources of wireless communication, therefore this chapter deals with the potential issue of bandwidth wastage arises in the proposed distributed MAC protocol for the cognitive radio communication system.

This chapter has been organized as follows. In Section 4.2, the system model and proposed method for the enhancement of throughput using the wasted bandwidth is described. Section 4.3 presents the numerical analysis for the proposed scheme. Further, in Section 4.4 numerically simulated results of the analysis have been presented. Finally, Section 4.5 concludes the chapter.

## 4.2 System Model

The system model is almost similar to the one that presented in the previous chapters in which there is one primary user network comprising $N_{\mathrm{ch}}$ licensed channels and a cognitive radio network having $N_{\mathrm{CU}}$ cognitive users. However in this chapter, a novel scheme is proposed in which the data is also transmitted over the idle licensed channels during the sensing-sharing and contention interval which is improvement over the proposed scheme in the previous chapters.

### 4.2.1 Proposed method

Since, in the sensing-sharing interval, the licensed channels are sensed during their assigned slot number in the control channel by cognitive users and in case the licensed channels are detected to be idle, only then after contention, the cognitive users are allowed to transmit their data in the data transmission interval of licensed channels. It interpret that there is bandwidth wastage during $T_{\mathrm{ss}}$ and $T_{\mathrm{ct}}$ interval in the proposed scheme as shown in Fig. 4.1. However, this whole process is performed on the control channel till the data transmission interval, which results the bandwidth wastage due to no information transmitted during that interval on the idle licensed channels. It reveals that before the $T_{\mathrm{tr}}$ interval the licensed channels are not utilized if they are idle, and the bandwidth is wasted. Hence, in order to avoid the bandwidth wastage, we have proposed a scheme to transmit data on the licensed idle channels during the sensing-sharing and contention interval which is shown in Fig. 4.2. Since a channel is sensed randomly by a cognitive user, for example suppose that channel 1 is sensed by tenth cognitive user (CU 10) on control channel during first slot of the sensing-sharing interval as shown in Fig. 4.2. Now, in the proposed scheme in case the sensed channel 1 is idle, then tenth cognitive user start transmitting its data on channel 1 following first slot of sensing-sharing interval till the start of data transmission interval, after which the idle channels selected by the cognitive users cooperative communication on control channel will be utilized. Similarly, first, fifth and second cognitive users have sensed channel 2, channel 3 and channel $N_{ch}$ during second, third and $N_{ch}$ slots, respectively and if the channels detected are idle, then these cognitive users start transmitting data. It is also assumed that a cognitive user after detecting first idle channel will start transmitting on that channel and will continue its transmission on the same channel even in case further idle channel is detected by the same user on the successive sensing-sharing slots which happens due to the parameter defining number of channels sensed by a cognitive user ($Ch_{max}$).

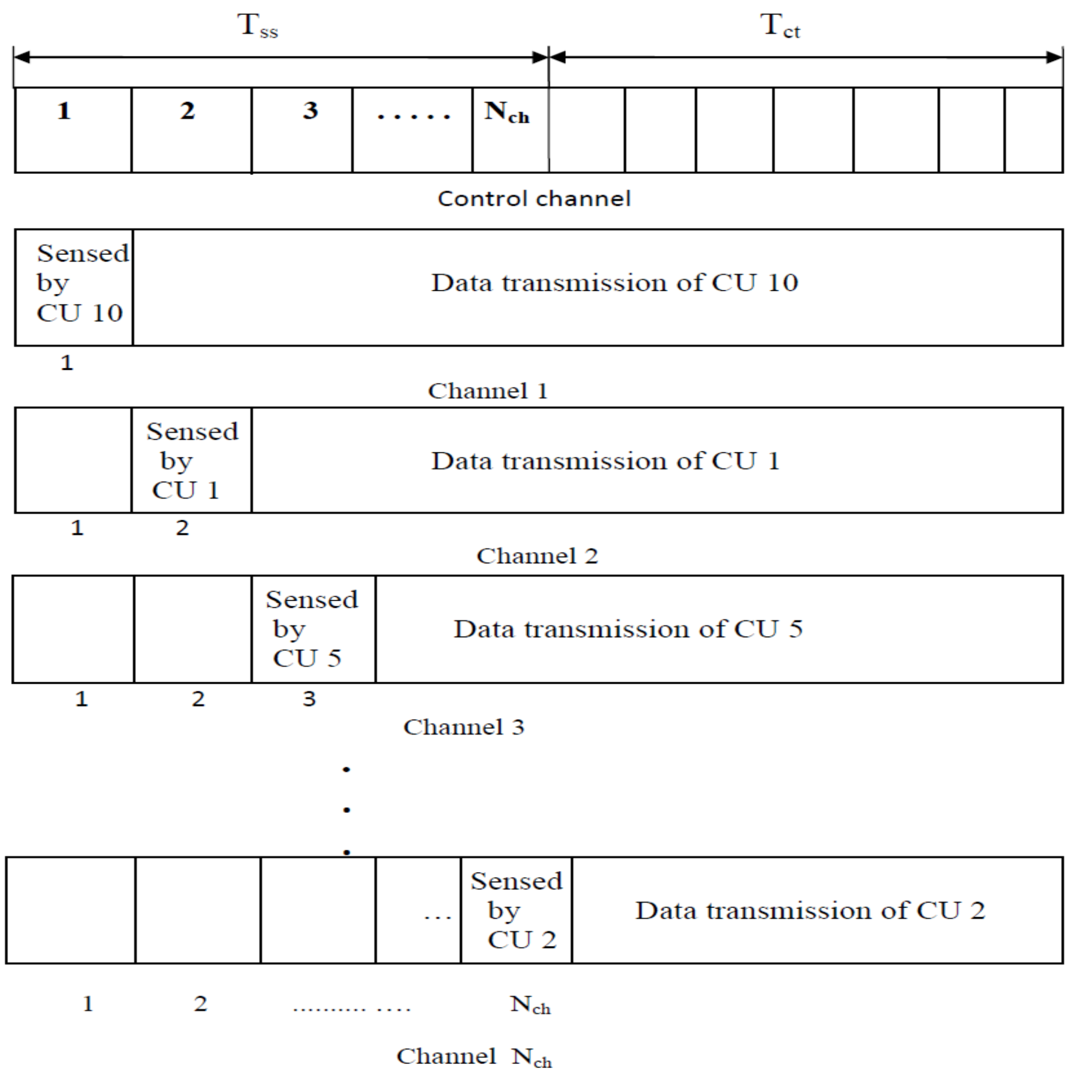



**Fig. 4.2** The proposed scheme to avoid bandwidth wastage in the proposed cognitive radio MAC protocol for the cooperative distributed network.

However, the wasted bandwidth of licensed channels in the sensing-sharing and contention interval cannot be utilized by the users which have not sensed the respective channel. In addition to this, it has been assumed that after sensing the licensed channel during sensing-sharing interval, the status of licensed channel availability does not change in that particular cycle time. Further, the proposed scheme presented in this chapter needs two transceivers, one transmit data over idle channels detected during sensing-sharing and contention interval and the other is tuned to the control channel during these intervals.

### 4.3 Performance Analysis

In this section, the numerical analysis of the proposed MAC protocol is performed and several performance parameters of the cognitive radio network are discussed.

#### 4.3.1 Sensing- sharing analysis

The probability distribution of the number of sensed idle channels $n$ by $N_{\mathrm{CU}}$ cognitive users are determined by using (2.2) and (2.7) as:

$$p(n) = \binom{E[L]}{n} p_{\mathrm{sensed}}{}^{n} \, (1 - p_{\mathrm{sensed}})^{E[L]-n}, \qquad 0 \le n \le E[L] \tag{4.1}$$

From (4.1), the average number of sensed idle channels by $N_{CU}$ cognitive users is calculated as:

$$E[N] = \sum_{n=0}^{E[L]} n \, p(n) \tag{4.2}$$

Therefore we can find from (4.2), the maximum number of cognitive users transmitting their data over the detected idle licensed channels $E[N]$, which yield maximum sensing sharing slots and is given as:

$$E[O] = min\{E[N], N_{CU}\} \tag{4.3}$$

The maximum number of slots is available for data transmission in sensing-sharing interval for the case when $E[O]$ number of cognitive users have sensed different licensed channel in the starting slots and detected those channels idle which is shown in the Fig. 4.3. For example, suppose there are 5 cognitive users, 10 licensed channels, $Ch_{\max}=1$ and idle channels detected for a particular traffic load value is 5. Therefore, when 5 cognitive users have selected first five slots for sensing and respective channels are idle as shown in Fig. 4.3, the first cognitive user to fifth cognitive user will have 9, 8, 7, 6, and 5 sensing-sharing slots, respectively available for data transmission on the respected licensed channels as numbered in Fig. 4.3. This is the maximum number of slots available for the data transmission during the sensing-sharing interval at this condition and not at any other way we can get more than these sensing-sharing slots for data transmission. Therefore, the maximum number of sensing-sharing slots available for the data transmission during sensing- sharing interval is given by:

$$X_{\max} = \sum_{i=N_{ch}-E[O]}^{N_{ch}-1} i \tag{4.4}$$

Similarly, the minimum number of cognitive users which can detect $E[N]$ idle channels yielding minimum sensing-sharing slots for data transmission is given as:

$$E[P] = min\left\{\frac{E[N]}{Ch_{\max}}, N_{CU}\right\} \tag{4.5}$$

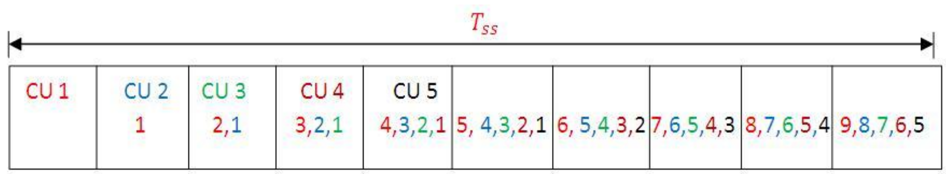



**Fig. 4.3** The maximum number of slots for data transmission.

The particular value of $i$, for which $Ch_{\max} \times i = E[N]$, where $1 \leq i \leq N_{CU}$, we will get minimum number of the slots for data transmission and in this case the idle channels detected by $i$ cognitive users at ending slots is shown in Fig. 4.4 and is given by:

$$X_{\min} = \sum_{i=0}^{E[P]-1} (Ch_{\max} \times i + (Ch_{\max} - 1)) \tag{4.6}$$

Fig. 4.4 shows the minimum number of slots available for the data transmission when $Ch_{max} = 1$, the idle channels detected according to (4.2) are 5 and licensed channels are 10. Therefore, the number of slots for data transmission would be 4, 3, 2, and 1 for first, second, third, fourth and fifth cognitive user, respectively.

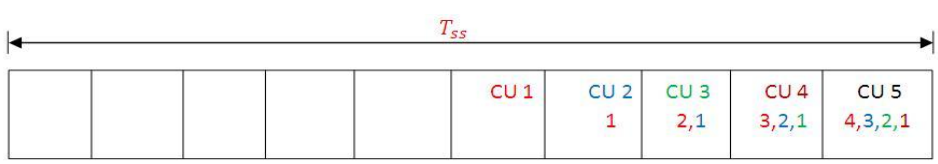



**Fig. 4.4** The minimum number of slots for data transmission

However, the minimum number of slots available is constant but the selection of a particular slot may vary among the cognitive users that is first cognitive user (CU 1) can select either first, second, third, fourth or fifth slot and similarly, other cognitive users also, therefore the maximum number of slots available is also constant. Hence, the number of sensing-sharing slots for data transmission varies in between the upper limit and lower limit given by (4.4) and (4.6), respectively and quantifies the number of slots utilized from the wasted bandwidth.

### 4.3.2 Data transmission and throughput analysis

The successful cognitive users transmit their data in the data transmission interval on the idle channels selected during the contention interval. Moreover, the data transmission interval $T_{tr}$ is defined by:

$$T_{tr} = T_{\text{cycle}} \text{-}(T_{\text{idle}} + T_{\text{ss}} + T_{\text{ct}}) = T_{\text{cycle}} \text{-}(T_{\text{idle}} + T_{\text{ss\_slot}} \times N_{\text{ch}} + \text{CW}_{\text{total}} \times T_{\text{ct\_slot}})$$

where $T_{\text{ss\_slot}} = 3 \times T_{\text{slot}}$ is the single sensing-sharing slot duration and $T_{\text{slot}}$ is the duration of the sub-slot of sensing-sharing slot. Similarly, $T_{\text{ct\_slot}}$ is the single contention slot duration. However, as have already discussed, the throughput of the proposed MAC protocol is given by:

$$Th_{\text{prop.}} = \frac{E[\min(\text{Ch}_{\text{idle}} \times T_{\text{total}}, \text{N})] \times T_{\text{tr}} \times R}{T_{\text{cycle}}} \tag{4.7}$$

where $E[T_{\text{total}}]$ is the number of successful users after the back-off algorithm in the contention interval and is obtained by using (3.22), $Ch_{\text{idle}}$ is the number of idle channels that a cognitive user is allowed to use, simultaneously. Moreover, the throughput of the SMC-MAC protocol proposed in [116] has been given as:

$$Th_{SMC-MAC} = \frac{E[\min(T \times Ch_{\text{idle}}, \text{N})] \times T_{\text{tr}} \times R}{T_{\text{cycle}}}$$

The proposed scheme throughput in which the data is also transmitted over sensing-sharing and contention interval is further presented. After utilizing the unoccupied bandwidth in the sensing-sharing interval, the cognitive users continue its transmission on the same occupied licensed channels during contention interval. Therefore, the total throughput is the sum of throughput computed in the previous chapter by applying back-off algorithm and the throughput of sensing sharing and contention interval, which is given as:

$$Th_{\text{total max}} = Th_{\text{prop.}} + \frac{\sum_{i=N_{ch}-E[O]}^{N_{ch}-1} \left(R \times \left(T_{ss\_slot} \times i + T_{ct\_slot} \times CW_{total}\right)\right)}{T_{cycle}} \tag{4.8}$$

$$Th_{\text{total min}} = Th_{\text{prop.}} + \frac{\sum_{i=0}^{E[P]-1} \left(R \times \left(T_{\text{ss\_slot}} \times \left((Ch_{\text{max}} \times i) + (Ch_{\text{max}} - 1)\right) + T_{\text{ct\_slot}} \times CW_{\text{total}}\right)\right)}{T_{\text{cycle}}} \tag{4.9}$$

Hence, (4.8) and (4.9) provides the maximum and minimum achievable throughput, respectively after utilizing the wasted bandwidth.

## 4.4 Results and Discussion

The simulation parameters for the proposed scheme are taken as: $N_{\text{ch}} = 20$, $Ch_{\text{idle}} = 1$, $T_{\text{slot}} = 900\mu s$, $T_{\text{idle}} = 1ms$, $T_{\text{ct\_slot}} = 2ms$, and $R = 1Mbps$. The simulation parameters are modified from the previous chapters to observe the prominent effect of bandwidth wastage on the throughput and cognitive radio system performance otherwise the data transmission over small time duration sensing-sharing and contention interval as considered in the previous chapters does not contribute much to the enhanced throughput. As shown in Fig. 4.5, the response of the number of cognitive users on the average number of channels sensed for different $\text{Ch}_{\text{max}}$ values, is shown. In addition to this, Fig. 4.5 reveals that as each cognitive user capability to sense the channels increases that is with increase in the value of $Ch_{\text{max}}$, more number of the licensed channels are sensed, however this would increase the complexity of the cognitive terminal [138]. Moreover, Fig. 4.6 depicts the probability of collision of cognitive users in the contention interval due to the selection of same slot by two or more cognitive users. It is also illustrated by Fig. 4.6 that with the increase in the number of cognitive users, the collision probability also increases which is obvious from the defined system model. However, for the fewer values of contention slots, the collision probability is significantly high in comparison to that of the higher values of contention slots.

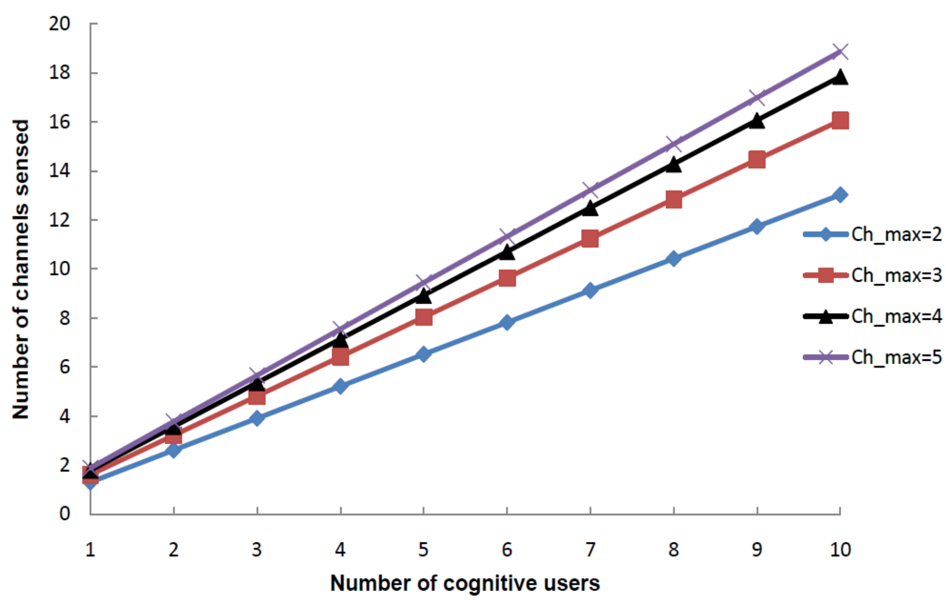



**Fig. 4.5** The response of the number of cognitive users on the average number of licensed channels sensed for different values of the parameter defining number of sensed channels by each cognitive user that is for $Ch_{max} = 2, 3, 4, 5$.

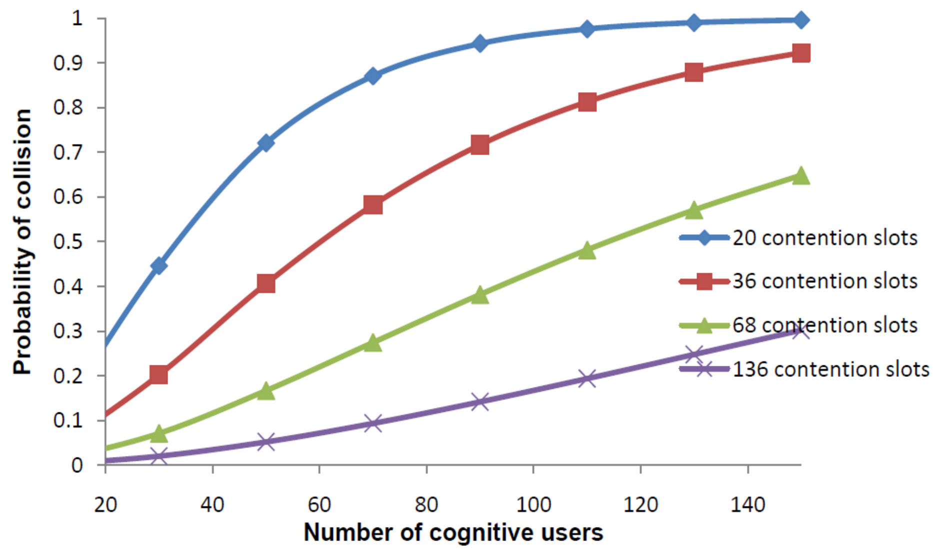



**Fig. 4.6** The role of number of cognitive users on the probability of collision for different number of contention slots.

Further, Fig. 4.7 depicts the maximum and minimum achievable throughput computed from (4.8) and (4.9) which utilizes the sensing-sharing and contention interval (wasted bandwidth) for the data transmission and compared the results with SMC-MAC and our earlier proposed scheme without utilizing wasted bandwidth. Since, it is obvious that more contention slots are required if we want to make more users successful, but at the same time, the data transmission time will be less. Therefore, the throughput of the proposed scheme increases initially in Fig. 4.7 due to more users gets success, till the all users become successful. However, there is reduction in the throughput of the proposed scheme without utilizing wasted bandwidth after optimum contention slots because further increase in the contention interval keeps the successful users same while decreasing data transmission interval and hence throughput. The SMC-MAC protocol proposed by Lim and Li in [116] does not have contention resolving algorithm in contention interval in which the collided users have no provision of getting success in the current cycle time and also wasted bandwidth in the sensing-sharing and contention interval is not utilized in SMC-MAC protocol which has resulted in the throughput degradation as shown in Fig. 4.7 in comparison to that of the proposed scheme in this chapter. Moreover, for the optimized contention slots the maximum and minimum achievable throughput proposed in this chapter is always greater than that of the throughput computed without utilizing wasted bandwidth and SMC-MAC protocol throughput. However, maximum and minimum achievable throughput remains constant after optimum contention slots because decrease in the data transmission interval throughput due to increasing contention slots is balanced with the increasing throughput of the contention interval since in this case data is also transmitted in contention interval. Further, in Fig. 4.8, the throughput of cognitive network with the traffic load of licensed channels is demonstrated for optimum contention slots and the simulation result depicts that there is significant improvement in the throughput when wasted bandwidth is also utilized for the data transmission in comparison to that of the SMC-MAC [116] and the other scheme proposed by us without utilizing wasted bandwidth. However, the throughput of the proposed scheme, for which all users are successful, is almost constant for the traffic load values from 0 to 0.2 because at these values all 10 cognitive users will transmit their data in 10 idle channels detected in the sensing-sharing interval. However, in the SMC-MAC protocol, all users are not successful at the selected optimum contention slots and therefore for traffic load values from 0 to 0.4, the number of successful users is less than the idle channels detected and hence throughput is only of the users which are successful and remains constant at these values. Furthermore, as traffic load is increasing from 0.4 in the SMC-MAC protocol, the idle channels detected are decreasing in comparison to the successful users and hence throughput is of number of idle channels detected which are decreasing with the increasing traffic load probability. Moreover, after traffic load of 0.4, the throughput of SMC-MAC and the one proposed without utilizing wasted bandwidth results similar throughput as shown in Fig. 4.8, because the increased number of successes in the later scheme does not result more throughput due to the insufficient idle channels.

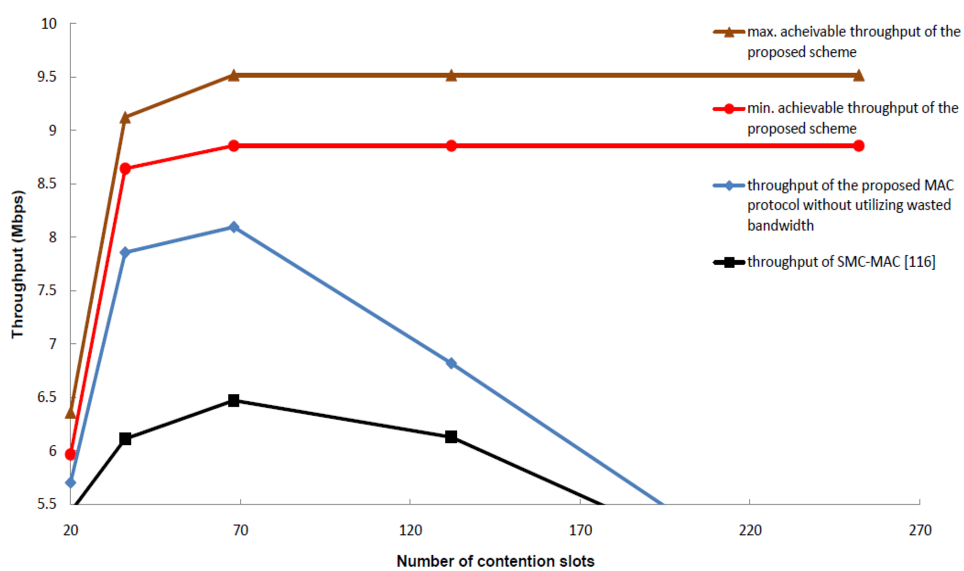



**Fig. 4.7** The throughput variation with the number of contention slots for 10 cognitive users, 20 licensed channel, α = 0.2 and $T_{\text{cycle}} = 1s$ for with and without utilizing wasted bandwidth.

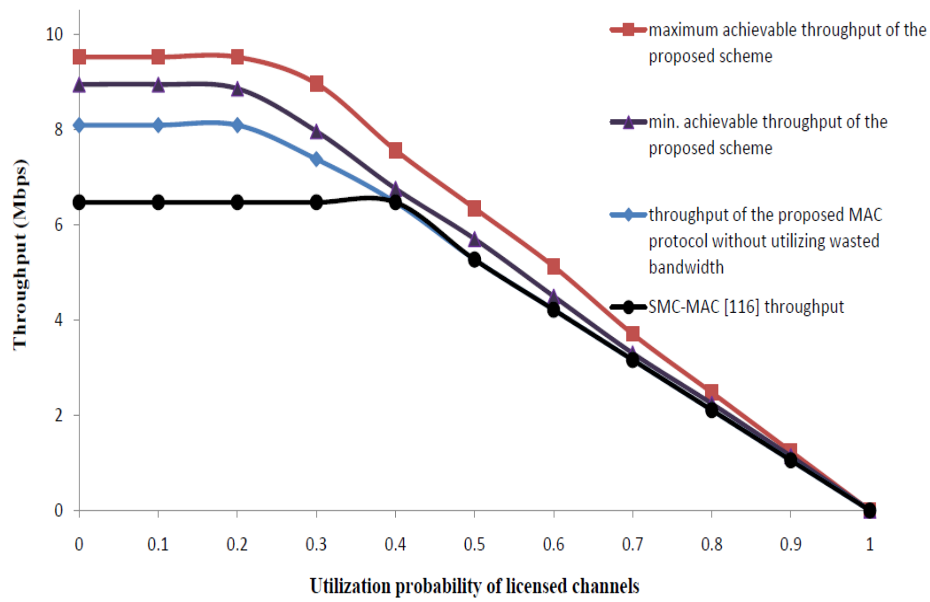



**Fig. 4.8** The throughput variation with the utilization probability of licensed channels for 10 cognitive users, $T_{\text{cycle}} = 1s$ and 68 contention slots.

### 4.5 Conclusion

In this chapter, the scheme for maximizing the bandwidth efficiency by utilizing the wasted bandwidth of the licensed channels in the distributed cognitive radio MAC protocol has been proposed. In addition to this, the contention resolving algorithm has been also applied in this proposed bandwidth maximization scheme as discussed in Chapter 2. Further, the bandwidth wastage in the cooperative distributed MAC protocol has been minimized by transmitting data of the cognitive users over the idle licensed channels, which are unutilized in the sensing-sharing and contention interval. The proposed technique has significantly enhanced the throughput of the cooperative distributed network. Moreover, the comparison of the proposed scheme in this chapter has been performed with the SMC-MAC protocol.

# CHAPTER 5

# Power Allocation for Optimum Energy Efficiency in MAC Protocol of Cognitive Radio Communication System

## 5.1 Introduction

Energy consumption is the major concern issue of the present wireless communication scenario. Since wireless devices run different services for example web browsing, gaming, social media and multimedia downloads, which quickly drain out battery of the user terminal, therefore it is needed to design an energy efficient user terminal which provides more life time to the battery. This chapter emphasizes on the design of energy efficient MAC protocol for the cognitive users. In Chapter 3 and [140], we have only computed the energy efficiency of the proposed cognitive radio MAC protocol and therefore in the present scenario for the need of minimizing energy consumption of the terminals, we have proposed an algorithm to maximize energy efficiency. The energy efficiency issue in the cognitive radio communication system has been discussed in detail in several reported literatures [136, 141-146]. Qian et al. [141] have maximized the energy efficiency of cognitive radio network utilizing the frequency of TV spectrum through the power control for both the centralized and distributed cognitive radio network. Moreover, in [141] the authors have implemented the power control in the MAC protocol of cognitive radio network. In [142], the game theory has been used for power allocation to the cognitive users in the MAC protocol and the proposed cost-based algorithm for the power allocation has minimized the energy consumption of the cognitive radio user's network.

In [143], the authors have achieved the optimal sensing and data transmission time in a frame of the cognitive radio user which maximizes the energy efficiency, however the throughput is limited due to high detection and low false-alarm probability requirement, which needed large sensing time duration resulting in small data transmission interval of the fixed frame duration. Therefore, Chatterjee et al. in [144] have considered joint spectrum sensing and data transmission method with the help of cognitive relays which has also maximized the throughput along with reliable sensing performance of the cognitive radio communication system. Further, in [144] the cognitive relays amplify and forward the cognitive user's source data to the destination in order to deal with the energy consumption issues. The optimal strategy for energy efficiency has been achieved with considering the interference threshold at the primary receiver, throughput of the cognitive user and high detection and low false alarm probability. However, the proposed method in [144] has delay issue because of no point-to-point communication among the source and destination cognitive users. However, in OFDM based cognitive radio network, the optimal power of the subcarriers has been computed with constraint on the total transmit power and interference constraint. The energy efficiency problem is a fractional programming method and different methods have been proposed for its solution [136, 145, 146]. In [145], the energy efficiency problem is first converted into convex programming problem and then iterative algorithm based on the sequential quadratic problem finds out the optimal power solution for the energy efficiency. However, the author's in [146] have converted the energy efficiency fractional programming problem into the parametric formulation and then dynamic strategy yield the optimal solution for the problem. Moreover, for the centralized cognitive radio network, the energy efficient heuristic algorithm is proposed in [136] for the optimal energy efficiency. However, the methods proposed in [136, 145, 146] for maximizing energy efficiency problem are complex for computation, therefore we have proposed a very simple method for easy computation of transmit power in order to maximize energy efficiency.

In this chapter, simple algorithm for computing the optimum transmit power of the cognitive radio for different channel gains which maximizes the energy efficiency has been proposed. The exchange of cognitive radio- request to send (CR-RTS) and cognitive radio- clear to send (CR-CTS) frame has provided the knowledge of channel gain and approximate distance of the cognitive transmitter and cognitive receiver, which are utilized for the computation of optimum transmit power for maximizing energy efficiency. Moreover, the cognitive user energy consumption in different intervals of the proposed MAC protocol that is the energy consumption in sensing-sharing, contention, and data transmission interval are also computed for the proposed algorithm. The simulation results are presented for the energy efficiency variation with the traffic load of licensed channels as well as for different channel gains. In this chapter, the minimization of energy consumption of the cognitive terminal in accessing the licensed channels through the distributed cognitive radio MAC protocol is proposed with simultaneously considering the throughput. Further, the algorithm for deciding the optimum transmit power of cognitive user is based on the channel conditions and distance metric. The chapter has been organized as follows. Section 5.2 discusses the system model. In Section 5.3 problem has been formulated and analysis is presented for the proposed scheme. Section 5.4 explores the results and discussion of the proposed system model. Finally, Section 5.5 concludes the work.

## 5.2 System Model

In this chapter, the main aim is to design a self-scheduled-MAC protocol for the cognitive radio network which maximizes the energy efficiency of the cognitive user, and schedules itself for having the highest energy efficiency. The cognitive user's optimum transmit power is computed through the proposed algorithm in Section 5.3 which maximizes the energy efficiency of the system. As similar to the proposed system design in the previous chapters, the MAC protocol have $N_{\mathrm{ch}}$ number of licensed channels and the idle channels utilized by the cognitive users have different channel characteristics which is defined by the following channel gain set: $H = \{h_1, h_2, \ldots h_{\mathrm{Nch}}\}$. Moreover, the $N_{\mathrm{CU}}$ number of cognitive users have maximum and minimum limit on the transmit power $P_{\mathrm{max}}$ and $P_{\mathrm{min}}$, respectively. In addition to this, the control channel is also available on which the cognitive users share the sensing results with each other. Moreover, we have assumed significantly high detection probability of the licensed channels such that probability of detection is almost equal to one and false alarm probability is ignored. The RTS frame is transmitted from the cognitive transmitter to the receiver during contention interval, in order to reserve the idle licensed channel and CTS frame is sent back to the transmitter from receiver, which contains the information about the channel gain of the reserved idle licensed channel. We have assumed the flat fading channels and cognitive receiver has information about the channel gain of the licensed channel. Moreover, the response interval of CTS frame is used for the calculation of distance between the transmitter and receiver of the cognitive user. With the help of this information, the optimum transmit power for the cognitive users are computed which maximizes the energy efficiency of the cognitive radio communication system and the rest of the system description is similar to the system that proposed in Chapter 2.

## 5.3 Problem Formulation and Performance Analysis

Our main aim is to maximize the energy efficiency [146] of the cognitive radio communication system, for which we have computed the optimum transit power. The energy efficiency of the proposed cognitive radio communication system is the ratio of the total amount of useful data delived to the total energy consumed and is given as:

$$EE = \frac{\text{Total amount of useful data delivered (bits)}}{\text{Total energy consumed (Joule)}} \tag{5.1}$$

where $EE$ is the energy efficiency of the proposed protocol. The total amount of useful data delivered by $i^{th}$ cognitive user is defined as throughput per cycle time and for a given licensed channel $k$ with probability of detection $\approx 1$ $(P_d \approx 1)$, is given as [146]:

$$R_i = w_k T_{tr} B \log_2 (1+SNR_k/\Gamma) \tag{5.2}$$

where $SNR_k$ is the received signal-to-noise ratio at the cognitive receiver on the $k^{th}$ licensed channel and $\Gamma$ is the SNR gap to channel capacity and is approximated as $\Gamma \approx -\frac{In(5BER)}{1.5}$ for an uncoded *M-QAM* with a given bit-error-rate (BER) [146]. *B* is the bandwidth of channel *k*. Further, the $\mathrm{SNR}_k$ is given as follows [146]:

$$\mathrm{SNR}_k = \frac{\rho_k h_k Pt_i}{LN_0 BN_f} \tag{5.3}$$

where $\rho_k = \left(\frac{c}{4\Pi d f_k}\right)^2$ measures the propagation loss for distance *d* between the cognitive transmitter and cognitive receiver and at $f_k$ carrier frequency of channel *k*. $Pt_i$ is the transmit power calculated for the $i^{th}$ cognitive user over channel *k* having channel gain $h_k$. *L* is the link margin compensating the hardware process variation and imperfection [146]. $N_0$ is the noise power spectral density, $N_f$ is the receiver noise figure, therefore $N_0 BN_f$ is the noise power at the receiver front end. Moreover, $w_k$ which is defined in [146] is the probability of accurately detecting the state of the licensed channel *k*, and is given as [146]:

$$w_k = \frac{(1-\alpha)(1-P_{f,k})}{(1-\alpha)(1-P_{f,k})+\alpha(1-P_{d,k})} \tag{5.4}$$

where $P_{f,k}$ and $P_{d,k}$ are the probability of false detection and probability of accurate detection of licensed channel *k*. Moreover, the energy consumed in sensing-sharing interval by a cognitive user which senses $Ch_{max}$ number of channels is:

$$E_{ss_i} = T_{s\_slot} P_{s\_slot} Ch_{max} + T_{s\_slot} P_{s\_idle} (N_{ch} - Ch_{max}) \tag{5.5}$$

where $T_{s\_slot}$ is the single sensing-sharing slot duration, $P_{s\_slot}$ and $P_{s\_idle}$ are the sensing and idle mode power of the cognitive user in a sensing-sharing slot. The first term of (5.5) computes the amount of energy consumption for sensing and sharing the results by $i^{th}$ cognitive user and second term gives the energy consumed by $i^{th}$ cognitive user for rest of the sensing-sharing interval in which the sensing is not performed by $i^{th}$ cognitive user. The difference in the energy computed in (3.26) and (5.5) is that in (3.26) the whole energy consumed by all cognitive users is computed and in (5.5) only single cognitive user energy consumption is computed. Further, the energy consumption by the $i^{th}$ cognitive user in the contention interval is:

$$E_{ct_i} = T_{ct\_slot} P_{ct\_slot} + T_{ct\_slot} P_{ct\_c} N[C] + T_{ct\_slo\,t} P_{ct\_idle} \left(CW_{total} - (N[C]+1)\right) \tag{5.6}$$

In (5.6), the first term gives the energy consumed by $i^{th}$ cognitive user during the successful contention slot, the second term represents the energy consumption in collided contention slot/slots, and the third term computes the energy during the idle contention slots. $N[C]$ is the number of collisions of the $i^{th}$ cognitive user in the $CW_{\mathrm{total}}$ contention slots. Moreover, the $i^{th}$ cognitive user energy consumption in the data transmission interval is [146]:

$$E_{\mathrm{tr}_{\mathrm{i}}} = T_{\mathrm{tr}}(\beta Pt_{\mathrm{i}} + P_{\mathrm{c}}) \tag{5.7}$$

where $\beta = \frac{\xi}{\varsigma}$ and $\xi$ is the peak-to-average ratio (PAR) of the power amplifier, $\varsigma$ is the drain efficiency of the power amplifier and $P_{\mathrm{c}}$ is the amount of power consumed by the transmitter and receiver circuit except of power amplifier which is a constant value [146]. Therefore, the total energy consumed by $i^{th}$ cognitive user in the single cycle time is:

$$E_{\mathrm{total}\,i} = E_{\mathrm{ss}_{\mathrm{i}}} + E_{\mathrm{ct}_{\mathrm{i}}} + E_{\mathrm{tr}_{\mathrm{i}}} \tag{5.8}$$

Further, in case the data is not transmitted over the transmission interval, then the total energy consumption of the cognitive user is:

$$\mathrm{E}_{\mathrm{total}\,i} = E_{\mathrm{ss}_{\mathrm{i}}} + E_{\mathrm{ct}_{\mathrm{i}}} \tag{5.9}$$

Therefore, the energy efficiency defined in (5.1) is formulated as:

$$EE = \sum_{k=1}^{N_{\mathrm{CU}}} \frac{R_{\mathrm{i}}}{E_{\mathrm{total}\,i}} \tag{5.10}$$

where $R_{\mathrm{i}}$ is the data rate and $E_{\mathrm{total}\,i}$ is the total energy consumption of the $i^{th}$ cognitive user. Furthermore, the assignment of the power to the different cognitive users for maximizing the energy efficiency is performed according to the following proposed algorithm:

**Proposed Algorithm**

**Step1:** *Variable declaration*

$N_{CU}$ = Number of cognitive users in the network.

$P_{\max}$ = Maximum transmit power allowed by a cognitive user.

$P_{\min}$ = Minimum transmit power allowed by a cognitive user.

$h_{\mathrm{k}}$ = Channel gain of the licensed channel *k*.

$CU_{\mathrm{i}}$ = $i^{th}$ cognitive user.

**Step2:** *Computation of optimum transmit power that maximizes the energy efficiency of* $CU_i$

$$Pt_i \leftarrow \underbrace{arg\ max}_{Pt_i}\ EE$$

Assign power $Pt_i$ to $CU_i$ for transmitting data in the data transmission interval. This step is followed for all $N_{CU}$ cognitive users and optimum transmit power is calculated for all the users.

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The above algorithm describes the simple linear optimization with constraints on the power that is the transmit power of cognitive users within the defined minimum and maximum transmit power limit. The aim of proposed linear optimization is to maximize the energy efficiency as defined in (5.10) and find the transmit power which resulted the maximum energy efficiency with the given constraints. Further, the complexity of the proposed algorithm is $O(N)$, where $N$ is the number of input power levels used for computation of the energy efficiency.

**5.4 Simulation Results**

The simulation parameters for the proposed method in this chapter are shown in Table 5.1. The energy efficiency variation of a cognitive user which is transmitting on the idle channel for the different channel gains and having utilization probability $\alpha = 0.5$ is shown in Fig. 5.1. From Fig. 5.1, it is clear that there is an optimum value of transmit power at which the energy efficiency has been maximized and this transmit power is computed during the contention interval by the algorithm proposed in Section 5.3. The cognitive user transmits at this optimum power in the data transmission interval to maximize the energy efficiency. Moreover, Fig. 5.1 interprets that as the channel condition is becoming good due to increase in the value of channel gain parameter, the energy efficiency is also improving. Further, Fig. 5.2 has depicted the energy efficiency with the transmit power for different traffic utilization probability. It is interpreted from Fig. 5.2 that with the increase in traffic load probability, the energy efficiency is decreasing.

Moreover, in Fig. 5.3 the optimum transmit power computed from the proposed algorithm is simulated for different channel gains and distances of cognitive radio transmitter and receiver. It is illustrated from Fig. 5.3 that with increase in the value of distances and for less channel gain, the transmit power requirement is more than that for the small distances and higher channel gain because the higher channel gains will deliver cognitive user information with higher data rate than that for lesser channel gains and hence the energy efficiency is high for the same circuit power consumption. Similarly, the higher distant user need higher power and vice versa.

**Table 5.1** The simulation parameters of the proposed system model.

| Simulation Parameters | Numerical values |
|---|---|
| Number of licensed channels ($N_{\mathrm{ch}}$) | 20 |
| Utilization probability of licensed channels (α) | 0-1 |
| Number of sensed channels by each cognitive user ($Ch_{\max}$) | 2 |
| Number of cognitive users ($N_{\mathrm{CU}}$) | 10 |
| Probability of false alarm ($P_{f,k}$) | 0.1 |
| Probability of detection ($P_{d,k}$) | 0.9 |
| Cycle time ($T_{\mathrm{cycle}}$) | 1s |
| Channel bandwidth ($B$) | 200kHz |
| Carrier frequency ($f_{\mathrm{k}}$) | 800MHz |
| Noise PSD ($N_0$) | -115dB |
| Noise figure | 10dB |
| Link margin (L) | 10dB |
| Distance between cognitive transmitter and receiver (d) | 100m-1000m |
| Bit error rate (BER) | $10^{-5}$ |
| Minimum transmit power limit ($P_{\min}$) | 100mW |
| Maximum transmit power limit ($P_{\max}$) | 3W |
| Circuit power (Pc) | 210mW |
| Idle interval ($T_{\mathrm{idle}}$) | 1ms |
| Data transmission interval ($T_{\mathrm{tr}}$) | 862ms |
| Sensing-sharing slot interval ($T_{\mathrm{s\_slot}}$) | 900us |
| Sensing power ($P_{\mathrm{s\_slot}}$) | 110mW |
| Idle power ($P_{\mathrm{s\_idle}}$) | 50mW |
| Contention slot interval ($T_{\mathrm{ct\_slot}}$) | 2ms |
| Successful contention slot power ($P_{\mathrm{ct\_slot}}$) | 110mW |
| Idle contention slot power ($P_{\mathrm{ct\_idle}}$) | 50mW |
| Collided contention slot power ($P_{ct\_c}$) | 120mW |
| Total number of contention slots ($CW_{\mathrm{total}}$) | 68 |
| PAR (ξ) | 6dB |
| Drain efficiency (ς) | 0.35 |

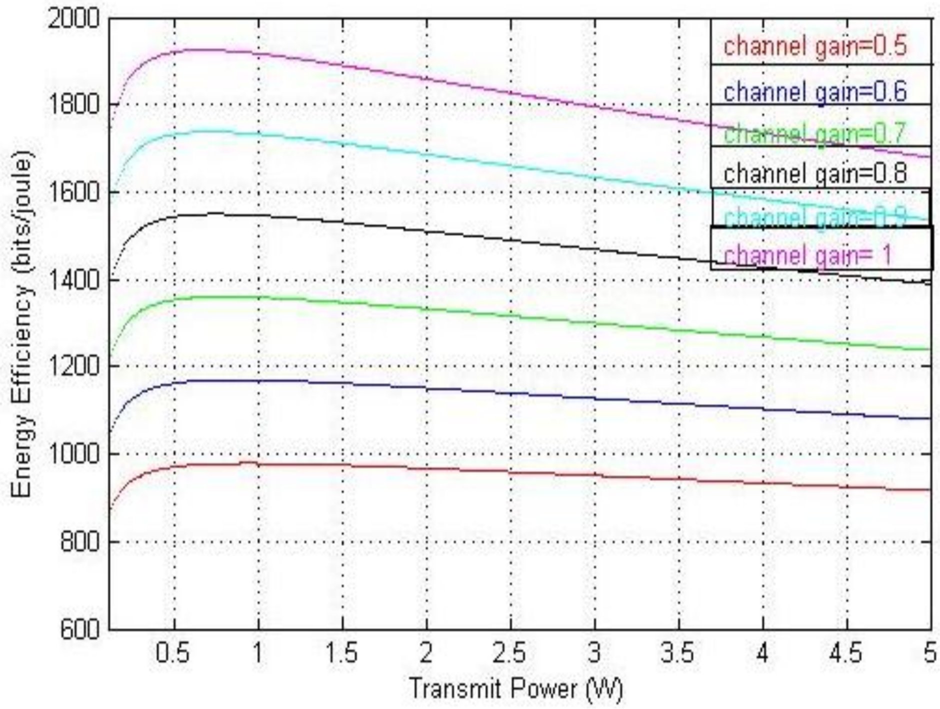



**Fig.5.1** The effect of the variation of transmit power of the cognitive user on the energy efficiency for different channel gain with α = 0.5 and d = 800m.

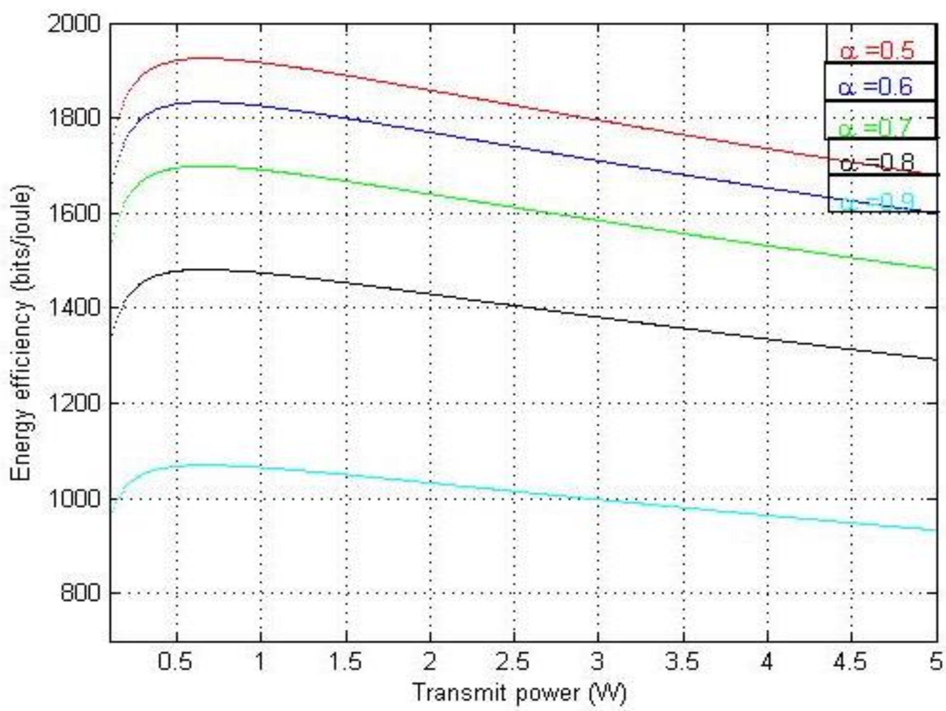



**Fig. 5.2** Variation of the transmit power of the cognitive user with energy efficiency for different traffic utilization probability and with channel gain 0.8.

Further, Fig. 5.4 has shown the energy efficiency of a cognitive user with the different values of traffic load for different channel gain values. In Fig. 5.4, the optimum transmit power which is computed from the proposed algorithm in Section 5.3, is utilized for different channel gains for the computation of energy efficiency and it is clear that the higher values of channel gains have enhanced energy efficiency of the cognitive user.

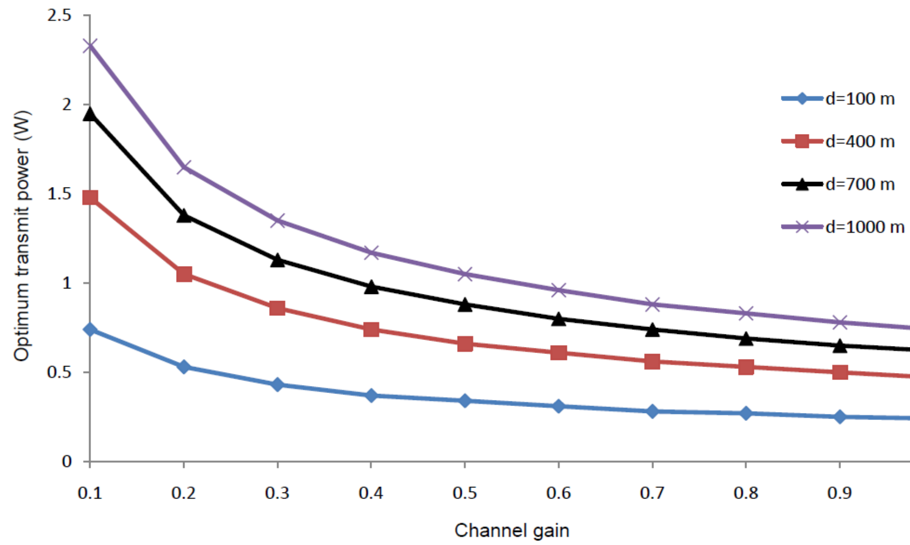



**Fig. 5.3** The response of the channel gain over the optimum transmit power with different cognitive user distances at chosen value of α=0.5.

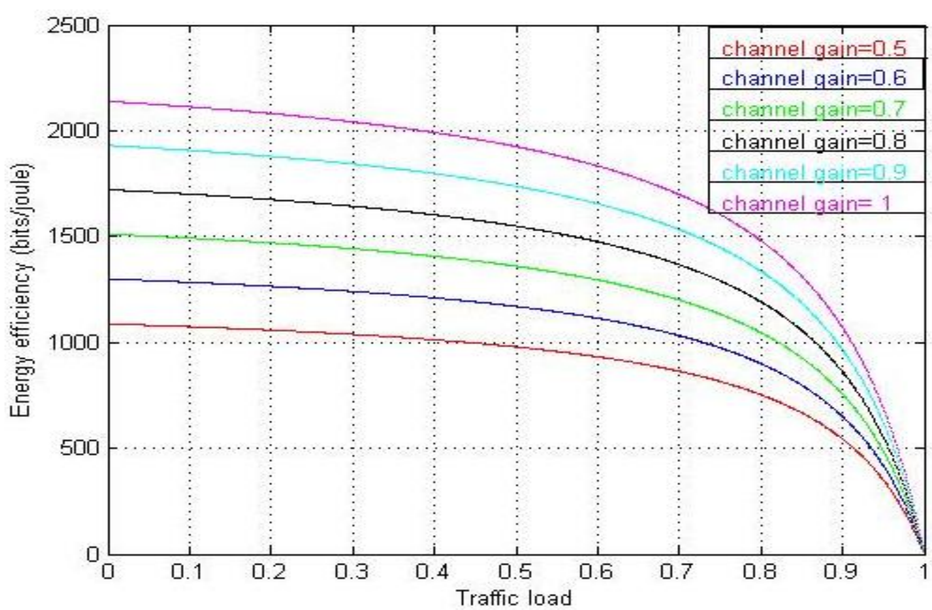



**Fig. 5.4** The response of traffic load at optimum transmit power over the energy efficiency for different channel gains for chosen distance of d=800m.ξ

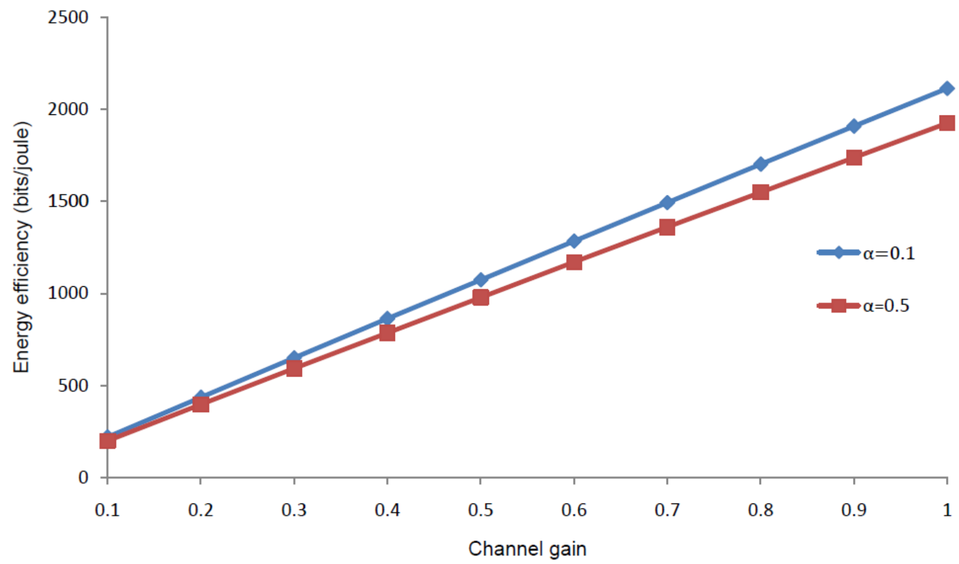



**Fig. 5.5** The effect of variation in the channel gain over energy efficiency of 10 cognitive user networks for different traffic loads.

However, in Fig. 5.5 the average value of the energy efficiency is simulated for all the 10 cognitive users for traffic load utilization of 0.1 and 0.5. Furthermore, by utilizing the information about the idle channels availability, we have computed the energy efficiency of the whole system. Since, the number of idle channels present in the system is less for higher traffic load than at lower values, therefore throughput for the latter case is higher than former while energy consumption is similar and hence energy efficiency is higher at low traffic load which is depicted from Fig. 5.5.

## 5.5 Conclusion

In this chapter, we concern about the energy efficiency of cognitive radio terminal and have obtained the optimum transmit power for the cognitive terminal at which the energy efficiency is maximum. It is further shown that the complexity of proposed algorithm for computing the optimum transmit power is very less. We have considered different scenario of channel conditions at different channel gain and have maximized the energy efficiency of the cognitive radio terminal.

# CHAPTER 6

# Cognitive Radio User Frame-Structure for Data Loss Rate Reduction and Throughput Maximization

## 6.1 Introduction

It is well known that in MAC protocol, the data is transmitted in frames therefore, in this chapter we have considered the frame structure of the cognitive radio user and have dealt with the sensing-throughput tradeoff problem in cognitive radio system. The cognitive radio users trying to access the licensed spectrum should consider the impact of their transmission on the reception quality of the primary licensee. In addition to this, the secondary access does not affect primary user (PU) operation as long as the total interference power at the primary receiver remains below a certain threshold. For a wireless receiver, any signal other than the signal originally destined to be received by that receiver is considered as interference [147, 148]. Therefore, one of the main difficulties of allocating resources to the cognitive radio (CR) systems is that the interference power generated by its users at the PU receiver should not exceed the predefined threshold [149] in order to protect the primary users. A potential approach has been proposed with aim to increase the throughput of cognitive radio user, in which the cognitive radio user first senses the status (active/idle) of a frequency band and then avoids harmful interference to PU by adapting transmit power based on the spectrum sensing decision [150, 151]. The significant parameters related to the spectrum sensing are: 1) false-alarm probability and 2) detection probability. It is required that false alarm probability should be low to maximize the opportunity of cognitive user data transmission. On the other hand, the higher detection probability provides better PU transmission protection. The cognitive user that employs conventional frame structure is shown in Fig. 6.1, in which first sensing and then transmission is performed and it depicts that the cognitive user ceases data transmission at the beginning of each frame. The spectrum sensing is performed firstly for $\tau$ units of time and then data is transmitted for remaining frame duration that is for ($T-\tau$). However, there is a potential problem in this scheme because it is well known from the classical detection theory [152, 153] that an increase in the sensing time results higher probability of detection and lower probability of false-alarm however, it results the less data transmission time and hence limits throughput of the cognitive radio user causing sensing-throughput tradeoff problem [154]. Apart from the sensing-throughput trade-off, there is another problem of unpredictable PU transmission during the transmission time of cognitive user.

In order to avoid the sensing-throughput trade-off and to maximize the throughput of spectrum sharing cognitive radio networks, an approach has been proposed by Stotas and Nallanathan in [155, 156]. The frame structure for this approach is shown in Fig. 6.2, in which both the spectrum sensing and data transmission is performed at the same time and for whole frame duration that increases both the sensing time and data transmission time. This enhancement in the sensing time provides better performance in the form of decreased false-alarm as well as increased detection probability and consequently, we achieved significant enhancement in the throughput of cognitive radio user [156]. This approach determines the action of cognitive radio user in the next frame which is based on the sensing decision of the previous frame. Moreover, the cognitive user adapts its transmit power in the next frame to stop transmission, in case the sensing result of previous frame shows PU transmission and resumes transmission if PU is not transmitting. Hence, the harmful interference to the PUs can be avoided. For example, as shown in Fig. 6.2, the sensing which has been performed during the frame $n$ is being utilized for data transmission in frame ($n$ + 1). The cognitive user during frame ($n$ + 1) transmits data in case sensing in the frame $n$ shows idle PU and vice-versa. However, potential problem arises if during the transmission time of cognitive user that is suppose during frame ($n$ + 1), the PU becomes active from previous frame's (frame $n$) idle state but cognitive user is not aware to this fact since current frame's (frame $n+1$) sensing results are not present. Therefore, based on the sensing decision of frame $n$, the cognitive user transmits, which results collision of the cognitive user's frame ($n + 1$) with the PU's frame and all the data carried in the collided frame will be lost. This problem has been until discussed only for case where the sensing and transmission are performed alternatively [157]. In this chapter, we have emphasized on this problem.

The remainder of the chapter has been organized as follows. Section 6.2 describes the system model of the cognitive user and problem formulation. Moreover, a novel approach for the cognitive user's data transmission has been proposed with the frame structure for data transmission in Section 6.2. Further, in Section 6.3, throughput and data loss rate for the proposed scheme has been discussed and Section 6.4 shows the numerically simulated results. Finally, Section 6.5 concludes the chapter.

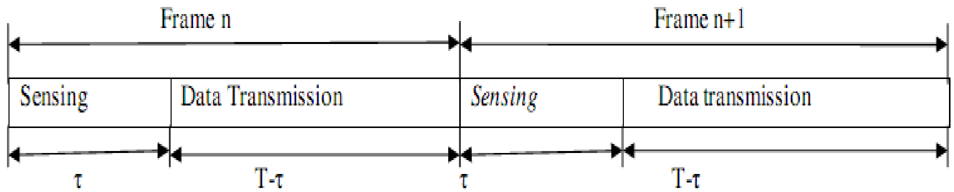



**Fig. 6.1** The frame structure of conventional sensing-based spectrum sharing approach for cognitive radio networks.

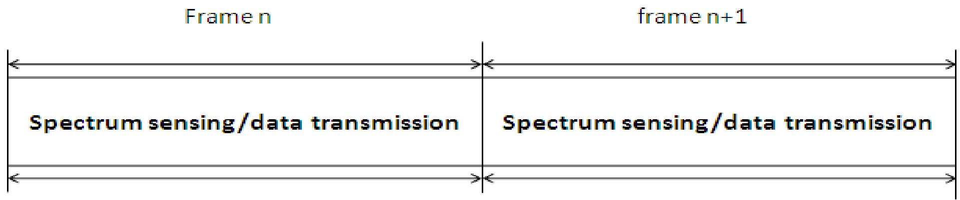



**Fig. 6.2** The frame structure of the proposed approach.

## 6.2 System Model and Problem Formulation

We have considered a primary user network utilized by the cognitive user. The cognitive user performs an initial spectrum sensing on the allocated spectrum band for knowing the current status of the channel. Based on the sensing result, the secondary transmitter communicates if the sensing result detects absence of primary user data transmission on that spectrum band and avoids transmission if primary user is transmitting. The secondary receiver decodes the signal sent by the secondary transmitter, strips it away from the received signal and uses the remaining signal to perform spectrum sensing so that the action of cognitive radio user in the next frame is determined. Further, at the end of the frame, if the status of primary user has changed after the initial spectrum sensing, the cognitive user adapts it's transmit power based on the sensing decision to avoid causing the harmful interference to the primary users and minimize the cognitive user data loss rate.

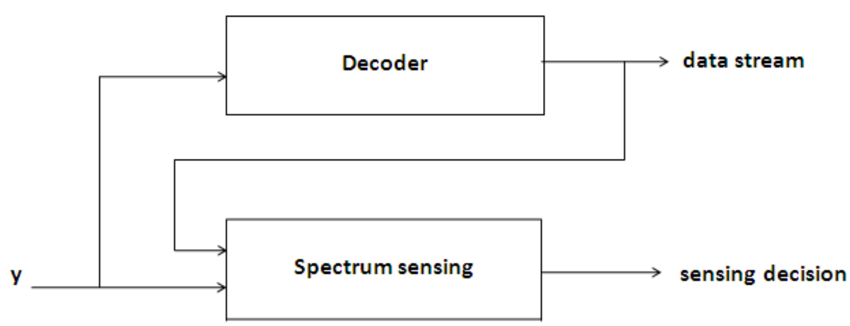



**Fig. 6.3** The receiver structure of cognitive user for the frame structure shown in Fig. 6.2 [156].

### 6.2.1 Cognitive receiver structure

The cognitive radio receiver structure for the cognitive radio user in which the spectrum sensing and data transmission is performed simultaneously is shown in Fig. 6.3. The received signal at the cognitive radio user is given by [156]:

$$y = \theta s_{\mathrm{p}} + h_{\mathrm{s}} x_{\mathrm{s}} + w(t) \tag{6.1}$$

where $\theta$ denotes the actual status of the frequency band ($\theta$ = 1 if the band is active and $\theta$ = 0 when it is idle) and $s_{\mathrm{p}}$ denote the received signal from the PU on that frequency band. Further, $h_{\mathrm{s}}$ denotes the channel gain between the cognitive transmitter and the cognitive receiver, $x_{\mathrm{s}}$ represents the signal from the cognitive transmitter and $w$(t) denotes the additive white Gaussian noise (AWGN). The received signal is initially passed through the decoder as shown in Fig. 6.3, which decodes the signal from the secondary transmitter. The signal from the cognitive transmitter is cancelled out from the aggregate received signal $y$, given in (6.1), therefore the remaining signal is:

$$\tilde{y} = \theta s_{\mathrm{p}} + w(t) \tag{6.2}$$

This signal represented in (6.2) is used for the spectrum sensing. This is the signal that cognitive receiver would receive if cognitive transmitter ceases transmission.

### 6.2.2 Frame structure

In the frame structure shown in Fig. 6.2, the sensing and data transmission is performed simultaneously for whole frame duration $T$, so that throughput is maximized as compared to the conventional frame structure in Fig. 6.1. The frame structure shown in Fig. 6.2 has following advantages:

1) It enables the detection of very weak PU signals, the detection of which under frame structure of Fig. 6.1 would significantly reduces the data transmission time due to large sensing time requirement.
2) It leads to an improved detection probability, thus better protection of the PUs from harmful interference,
3) It results significantly reduced false-alarm probability, which enables a better utilization of the available unused spectrum,
4) The computation of optimal sensing time as in the conventional frame structure [154] is no longer an issue, since it is maximized and is equal to the frame duration, and

5) The continuous spectrum sensing can be achieved under the proposed cognitive radio system, which ensures better protection of the primary networks.

Apart from the aforementioned advantages of the frame structure shown in Fig. 6.2, there is a technical problem in this frame structure because sensing result of the previous frame is used by the next frame for making data transmission decision on the sensed spectrum. Therefore in that case, if during the transmission in a frame, primary user changes the state (for example, if $\theta$ changes from 0 to 1), the cognitive user's frame collides with the primary user's data due to the current frame's sensing results not being used in the same frame to stop the cognitive user's data transmission and all the data carried in collided frame will be lost. To reduce the data loss due to collision, we have proposed a (Fig. 6.4) novel frame structure, which is modified form of Fig. 6.2. In this modified frame structure, the sensing and data transmission are performed simultaneously however, instead of sending one long block of data in each frame shown in Fig. 6.2, we send multiple shorter blocks (sub-frames) of data as shown in Fig. 6.4 and the data transmission is for whole frame duration $T$. In addition to this, the sensing results of the previous frame and current frame that is computed till the start of the sub-frame, both are utilized for transmitting sub-frame of a frame as shown in Fig. 6.4. The sensing results computed throughout the previous frame and till the particular sub-frame in the current frame, both are used to either stop or resume cognitive user's data transmission. The previous frame's whole sensing duration ($T$ ms) results in high detection and low false alarm probability and the current frame's sensing duration till the start of the next sub-frame reduces the data loss rate in case PU's presence has been detected in that duration of the current frame.

Now, if during the transmission in a frame, PU changes from idle to active ($\theta$ changes from 0 to1) and its presence is detected by sensing in the frame, only the data carried in the collided sub-frame of that frame will be lost and all the earlier sub-frame's are transmitted successfully along with the avoiding transmission of next sub-frame's to prevent collision with primary user. Therefore, it is required that shorter the sub-frame duration (($T/n$) *ms*, where $n$ is the number of sub-frames in a frame) less will be data loss rate and collision with primary users. However since we know that in a frame, some control information is required to be transmitted along with information for each frame's successful delivery to its receiver as shown in Fig. 6.4, where frame overhead specifies the control information. In addition to this, in the proposed scheme where we are dividing each frame into multiple sub-frames, and have to add overhead with each sub-frame of approximately of the same amount as that that has been added in the single long frame.

Therefore, the proposed scheme has decreased the data loss rate at the cost of increased overhead and it needs to be specified by the cognitive user that how much data loss it can tolerate. Further the effective throughput, which is the throughput of useful data that is of information without including overhead throughput, and data loss rate both decreases as we increases the number of sub-frames therefore, there is tradeoff between the number of sub-frames and effective throughput. Hence in the proposed scheme, the sensing result of the previous frame and same frame that is calculated up till current sub-frame has removed the limitations of Fig. 6.2 in which only previous frame's sensing result is applied to current frame. Further, this method is an efficient method for cognitive user's data transmission as compared to that of conventional cognitive user data transmission with alternate sensing and data transmission time.

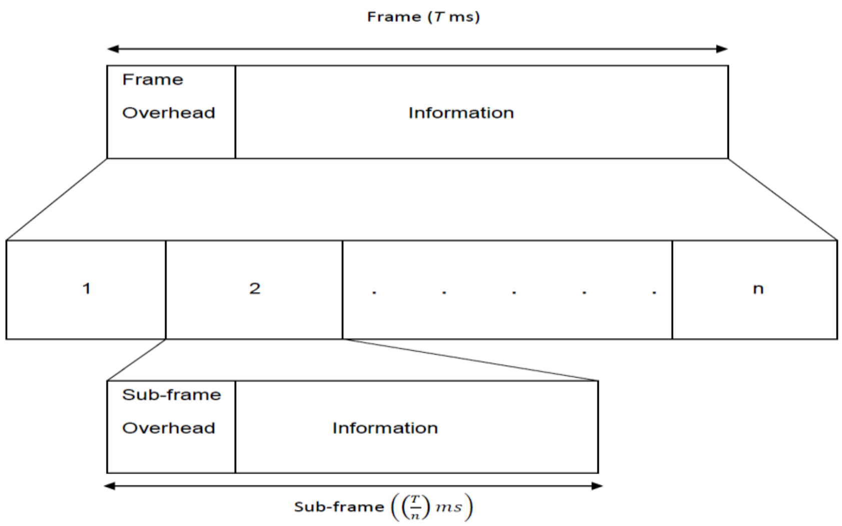



**Fig. 6.4** The detailed frame structure of the proposed scheme.

### 6.3 Throughput Analysis

There are two probabilities of interest defined under the hypothesis model, which are used for the spectrum sensing:

1) probability of detection ($P_d$), which is defined as the probability of algorithm correctly detecting the presence of primary signal under hypothesis $H_1$ [14], and
2) probability of false-alarm ($P_f$), which is defined as the probability of algorithm falsely declaring the presence of the PU's signal under hypothesis $H_0$, [14].

Earlier as have discussed, from the PU's perspective, if the probability of detection is high, the primary receiver protection is better. However, from the cognitive user's perspective, if the probability of false-alarm is low, there are more chances of free spectrum being correctly detected and used by cognitive users. Obviously, for a good detection algorithm, the probability of detection should be as high as possible while the probability of false-alarm should be as low as possible. $P(H_0)$ and $P(H_1)$ are the probabilities that frequency band is idle and active, respectively. Therefore, with the given target probability of detection $\overline{P_{\mathrm{d}}}$, for which the PUs are defined as being sufficiently protected, the probability of false-alarm is defined as follows [156]:

$$P_{\mathrm{f}} = Q\left(\sqrt{2\gamma + 1}Q^{-1}(\overline{P_{\mathrm{d}}}) + \sqrt{\tau f_{\mathrm{s}}}\gamma\right) \tag{6.3}$$

On the other hand, for a target probability of false-alarm $\overline{P_{\mathrm{f}}}$, the detection probability is given by [156]:

$$P_{\mathrm{d}} = Q\left(\frac{1}{\sqrt{2\gamma+1}}\left(Q^{-1}(\overline{P_{\mathrm{f}}}) - \sqrt{\tau f_{\mathrm{s}}}\gamma\right)\right) \tag{6.4}$$

In Equation (6.3) and (6.4), $\gamma$ is the signal-to-noise ratio of the PU's signal at the secondary detector, $f_{\mathrm{s}}$ is the sampling frequency. $N$ is the number of samples used for the spectrum sensing by cognitive user where $N = \tau f_s$. The energy detection is most popular spectrum sensing technique and its test statistics for received signal $y$ is given as follows:

$$T(y) = \frac{1}{N}\sum_{n=1}^{N}|y(n)|^2$$

where $T(y)$ is a random variable whose value determines the presence and absence of PU by cognitive user's sensing technique. $Q$ is the complementary unit Gaussian distribution function and is defined as [157]:

$$Q(x) = \int_x^\infty \frac{1}{\sqrt{2\pi}} exp\left(-\frac{\mathrm{u}^2}{2}\right) du \tag{6.5}$$

and,

$$Q^{-1}(x) = 1 - Q(x) \tag{6.6}$$

Also,

$$P(H_0) = 1 - P(H_1) \tag{6.7}$$

Therefore, for conventional scheme the throughput of a cognitive radio user is given by the expression [154]:

$$Th_{\text{conv.}} = \frac{T-\tau}{T}\left[P(H_1)(1-P_{\text{d}})\log_2\left(1+\frac{SNR_{\text{s}}}{1+SNR_{\text{p}}}\right)+P(H_0)(1-P_{\text{f}})\log_2(1+SNR_{\text{s}})\right] \tag{6.8}$$

The equation (6.8) represents the throughput for frame structure of Fig. 6.1. $SNR_{\text{s}}$ is signal-to-noise ratio of the secondary link that is signal-to-noise ratio from cognitive transmitter to cognitive receiver and $SNR_{\text{p}}$ is the signal-to-noise ratio of the primary user signal at the receiver of the cognitive transmission link. The frame structure of Fig. 6.1 whose throughput is given by (6.8) disrupts the continuous communication in the spectrum sharing cognitive radio network and decreases throughput by the factor of $\left(\frac{T-\tau}{T}\right)$. However, for the proposed approach in which sensing and transmission is performed simultaneously, the expression for the throughput is given by:

$$Th_{\text{prop.}} = P(H_1)(1-P_{\text{d}})\log_2\left(1+\frac{SNR_{\text{s}}}{1+SNR_{\text{p}}}\right)+P(H_0)(1-P_{\text{f}})\log_2(1+SNR_{\text{s}}) \tag{6.9}$$

From (6.9), it is clear that throughput is not decreased by the amount $\left(\frac{T-\tau}{T}\right)$ as in the conventional approach because sensing and transmission are performed, simultaneously. Thus, by comparing (6.8) and (6.9), it is clear that throughput for the frame structure of Fig. 6.2 and Fig. 6.3 is more than that of the one represented in Fig. 6.1. Further, the effective throughput of a single frame in the proposed scheme which is defined as the throughput of the useful information has been given by:

$$\begin{aligned} Th_{\text{eff}} &= P(H_1)(1-P_{\text{d}})\log_2\left(1+\frac{SNR_{\text{s}}}{1+SNR_{\text{p}}}\right)+P(H_0)(1-P_{\text{f}})\log_2(1+SNR_{\text{s}}) - \frac{x\times n}{T}\times \\ &\quad \left(P(H_1)(1-P_{\text{d}})\log_2\left(1+\frac{SNR_{\text{s}}}{1+SNR_{\text{p}}}\right)+P(H_0)(1-P_{\text{f}})\log_2(1+SNR_{\text{s}})\right) \end{aligned} \tag{6.10}$$

where $x$ denotes the overhead duration, $n$ and $T$ denotes the number of sub-frame's in a frame and frame duration, respectively. Since there is single frame in the frame structure proposed in [156], therefore, in this case we have $n=1$ that is there is single information block, however in our proposed scheme we have multiple information blocks in each frame. Furthermore, the data loss rate for the proposed scheme in a single frame is given by:

$$Data\ loss\ rate\ (\%) = \frac{1}{n}\times 100 \tag{6.11}$$

From the Equation (6.11), it is clear that higher the number of sub-frames in a frame less is the data loss rate. Hence, the proposed scheme with multiple sub-frames has less data loss rate in comparison to that of the earlier proposed scheme by the researchers in [156].

### 6.4 Simulation Results

In this section, we have presented the simulation results of the proposed frame structure and compared it with that of the earlier frame structures proposed. For the simulation, the frame duration is set to $T$ = *100 ms* and the probability for the active frequency band is $P(H_1)$ = 0.2, therefore from equation (6.7), $P(H_0)$ = 0.8. The received SNR from the secondary transmitter is $SNR_s = 20\,dB$, whereas the bandwidth of the channel and the sampling frequency $f_s$ are assumed to be 6 MHz. Moreover, overhead duration is taken *10 ms* that is *x=10 ms*. Further, in this section, we have numerically simulated the throughput of the cognitive user for the conventional and proposed frame structure by taking different values of SNR from the primary user. With the help of Fig. 4 of [156], we have compared the results for conventional and proposed approach for low SNR region. Since in the proposed scheme, the sensing and data transmission both have been performed simultaneously as also done by Stotas and Nallanathan in [156], therefore the throughput of proposed scheme as shown in Fig. 6.5 for different values of the PUs SNR and the target probability of detection 0.9999 ( $\bar{P}_d$ = 99.99%) is verified with that of Fig. 5 of [156]. Fig. 6.5 reveals that the throughput of cognitive user for higher values of the PU's SNR is much less than that of low values of the received SNR.

Furthermore, Fig. 6.6 compares the effective throughput of the proposed scheme and earlier reported scheme [156] for different SNR from the primary user. It is clear from Fig. 6.6 that the earlier scheme which have single sub-frame is having constant throughput however, the throughput of the proposed scheme decreases with increasing the number of sub-frames due to the increase in the amount of overhead. However, the higher throughput of the earlier scheme [156] is at the cost of higher data loss rate if the primary user resumes its transmission in the current frame which is shown in Fig. 6.7 . Fig. 6.7 represents the percentage of data loss with respect to the time at which the primary user comes back in a frame, when there are 4 sub-frames in the frame for the proposed scheme. For example, consider in the proposed scheme PU resumes transmission during first sub-frame of *100 ms* frame duration, then only first sub-frame is lost and all the remaining three sub-frames are avoided tranmission untill primary user becomes inactive, therefore only 25% data is lost in the proposed scheme. However in the earlier reported scheme [156], whole frame of duarion *100 ms* is lost in case primary user resumes transmission during this frame. Furthermore, only single sub-frame is lost in the proposed scheme irrespective of the time at which primary user comes back into transmission which has reduced the data loss rate of the proposed scheme in comparison to that of earlier scheme as shown in Fig. 6.7.

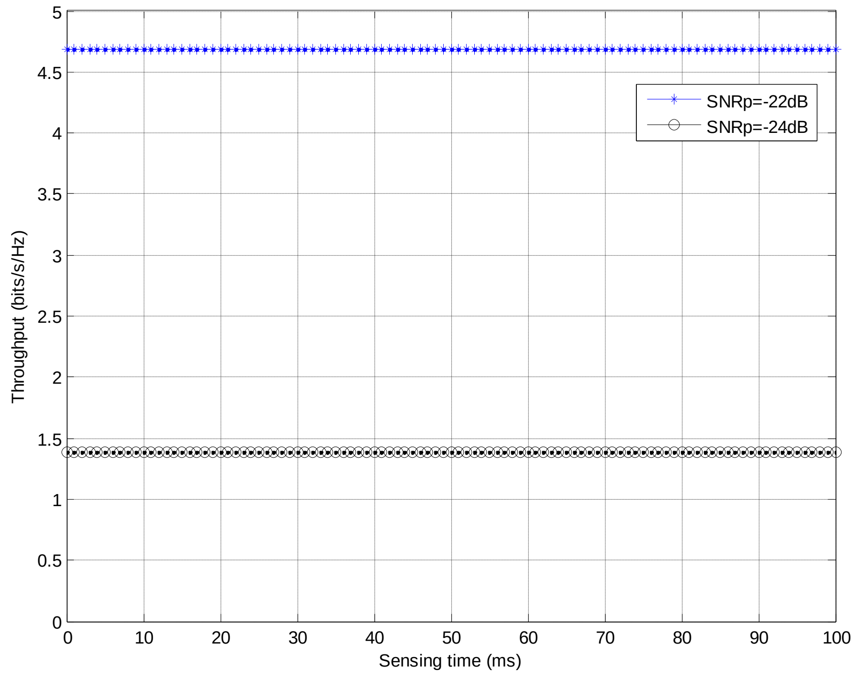



**Fig. 6.5** The throughput (bits/second/Hz) of cognitive user versus sensing time (ms) of the current frame for different values of the SNR from the PU.

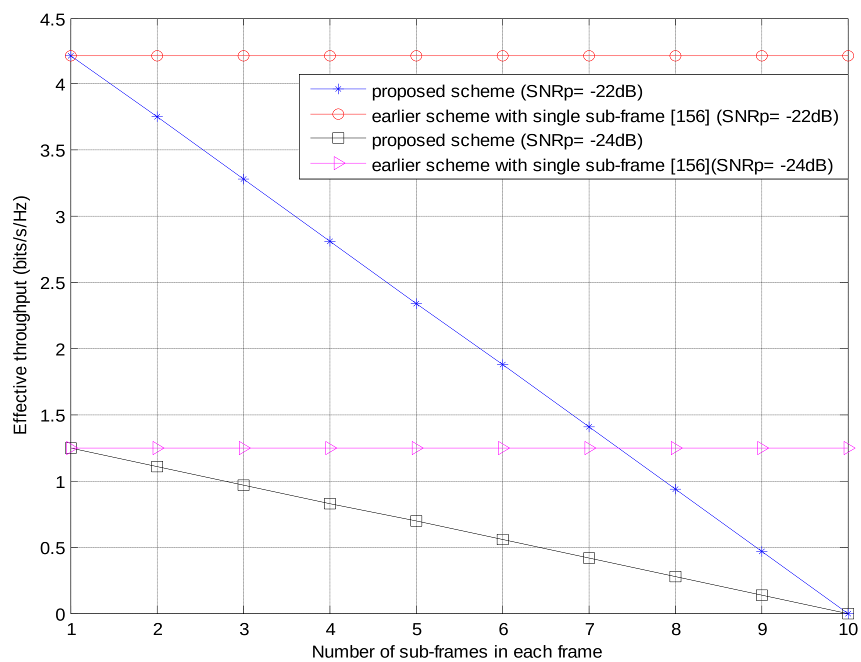



**Fig. 6.6** The response of the effective throughput with number of sub-frames in the proposed scheme and the earlier scheme [156] having single sub-frame, in 100 ms frame duration, 10 ms overhead and different SNR from primary users.

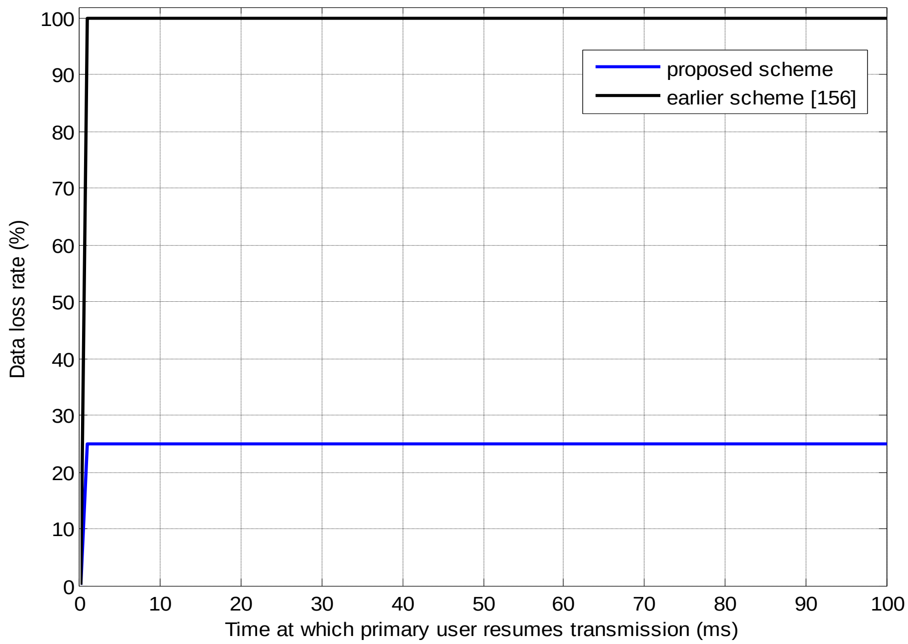



**Fig. 6.7** The response of the data loss rate in the proposed and earlier scheme [156] with the time at which primary user resumes transmission in a 100 ms frame duration with 4 sub-frames in the proposed scheme.

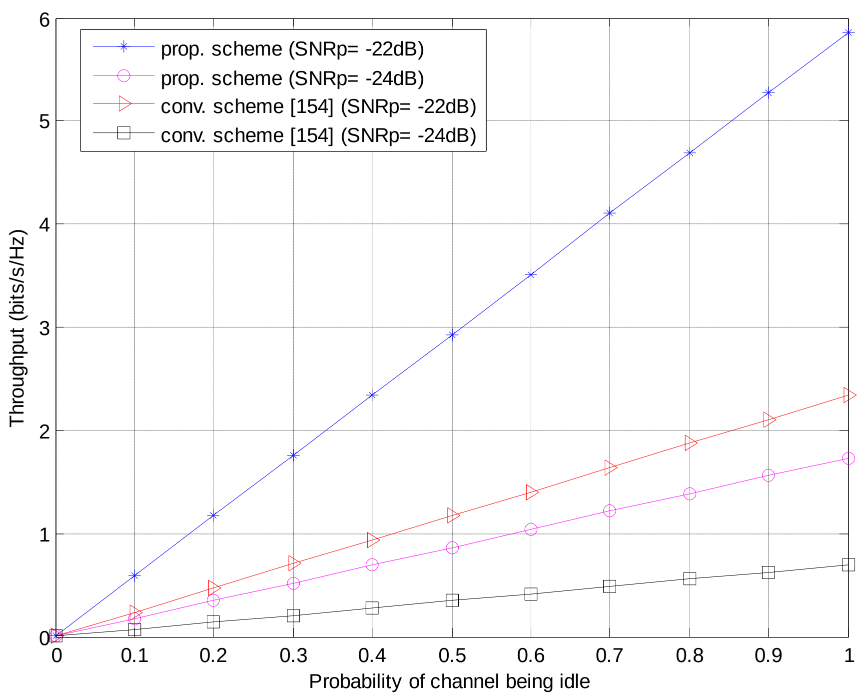



**Fig. 6.8** The throughput (bits/second/Hz) of the cognitive users versus probability of the primary user being idle $P(H_0)$ for different values the SNR from the primary user.

Fig. 6.8 represents the throughput versus $P(H_0)$ that is the probability of frequency band being idle for the chosen target probability of detection 99.99% and it is clear that as the probability of frequency band being idle increases, the throughput of the cognitive users is also increases and is more for the proposed approach as compared to that of the conventional approach where the sensing and data transmission are performed alternatively in a frame [154]. Moreover, Fig. 6.9 shows the variation of throughput of the cognitive users with the target probability of detection for the proposed scheme with different SNR from primary user. It is further depicted from Fig. 6.9 that as the target probability of detection increases, the throughput of cognitive user's decreases slightly, however in the conventional frame structure the throughput degradation rate is high with slight change in the target probability of detection as is clear from Fig. 6 of [156]. Thus, in the proposed approach, we have obtained the high protection of data in a frame against the interference for PU and significantly enhanced the throughput of cognitive users, simultaneously.

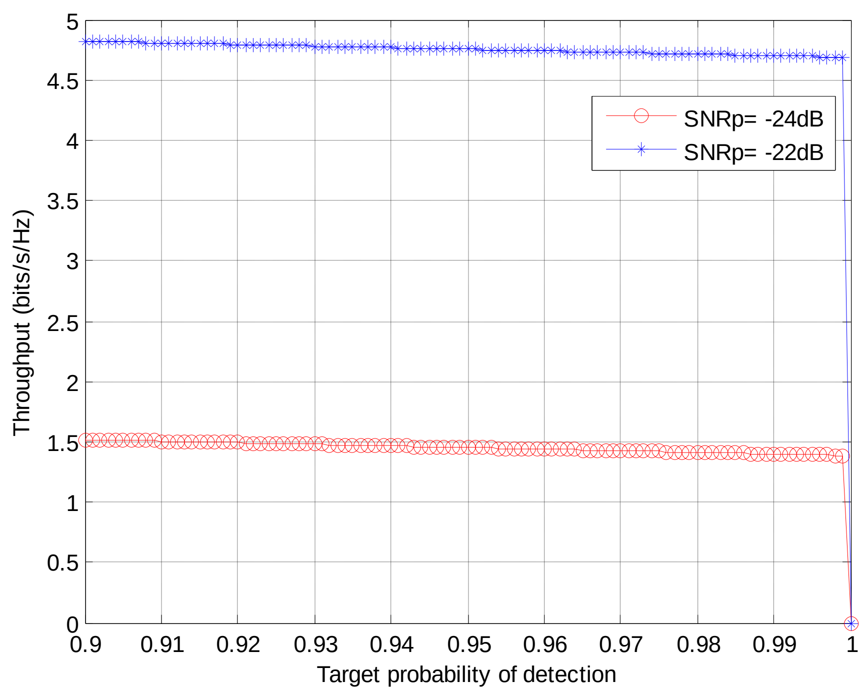



**Fig. 6.9** The throughput (bits/second/Hz) of the cognitive user versus target probability of detection for $SNR_p = -22dB$.

### 6.5 Conclusion

This chapter deals with the throughput maximization of the cognitive radio user with reduced data loss rate. We have compared numerically simulated results of throughput of the cognitive user for the proposed approach with that of the earlier approaches. The simulation results reveal that the significant improvement in the throughput of the cognitive user has been achieved for the proposed approach however, the method of simultaneous sensing and data transmission presented in [156] has a drawback that is solved by an enhancement in the frame structure discussed in this chapter. The frame structure enhancement has decreased the data loss rate in comparison to that of the earlier scheme. Thus, the data loss rate has been minimized by dividing the transmission time into small segments consisting of multiple sub-frames in a frame. Moreover, the effect of dividing a frame into multiple sub-frames on the effective throughput is also shown and the number of sub-frames versus effective throughput tradeoff problem is discussed. Therefore, in the proposed frame structure, the primary users are also adequately protected against the harmful interference by the cognitive user’s transmission in the same frequency band.

# CHAPTER 7

# Channel Capacity of Cognitive Radio in Fading Environment with CSI and Interference Power Constraints

## 7.1 Introduction

In general, the channel capacity is used as a basic performance measurement tool for the analysis and design of new and more efficient techniques to improve the spectral efficiency of wireless communication systems. The adaptive power transmission scheme that achieves the Shannon capacity under the fading environment is discussed in [158] and average transmit power constraint along with the availability of channel state information (CSI) at the cognitive transmitter have been initially considered in [159]. Further, the power optimization problem with peak and average transmit power constraints have been investigated [160]. However, in the spectrum-sharing systems, CSI is used at the cognitive/secondary transmitter to adaptively adjust the transmission resources as discussed in [161, 162]. In [162], the knowledge of secondary link CSI and information at secondary transmitter (ST)/cognitive radio transmitter about the channel between secondary transmitter and primary receiver (PR) have been used to obtain the optimal power transmission policy of the secondary user (SU) under the constraints on the peak and average received-power at the primary receiver. Ghasem and Sousa [163] have demonstrated that the secondary user may take advantage in the fading environment between the primary and secondary user by opportunistically transmitting with high power when its signal received by the licensed receiver is deeply faded.

One of the most efficient ways to determine the spectrum occupancy is to sense the activity of primary users operating in the secondary user's range of communication [27]. Practically, it is difficult for a secondary user to have direct access to the CSI pertaining to the primary user link. Recent works on the spectrum-sharing systems concentrated on sensing the primary transmitter's activity are based on the local processing at the secondary user side [164]. In this context, the sensing ability is provided by a sensing detector mounted on the secondary user's equipment, which scans the spectrum for specific time [13]. The activity statistics of the primary user's signal in the shared spectrum is computed and, based on the sensing information, the cognitive user has capability to determine the local presence of the primary transmitter in a specific spectrum band. For instance, the received signals at energy-based detector [17, 165] are used to detect the presence of unknown primary transmitters. However, using this sensing information obtained from the spectrum sensor and considering that the secondary transmitter does not has information about the state of its corresponding channel, the power adaptation strategy that maximizes the channel capacity of the secondary user's link is investigated in [166]. Rezki and Alouini in [167] have considered the limited/imperfect CSI at the secondary transmitter and computed the Ergodic channel capacity. Further, in [168] the power allocation for erroneous estimated channel gain between the secondary user and primary base station is performed through the geometric programming problem which is solved by Lagrange dual decomposition. However, only the underlay spectrum sharing model is considered in [168]. Parsaeefard and Sharafat in [169] have considered the cognitive nodes as relay nodes and illustrated the power and channel allocation strategy to the cognitive users in the Rayleigh fading environment. In [170], the rate loss constraint (RLC) is considered instead of conventional interference power constraint in order to protect the primary user, and the channel capacity of cognitive user which utilizes primary users OFDM (orthogonal frequency division multiplexing) subcarriers, is maximized by RLC and cognitive user transmit power constraint. However, in [167-170] the authors have computed the channel capacity of the cognitive user without considering the channel sensing information available at secondary transmitter.

In this chapter, we have emphasized on the cognitive radio wireless communication system with maximum achievable Ergodic channel capacity, considering single cognitive user. In a collaborative communication framework, either extra relay terminals assist the communication between some dedicated sources and their corresponding destinations and/or allow the users in a network to help each other to achieve higher communication system capacity than the single point-to-point communication between source and destination [171, 172]. However, in this chapter we have considered point-to-point communication between the cognitive users without any kind of cooperation/collaboration among them. Therefore, if more than one cognitive user's are competing to access the primary user's same spectrum hole, then due to probable inter cognitive user's interference the maximum achievable channel capacity is upper bounded by only single cognitive user's case. The proposed spectrum-sharing system has a pair of primary transmitter (PT) and PR as well as a pair of ST and secondary receiver (SR) as shown in Fig. 7.1. Further, the small-scale fading effects over the transmit power of secondary transmitter in the proposed system has been explored. However, in [173] such type of system model is considered without the fading in the link channel between the ST and PR. Therefore, the Ergodic channel capacity for the Nakagami-*m* fading channel in the secondary and primary links is the basic motivation of this chapter. The power of secondary transmitter is controlled based on the:

i) Sensing information about the primary user's activity, and
ii) CSI of secondary and primary link.

Moreover, the constraint on average interference at the primary radio receiver is considered for the channel capacity. Since the cognitive user is able to adapt any modulation strategy, therefore it can change its modulation strategy according to the fading environment and hence both adaptation policies in the rate and power are established [174], which is referred as the variable rate and power transmission scheme. In this context, we have also considered the variable rate and power *M*-QAM transmission strategy in the cognitive radio communication system where the rate and power of the ST is adaptively controlled based on the availability of secondary user's link CSI and the sensing information about the primary user's activity. Therefore, in this chapter we have numerically computed the channel capacity in fading environment under the average interference power constraint with two above aforementioned adaptation policies for the spectrum sharing. The channel capacity is maximized for these two policies by considering the Lagrange optimization problem for average interference power constraint. The small-scale fading effect over the transmit power of the secondary transmitter is also presented.

The remainder of the chapter is organized as follows. Section 7.2 concerns with the spectrum sharing system model. Further, Section 7.3 discusses about the power and rate adaptation policy and in Section 7.4 Ergodic channel capacity of the adaptation policies under Nakagammi-*m* fading is computed. In Section 7.5 the numerical simulation results of the proposed spectrum sharing model is presented and finally, Section 7.6 concludes the work.

## 7.2 Spectrum Sharing System

### 7.2.1 System model

This proposed spectrum-sharing system consists of a pair of PT and PR as well as a pair of ST and SR as shown in Fig 7.1. In this scenario, the secondary user is allowed to use the spectrum band assigned to the primary user as long as the interference power imposed by secondary transmitter on the primary receiver is less than a predefined threshold value that is the interference temperature limit. We have considered that the primary user link that is the channel between the PT and PR is a stationary block-fading channel. According to the definition of block-fading, the channel gain remains constant over some block length $T$ and after that time, the channel gain changes to a new independent value based on its distribution [173].

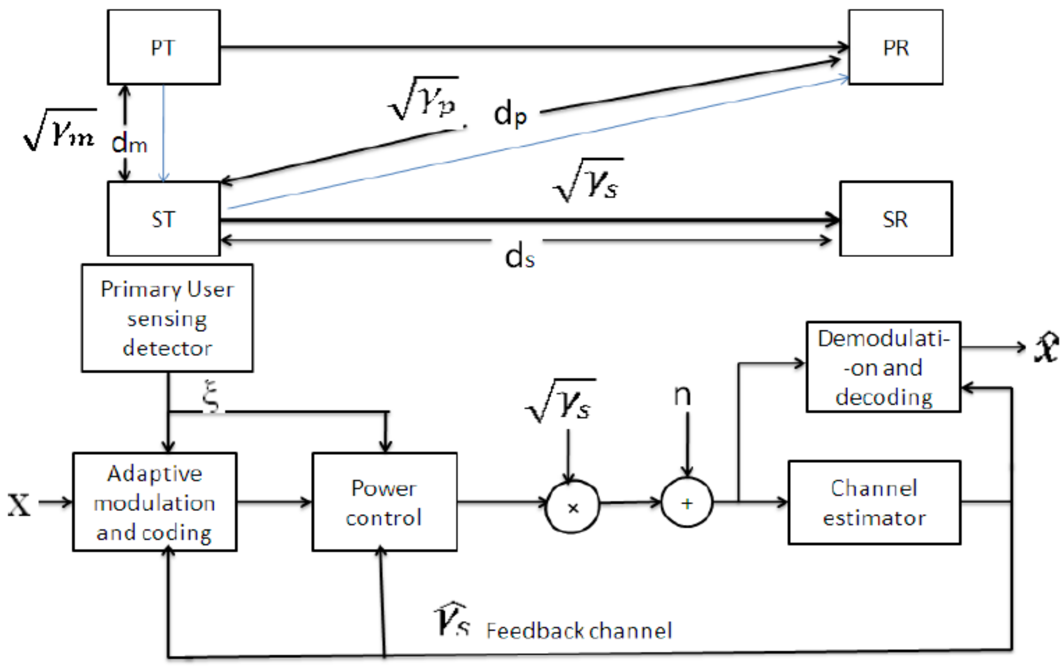



**Fig. 7.1** The proposed spectrum-sharing system model.

The average transmit power of the PT is assumed to be $P_t$ and its average ON/active time is $\alpha$ or average OFF/inactive time is $\bar{\alpha} = 1 - \alpha$ [166]. In addition to this, we have considered a discrete-time flat-fading channel with perfect CSI at the receiver and transmitter of the secondary user. As shown in Fig. 7.1, the secondary/cognitive receiver generates and estimates the channel power gain ($\hat{\gamma}_s$) between the secondary transmitter and secondary receiver (SR). We have assumed that the channel power gain is fed back to the secondary transmitter error-free and without delay. Further, the channel gain between the transmitter and receiver of the secondary user, ST and PR as well as between the PT and ST are given by $\sqrt{\gamma_s}$, $\sqrt{\gamma_p}$, and $\sqrt{\gamma_m}$, respectively. However, the channel power gains $\gamma_s$ , $\gamma_p$, and $\gamma_m$ are independent to each other. We have obtained the cognitive radio communication system Ergodic channel capacity by considering the distribution of $\gamma_s$ and $\gamma_p$ as the Nakagami-$m$ distribution. $d_m$, $d_s$ and $d_p$ are the distances between ST to PR, ST to SR, and ST to PR, respectively. Moreover, the channel between the PT and SR is considered additive white Gaussian noise (AWGN) channel, denoted as $n$ and can be modeled as zero-mean Gaussian random variable with variance $N_0B$, where $N_0$ and $B$ denote the noise power spectral density and the signal bandwidth, respectively. $x$ is the data transmitted from ST and $\hat{x}$ is the estimated transmitted data at SR as shown in Fig. 7.1.

### 7.2.2 Spectrum sensing module

As is clear from Fig. 7.1, the secondary transmitter is equipped with a spectrum sensing detector whose function is to sense the frequency band of primary user for secondary user's transmission. However, based on the received signals, the detector computes a single sensing metric denoted by ξ, [165]. The sensing metric is the total primary signal power in the number of independent signal samples [166]. We consider the statistics of ξ conditioned on the primary user being active or idle are known prior to the ST. Using the energy detection method for sensing information on the primary user being active or idle, the sensing parameter $\xi$ is modeled according to Chi-square probability distribution functions (pdfs) with $\nu$ degrees of freedom as discussed in [17], where $\nu$ is related to the number of samples used in the sensing period, $N$. We define the pdf of ξ given that the PT is active or idle by, $f_1(\xi)$ and $f_0(\xi)$, respectively that is the $f_1(\xi)$ and $f_0(\xi)$ are conditional probabilities. According to [175, pp. 941], for a large number of $\nu$ (for example $\geq$ 30), one can approximate the Chi-square distribution with a Gaussian pdf. Since the number of observation samples can be large enough for the approximation to be valid, we choose $f_1(\xi)\sim\mathcal{N}(\mu_{1,}\delta_1^2)$ and $f_0(\xi)\sim\mathcal{N}(\mu_{0,}\delta_0^2)$ where $(\mu_{1,}\delta_1^2)$ and $(\mu_{0,}\delta_0^2)$ are given by [164]. The probability distribution of $\xi$ depends on [166]:

$$\left.\begin{array}{ll}\left.\begin{array}{l}\mu_1 = \mathrm{N}\left(\frac{\mathrm{P_t}}{\mathrm{d_m^2}}+1\right)\\ \delta_1^2 = 2\mathrm{N}\left(\frac{\mathrm{P_t}}{\mathrm{d_m^2}}+1\right)^2, \text{ and}\end{array}\right\} & \text{when PT is active}\\ \left.\begin{array}{l}\mu_0 = \mathrm{N}\\ \delta_0^2 = 2\mathrm{N}\end{array}\right\} & \text{when PT is idle}\end{array}\right\} \tag{7.1a}$$

and the probability distributions of $\xi$ are given as [164]:

$$\left.\begin{array}{l}f_0(\xi) = \frac{1}{\sqrt{2\pi\delta_0^2}} exp\left(\frac{-(\xi-\mu_0)^2}{2\delta_0^2}\right)\\ f_1(\xi) = \frac{1}{\sqrt{2\pi\delta_1^2}} exp\left(\frac{-(\xi-\mu_1)^2}{2\delta_1^2}\right)\end{array}\right\} \tag{7.1b}$$

In this chapter, we have used the energy detector for spectrum sensing due to its easy implementation and low computational complexity as discussed in [17]. The other sensing detectors can also be used for spectrum sensing since the authors main motive is to compute the sensing metric $\xi$, which represents the total signal power observed or the correlation between the observed signal and a known signal pattern [166]. However, the main difference lie in the number of samples required for the same performance in different detectors and that depends on the required signal-to-noise ratio [17]. In addition to this, the cognitive radio user transmission should be limited so that it does not cause harmful interference to the primary user. Therefore, a limit or constraint is set at PR called the average interference power constraint or simply interference constraint. When PU is active, ST cannot transmit power which crosses the average interference power constraint at the primary receiver, which is given as [173]:

$$E_{\gamma_{s},\xi,\gamma_{p}}\left[P(\gamma_{s,}\gamma_{p,}\xi)\gamma_{p}|PU\ is\ ON\right] \leq Q_{\mathrm{int}}\,;\forall\,\gamma_{s},\gamma_{p,}\xi \tag{7.2}$$

where the transmit power of SU is $P(\gamma_{s,}\gamma_{p,}\xi)$ and expectation over the joint pdf of random variables $\gamma_s, \gamma_p$ and $\xi$ is denoted by $E_{\gamma_{s},\xi,\gamma_{p}}[.]$. $Q_{\mathrm{int}}$ is the interference limit set at PR that is the maximum interference power, which it can tolerate without degrading its own performance. The constraint defined in (7.2) is used to compute the Ergodic channel capacity. However, the average interference power constraint is considered only because we have assumed that the licensed user performance is measured by the average signal-to-noise ratio (SNR) and not by instantaneous SNR. Moreover, the Ergodic channel capacity under the average received power constraint is, in general, higher than that of the peak received power constraint due to the more restrictive nature of the peak power as opposed to the average interference power constraint.

### 7.3 Rate and Power Adaptation Policy for M-QAM

The data rate and power adaptation is a potential transmission strategy, which adjusts the transmit power and data rate of cognitive radio system to improve the spectrum efficiency for utilizing the shared spectrum [157, 173, 176, 177]. Further, the data rate adaptation is a spectral efficient technique and its adaptation can be achieved either through the variation of the symbol time duration [178] or by varying the constellation size [179]. However, the former method is spectral inefficient and requires variable-bandwidth system design as discussed in [180]. The variable data rate adaptation policy using varying constellation size is fixed bandwidth with spectral efficient method [180]. The Ergodic channel capacity under adaptation policy of the variable data rate and power transmission strategy in $M$-QAM signal constellation is considered with the knowledge of

CSI and spectrum-sensing information at the secondary transmitter side, which satisfy the predefined bit-error-rate (BER) requirements and adhering to the constraints on the average interference power at the primary user. In this case, the cognitive radio adapts the transmit power according to:

i) the primary and secondary channel power gain $\gamma_{\mathrm{p}}$ and $\gamma_{\mathrm{s}}$, respectively,

ii) the primary user's activity states ξ, subjected to the average interference, and

iii) the instantaneous bit-error-rate constraint $P_b(\gamma_{\mathrm{s}},\xi) = P_{\mathrm{b}}$.

The $P_b$ bound for each value of $\gamma_{\mathrm{s}}$ and ξ is given as [173]:

$$P_b(\gamma_{\mathrm{s}},\xi) \leq 0.2exp\left(\frac{-1.5}{M-1} \times \frac{P(\gamma_{\mathrm{s}},\gamma_{\mathrm{p}},\xi)\gamma_{\mathrm{s}}}{N_0 B}\right) \tag{7.3}$$

where $M$ is the constellation size or the number of symbols in the particular modulation format. $P(\gamma_{\mathrm{s}},\gamma_{\mathrm{p}},\xi)$ is the transmit power of ST. To satisfy the conditions as discussed in (7.3), we can adjust the values of $M$ and $P(\gamma_{\mathrm{s}},\gamma_{\mathrm{p}},\xi)$. However, instantaneous bit error rate constraint given by (7.3) holds for $M \geq 4$ [173]. We can also express (7.3) by the following mathematical expression:

$$P_{\mathrm{b}}(\gamma_s,\xi) \leq 0.2exp\left(\frac{-1.5}{M-1} SNR_{\mathrm{ss}}\right) \tag{7.3a}$$

where $SNR_{\mathrm{ss}}$ is the signal-to-noise power ratio of the ST to SR. For both the adaptive data rate and adaptive power transmission policy, (7.3) should be satisfied for the following constraint on average interference power:

$$\frac{P(\gamma_{\mathrm{s}},\gamma_{\mathrm{p}},\xi)\gamma_{\mathrm{p}}}{N_0 B} \leq Q_{\mathrm{int}} \tag{7.3b}$$

or

$$SNR_{\mathrm{sp}} \leq Q_{\mathrm{int}}$$

where $SNR_{\mathrm{sp}}$ is the signal-to-noise power ratio of secondary transmitter to primary receiver. After some mathematical manipulation of Equation (7.3), we yields the following maximum constellation size for a given $P_b(\gamma_{\mathrm{s}},\xi)$:

$$M(\gamma_{\mathrm{s}},\xi) = 1 + K\left(\frac{P(\gamma_{\mathrm{s}},\gamma_{\mathrm{p}},\xi)\gamma_{\mathrm{s}}}{N_0 B}\right) \tag{7.3c}$$

Moreover, we can achieve the constellation size that is the value of $M$ in $M$-QAM modulation format for an arbitrary chosen bit-error-rate, the average interference power and the ratio of $\frac{\gamma_{\mathrm{s}}}{\gamma_{\mathrm{p}}}$ and is given by the following expression:

$$M = 1 + K\left(\frac{\gamma_{\mathrm{s}}}{\gamma_{\mathrm{p}}}\right)Q_{\mathrm{int}}$$

and, $M = 2^n = 2^{log_2\left(1+K\left(\frac{\gamma_{\mathrm{s}}}{\gamma_{\mathrm{p}}}\right)Q_{\mathrm{int}}\right)}$ (7.4)

where

$$K = \frac{-1.5}{In(5P_{\mathrm{b}})} < 1 \tag{7.5}$$

and $n$ is the number of bits per symbol. However, for $M < 4$ that is suppose for BPSK the error rate is given in [180]. Therefore, the Ergodic channel capacity under average interference power constraint and given $P_{\mathrm{b}}$ is:

$$\frac{C_{\mathrm{er}}}{B} = \max_{P(\gamma_{\mathrm{s}},\gamma_{\mathrm{p}},\xi)} \iint log_2\left(1 + \frac{K\gamma_{\mathrm{s}}P(\gamma_{\mathrm{s}},\gamma_{\mathrm{p}},\xi)}{N_0 B}\right) f_{\mathrm{s}}(\gamma_{\mathrm{s}})f_{\mathrm{p}}(\gamma_{\mathrm{p}})(\alpha f_1(\xi) + \bar{\alpha} f_0(\xi))d\gamma_{\mathrm{s}}d\gamma_{\mathrm{p}} \tag{7.6}$$

With the constraint: $\iint \gamma_{\mathrm{p}} P(\gamma_{\mathrm{s}},\gamma_{\mathrm{p}},\xi) f_{\mathrm{s}}(\gamma_{\mathrm{s}}) f_{\mathrm{p}}(\gamma_{\mathrm{p}}) f_1(\xi) d\gamma_{\mathrm{s}} d\gamma_{\mathrm{p}} \le Q_{\mathrm{int}}$ (7.7)

The transmitter power $P(\gamma_{\mathrm{s}},\gamma_{\mathrm{p}},\xi)$ of cognitive transmitter is the joint function of secondary channel gain, primary channel gain and sensing metric. Asghari and Aissa [173] have provided a mathematical expression for the channel capacity of the secondary user's link for power adaptation policies under the interference and peak power constraint with the sensing pdf's. However, the primary user's link channel power gain $\gamma_p$, which is presented in (7.6) was not considered in [15]. Now, we have to maximize the Ergodic capacity of the system as given by (7.6) by simultaneously satisfying the constraint given in (7.7). Therefore, to yield the optimal power allocation $P(\gamma_{\mathrm{s}},\gamma_{\mathrm{p}},\xi)$, we form the Lagrangian multiplier, $\lambda$ [181] and construct the following Lagrangian function:

$$L(P(\gamma_{\mathrm{s}},\gamma_{\mathrm{p}},\xi),\lambda) = \iint log_2\left(1 + \frac{K\gamma_{\mathrm{s}}P(\gamma_{\mathrm{s}},\gamma_{\mathrm{p}},\xi)}{N_0 B}\right) f_{\mathrm{s}}(\gamma_{\mathrm{s}})f_{\mathrm{p}}(\gamma_{\mathrm{p}})(\alpha f_1(\xi) + \bar{\alpha} f_0(\xi))d\gamma_{\mathrm{s}}d\gamma_{\mathrm{p}} - \lambda\left(\iint \gamma_{\mathrm{p}} P(\gamma_{\mathrm{s}},\gamma_{\mathrm{p}},\xi) f_{\mathrm{s}}(\gamma_{\mathrm{s}}) f_{\mathrm{p}}(\gamma_{\mathrm{p}}) f_1(\xi) d\gamma_{\mathrm{s}} d\gamma_{\mathrm{p}} - Q_{\mathrm{int}}\right) \tag{7.8}$$

$L(P(\gamma_{\mathrm{s}},\gamma_{\mathrm{p}},\xi),\lambda)$ is the concave function of $P(\gamma_{\mathrm{s}},\gamma_{\mathrm{p}},\xi)$ and interference constraint defined in (7.7) is convex, therefore the 1st order condition that is the derivative of $L(P(\gamma_{\mathrm{s}},\gamma_{\mathrm{p}},\xi),\lambda)$ with respect to $P(\gamma_{\mathrm{s}},\gamma_{\mathrm{p}},\xi)$ is sufficient KKT condition for the optimality [182] and the sufficient condition allows us to obtain a solution. Now, the optimization problem being convex (i.e. this problem is a maximization problem with a concave cost function and a convex set of constraints), there is a unique solution. Hence, the solution given by the sufficient condition is the only solution and is given by:

$$\frac{\partial L(P,\lambda)}{\partial P} = \frac{1}{1+\frac{K\gamma_{\mathrm{s}}P(\gamma_{\mathrm{s}},\gamma_{\mathrm{p}},\xi)}{N_0 B}}\frac{K\gamma_{\mathrm{s}}}{N_0 B}\left(\alpha f_1(\xi)+\bar{\alpha}f_0(\xi)\right)f_{\mathrm{s}}(\gamma_{\mathrm{s}})f_{\mathrm{p}}(\gamma_{\mathrm{p}}) - \lambda\gamma_{\mathrm{p}}f_1(\xi)f_{\mathrm{s}}(\gamma_{\mathrm{s}})f_{\mathrm{p}}(\gamma_{\mathrm{p}}) = 0$$

or

$$\frac{\partial L(P,\lambda)}{\partial P} = \frac{K\gamma_{\mathrm{s}}}{N_0 B+K\gamma_s P(\gamma_{\mathrm{s}},\gamma_{\mathrm{p}},\xi)}\left(\alpha f_1(\xi)+\bar{\alpha}f_0(\xi)\right) - \lambda\gamma_{\mathrm{p}}f_1(\xi) = 0 \tag{7.9}$$

and

$$P(\gamma_{\mathrm{s}},\gamma_{\mathrm{p}},\xi) = \frac{\gamma_{\mu}(\xi)}{\lambda\gamma_{\mathrm{p}}} - \frac{N_0 B}{\gamma_{\mathrm{s}}K} \tag{7.10a}$$

If we assume $P(\gamma_{\mathrm{s}},\gamma_{\mathrm{p}},\xi) = 0$ for some values of $\gamma_{\mathrm{s}}$, $\gamma_{\mathrm{p}}$, and $\xi$, which take placed in the condition defined below and after putting $P(\gamma_{\mathrm{s}},\gamma_{\mathrm{p}},\xi) = 0$ in (7.10a), we get:

$$\frac{\gamma_{\mathrm{p}}}{\gamma_{\mathrm{s}}} > \frac{\gamma_{\mu}(\xi)K}{\lambda N_0 B} \tag{7.10b}$$

Therefore, from (7.10a) and (7.10b), the power $P(\gamma_{\mathrm{s}},\gamma_{\mathrm{p}},\xi)$ is adapted to maximize the Ergodic channel capacity as defined in (7.6), which is given as:

$$P(\gamma_{\mathrm{s}},\gamma_{\mathrm{p}},\xi) = \begin{cases} \frac{\gamma_{\mu}(\xi)}{\lambda\gamma_{\mathrm{p}}} - \frac{N_0 B}{\gamma_s K}, & \frac{\gamma_{\mathrm{p}}}{\gamma_{\mathrm{s}}} \le \frac{\gamma_{\mu}(\xi)K}{\lambda N_0 B} \\ 0, & \frac{\gamma_{\mathrm{p}}}{\gamma_{\mathrm{s}}} > \frac{\gamma_{\mu}(\xi)K}{\lambda N_0 B} \end{cases} \tag{7.10c}$$

where

$$\gamma_{\mu}(\xi) = \alpha + \bar{\alpha}\frac{f_0(\xi)}{f_1(\xi)}. \tag{7.11}$$

The optimal power allocation obtained by (7.10a) represents the more transmission power, which can be used when $\gamma_{\mathrm{s}}$ increases and $\gamma_p$ decreases and the average interference constraint at primary receiver is satisfied. This is due to the primary user's fading channel advantage which has enhanced the cognitive user's capacity. The sensing decision is considered in Equation (7.11) and it is observed that when the conditional probability that the PU is idle ($f_0(\xi)$) gets higher than that of being active ($f_1(\xi)$), then the value of $\gamma_{\mu}(\xi)$ has an ascending behavior and $\gamma_{\mu}(\xi) > 1$

otherwise, $\gamma_\mu(\xi) < 1$. Therefore, as the conditional probability distribution of the primary user being idle gets higher than being active, $\gamma_\mu(\xi)$ increases and, consequently, we can increase the secondary user's transmission power without causing harmful interference to the PR. Note that when $\gamma_\mu(\xi) = 1$, the ST has no information about the primary user activity. Accordingly, it considers that the primary user is always active $\left(\frac{f_0(\xi)}{f_1(\xi)} = 1\right)$ and continuously transmits with the same power level with which it is already transmitting. For $\gamma_\mu(\xi)$, the values of $f_0(\xi)$ and $f_1(\xi)$ should be taken at that value of $\xi$ which is computed by the sensing detector for a given detection and false alarm probabilities. The higher value of $\xi$ as compared to threshold that is the energy computed in a particular time interval over a spectrum, indicates the presence of PU signal and vice versa [166]. However, if we modify the probability of false alarm, the value of $\xi$ is also modified. By substituting (7.10a) in (7.7), we get:

$$\iint_0^{\frac{K\gamma_\mu(\xi)}{\lambda_0 N_0 B}} \left(\frac{\gamma_\mu(\xi)}{\lambda_0} - \frac{N_0 B\gamma_p}{\gamma_s K}\right) f_s(\gamma_s) f_p(\gamma_p) f_1(\xi) d\gamma_s d\gamma_p = Q_{int}$$

where $\lambda_0$ is determined in such a way that the average interference power constraint in (7.7) is equal to $Q_{int}$.

$$\iint_0^{\frac{K\gamma_\mu(\xi)}{\lambda_0 N_0 B}} \left(\frac{\gamma_\mu(\xi)}{\lambda_0 N_0 B} - \frac{\gamma_p}{\gamma_s K}\right) f_s(\gamma_s) f_p(\gamma_p) f_1(\xi) d\gamma_s d\gamma_p = \frac{Q_{int}}{N_0 B} = \Phi$$

or

$$\iint_0^{K\gamma_\mu(\xi)\gamma_0} \left(\gamma_\mu(\xi)\gamma_0 - \frac{\gamma_p}{\gamma_s K}\right) f_s(\gamma_s) f_p(\gamma_p) f_1(\xi) d\gamma_s d\gamma_p = \Phi \qquad (7.12)$$

where $\gamma_0 = \frac{1}{\lambda_0 N_0 B}$, and $\Phi = \frac{Q_{int}}{N_0 B}$ is the average SNR [161]. By substituting (7.10a) in (7.6), gives the following Ergodic channel capacity expression:

$$\frac{C_{er}}{B} = \int_{\frac{\gamma_s}{\gamma_p} \geq \frac{N_0 B \lambda_0}{K\gamma_\mu(\xi)} = \frac{1}{K\gamma_0\gamma_\mu(\xi)}}^{\infty} log_2\left(1 + \frac{K\gamma_s}{N_0 B}\left[\frac{\gamma_\mu(\xi)}{\lambda_0\gamma_p} - \frac{N_0 B}{\gamma_s K}\right]\right) f_s(\gamma_s) f_p(\gamma_p)(\alpha f_1(\xi) + \bar{\alpha} f_0(\xi)) d\gamma_s d\gamma_p$$

or

$$\frac{C_{er}}{B} = \int_{\frac{\gamma_s}{\gamma_p} \geq \frac{N_0 B \lambda_0}{K\gamma_\mu(\xi)} = \frac{1}{K\gamma_0\gamma_\mu(\xi)}}^{\infty} log_2\left(\frac{K\gamma_s\gamma_\mu(\xi)}{N_0 B \lambda_0\gamma_p}\right) f_s(\gamma_s) f_p(\gamma_p)(\alpha f_1(\xi) + \bar{\alpha} f_0(\xi)) d\gamma_s d\gamma_p$$

or

$$\frac{C_{\mathrm{er}}}{B} = \int_{\frac{\gamma_{\mathrm{s}}}{\gamma_{\mathrm{p}}} \geq \frac{N_0 B \lambda_0}{K\gamma_{\mu}(\xi)} = \frac{1}{K\gamma_0 \gamma_{\mu}(\xi)}}^{\infty} log_2\left(\frac{K\gamma_{\mathrm{s}}\gamma_{\mu}(\xi)\gamma_0}{\gamma_{\mathrm{p}}}\right) f_{\mathrm{s}}(\gamma_{\mathrm{s}}) f_{\mathrm{p}}(\gamma_{\mathrm{p}})(\alpha f_1(\xi) + \bar{\alpha} f_0(\xi)) d\gamma_{\mathrm{s}} d\gamma_{\mathrm{p}} \tag{7.13}$$

or

$$\frac{C_{\mathrm{er}}}{B} = \underset{\frac{\gamma_{\mathrm{s}}}{\gamma_{\mathrm{p}}} \geq \frac{N_0 B \lambda_0}{K\gamma_{\mu}(\xi)}}{E_{\gamma_{\mathrm{s}}, \gamma_{\mathrm{p}}, \xi}} \left[ log_2\left(\frac{K\gamma_{\mathrm{u}}(\xi)\gamma_{\mathrm{s}}}{\lambda_0 N_0 B \gamma_{\mathrm{p}}}\right)\right] \tag{7.14}$$

where $C_{er}$ denotes the Ergodic capacity and *E*[.] denotes the expectation operator. Equation (7.14) is similar to that presented in [173, Equation (30)] except the term $\gamma_{\mathrm{p}}$, which is due to the consideration of the primary channel gain in the cognitive user's system capacity. However, when only the power adaptation policy is considered instead of power and rate adaptation policy, then the additional constraint of (7.5) is not needed and the Ergodic channel capacity of adaptive power transmission policy is given by the following mathematical expression by substituting *K*=1 in (7.14):

$$\frac{C_{\mathrm{er}}}{B} = \underset{\frac{\gamma_{\mathrm{s}}}{\gamma_{\mathrm{p}}} \geq \frac{N_0 B \lambda_0}{\gamma_{\mu}(\xi)}}{E_{\gamma_{\mathrm{s}}, \gamma_{\mathrm{p}}, \xi}} \left[ log_2\left(\frac{\gamma_{\mathrm{u}}(\xi)\gamma_{\mathrm{s}}}{\lambda_0 N_0 B \gamma_{\mathrm{p}}}\right)\right] \tag{7.15}$$

However, comparing the Ergodic capacity of power adaptation policy as given by (7.15) and rate and power adaptation policy for *M*-QAM modulation format in (7.14), the equation (7.14) reveals that there is an effective power loss of *K* for adaptive *M*-QAM as compared to that of (7.15). However, for the adaptive power transmission policy the probability of error is significantly more and fixed, which is 0.0446 in comparison to that of the adaptive rate and power transmission policy where the probability of bit error can be varied according to the quality-of-service requirement.

### 7.4 Effect of Channel Conditions

In this section, we have explored the fading channel effect on the cognitive radio communication system performance and numerically computed the Ergodic channel capacity in different fading environments.

- Nakagami-*m* fading

The Nakagami-*m* distribution often provides the best fit to the urban [183] and indoor [184] multipath propagation and gives AWGN, Rayleigh and Rician fading channel model by adjusting the fading parameter *m*, which is the ratio of line-of-sight (LOS) signal power to the multipath signal power. The channel fading model based on Nakagami distribution, both $\gamma_s$ and $\gamma_p$ would be distributed according to the following Gamma distribution [163]:

$$f(\gamma) = \frac{m^m \gamma^{m-1}}{\Gamma(m)} e^{-m\gamma}$$

where $m$ and $\gamma$ are shape parameter and channel power gain, respectively. Therefore, the pdf $f_\mathrm{s}(\gamma_\mathrm{s}) f_\mathrm{p}(\gamma_\mathrm{p})$ is given as:

$$f_\mathrm{s}(\gamma_\mathrm{s}) f_\mathrm{p}(\gamma_\mathrm{p}) = \left(\frac{m_0}{m_1}\right)^{m_0} \frac{z^{m_1 - 1}}{\beta(m_0, m_1)\left(x + \frac{m_0}{m_1}\right)^{m_0 + m_1}} \tag{7.16}$$

where $m_0$ and $m_1$ are $m$ parameters [163] for $\gamma_\mathrm{p}$ and $\gamma_\mathrm{s}$, respectively. $\frac{\gamma_\mathrm{p}}{\gamma_\mathrm{s}} = z$, where z is a random variable. $\beta(.)$ is the beta function. When $m_0 = m_1 = m$, the equation (7.16) becomes:

$$f_\mathrm{s}(\gamma_\mathrm{s}) f_\mathrm{p}(\gamma_\mathrm{p}) = \frac{z^{m-1}}{\beta(m,m)(z+1)^{2m}} \tag{7.17}$$

By substituting (7.17) in (7.12), we yield the following value of secondary transmit power, which satisfies the average interference constraint for the Nakagami-*m* fading channel:

$$\iint_0^{K\gamma_\mu(\xi)\gamma_0} \left(\gamma_\mu(\xi)\gamma_0 - \frac{\gamma_\mathrm{p}}{\gamma_\mathrm{s} K}\right) \frac{z^{m-1}}{\beta(m,m)(z+1)^{2m}} f_1(\xi) d\gamma_\mathrm{s} d\gamma_\mathrm{p} = \frac{Q_\mathrm{int}}{N_0 B} \tag{7.18}$$

and the Ergodic channel capacity from (7.13), for the Nakagami-*m* fading environment is given by:

$$\frac{C_\mathrm{er}}{B} = \int_{\frac{\gamma_\mathrm{s}}{\gamma_\mathrm{p}} \geq \frac{N_0 B\, \lambda_0}{K\gamma_\mu(\xi)} = \frac{1}{K\gamma_0 \gamma_\mu(\xi)}}^{\infty} log_2\left(\frac{K\gamma_\mathrm{s}\gamma_\mu(\xi)\gamma_0}{\gamma_\mathrm{p}}\right) \frac{z^{m-1}}{\beta(m,m)(z+1)^{2m}} \left(\alpha f_1(\xi) + \bar{\alpha} f_0(\xi)\right) d\gamma_\mathrm{s} d\gamma_\mathrm{p} \tag{7.19}$$

### 7.4.1 Rayleigh fading

Since the Nakagami-*m* distribution with fading parameter equal to 1 represent the Rayleigh fading channel, and the pdf $f_\mathrm{s}(\gamma_\mathrm{s}) f_\mathrm{p}(\gamma_\mathrm{p})$ will have log-logistic distribution [163]. Therefore, by substituting $m = 1$ in (7.18), we get:

$$\int_0^{K\gamma_\mu(\xi)\gamma_0} \left(\gamma_\mu(\xi)\, \gamma_0 - \frac{z}{K}\right) \frac{1}{(1+z)^2}\, f_1(\xi) dz = \frac{Q_\mathrm{int}}{N_0 B}$$

or

$$f_1(\xi)\left(-\frac{1}{K} log_2\left(1 + K\gamma_\mu(\xi)\gamma_0\right) + \gamma_\mu(\xi)\, \gamma_0\right) = \frac{Q_\mathrm{int}}{N_0 B} = \Phi \tag{7.20}$$

Therefore the capacity of the cognitive radio communication system in the Rayleigh fading environment is achieved by putting $m$ = 1 in (7.19):

$$\frac{C_{\text{er}}}{B} = \int_{\frac{1}{\gamma_0\gamma_\mu(\xi)}}^{\infty} log_2\big(K\gamma_0\gamma_\mu(\xi)z\big)\frac{1}{(1+z)^2}(\alpha f_1(\xi)+\bar{\alpha} f_0(\xi))dz$$

or $\frac{C_{\text{er}}}{B} = \big(\alpha f_1(\xi)+\bar{\alpha} f_0(\xi)\big)\log_2\Big(1+K\gamma_\mu(\xi)\gamma_0(\Phi)\Big)$ (7.21)

where $\gamma_0(\Phi)$ is from the (7.20) for a given $\Phi$. Equation (7.21) gives the Ergodic channel capacity of adaptive rate and power transmission policy under the Rayleigh fading environment. Further, the capacity of adaptive power transmission policy under the Rayleigh fading environment is as given below:

$$\frac{C_{\text{er}}}{B} = \big(\alpha f_1(\xi)+\bar{\alpha} f_0(\xi)\big)log_2\Big(1+\gamma_\mu(\xi)\gamma_0(\alpha)\Big) \tag{7.22}$$

### 7.4.2 Rician fading

The Nakagami-$m$ distribution with the fading parameter greater than or equal to 2 represent the Rician fading channel. Now, by substituting $m = 2$ in (7.18), we get the following expression for Rician fading channel:

$$\int_0^{K\gamma_\mu(\xi)\gamma_0}\Big(\gamma_\mu(\xi)\,\gamma_0-\frac{z}{K}\Big)\frac{6z}{(1+z)^4}\,f_1(\xi)dz = \frac{Q_{\text{int}}}{N_0B}$$

or

$$f_1(\xi)\left(\frac{3K\gamma_0\gamma_\mu(\xi)+2}{6K\big(1+K\gamma_0\gamma_\mu(\xi)\big)^2}+\frac{\gamma_0\gamma_\mu(\xi)}{6}-\frac{2}{6K}\right) = \frac{Q_{\text{int}}}{N_0B} = \Phi \tag{7.23}$$

Therefore, for the spectrum-sharing system operating under the predefined power constraints and a target BER value $P_{\text{b}}$, the Rician fading channel capacity expression of the secondary user's link, based on the adaptive rate and power $M$-QAM transmission policy, is obtained by putting $m$ = 2 in (7.19):

$$\frac{C_{\text{er}}}{B} = \int_{\frac{1}{K\gamma_0\gamma_\mu(\xi)}}^{\infty} log_2\big(K\gamma_0(\Phi)\gamma_\mu(\xi)z\big)\frac{6z}{(1+z)^4}(\alpha f_1(\xi)+\bar{\alpha} f_0(\xi))dz \tag{7.24}$$

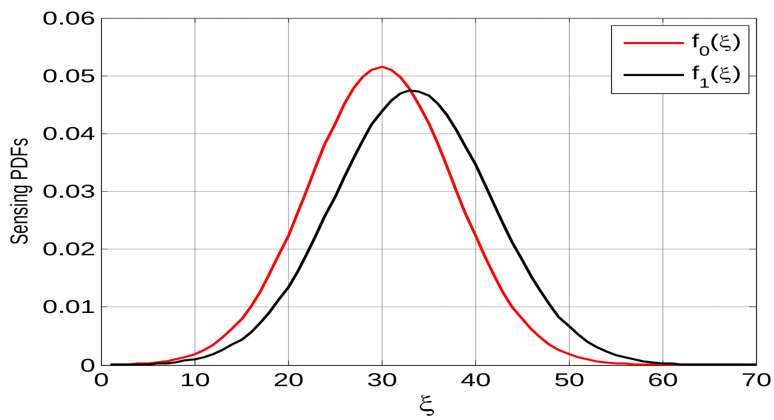
where $\gamma_0(\Phi)$ is from (7.23) for a given $\Phi$. Furthermore, the Ergodic channel capacity of adaptive power transmission policy in the Rician fading environment is given by the following expression:

$$\frac{C_{\mathrm{er}}}{B} = \int_{\frac{1}{\gamma_0 \gamma_\mu(\xi)}}^{\infty} log_2\big(\gamma_0 \gamma_\mu(\xi) z\big) \frac{6z}{(1+z)^4} \big(\alpha f_1(\xi) + \bar{\alpha} f_0(\xi)\big) dz \tag{7.25}$$

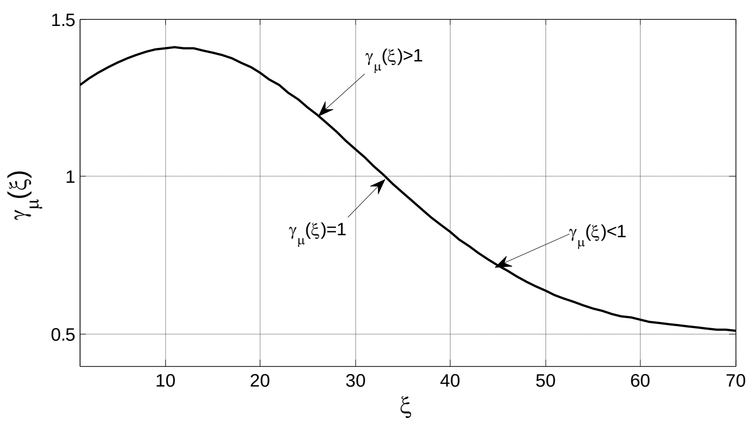
Similarly, we can compute the channel capacity for different fading parameter values, however it leads to cumbersome mathematical expressions.

### 7.5 Simulation Results

In this section, we have numerically simulated the proposed spectrum sharing system model that operates under the constraints on the average received-interference power in the Nakagami-*m* fading environment for the adaptation strategies such as variable power and variable rate and power as presented in the preceding Sections 7.3 and 7.4.




(a)



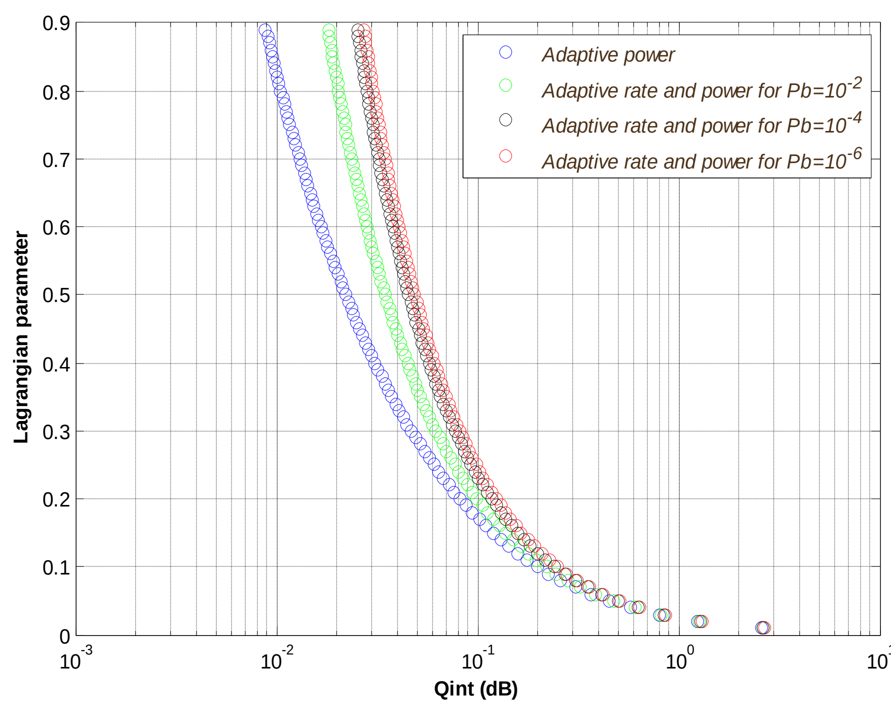

(b)

**Fig. 7.2** The soft sensing information (a) Spectrum sensing probability density functions given that the primary user is idle $f_0(\xi)$ and active $f_1(\xi)$ [173] , and (b) $\gamma_\mu(\xi)$ variation for $N$ = 30, $P_t$ = 1, α = 0.5 and $d_m$ = 3 [173].

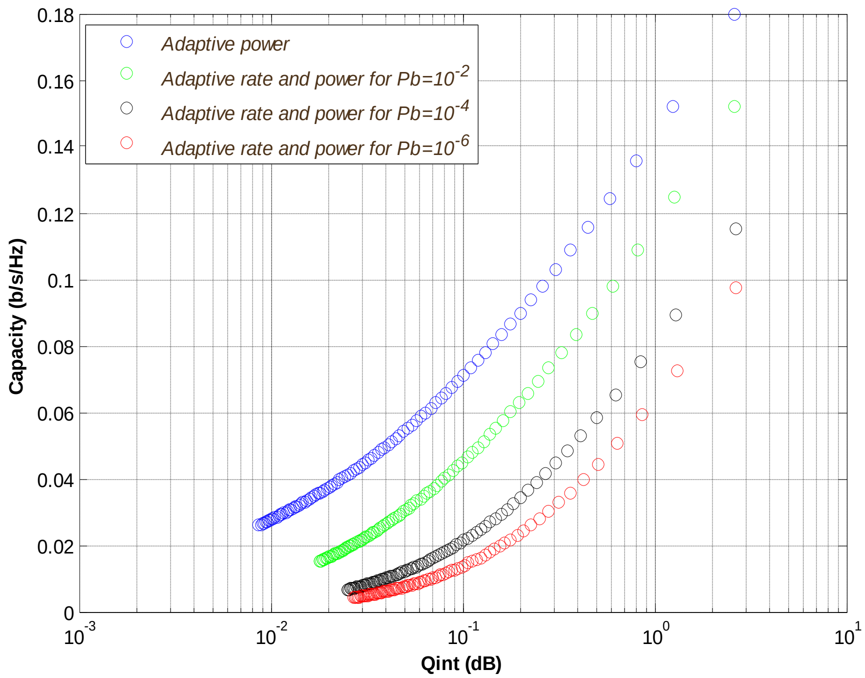
The position of terminals as shown in Fig. 7.1 is assumed in such a way that $d_s = d_p = 1$ (unit) and $d_{\mathrm{m}} = 3$ (unit). The channel gains $(\gamma_{\mathrm{s}})^{1/2}$ and $(\gamma_{\mathrm{p}})^{1/2}$ are distributed according to the Nakagami-*m* fading pdf. Furthermore, we assumed $\mathrm{N_0 B} = 1$ and the sensing detector computes the sensing-information metric for $N = 30$ observation samples. We suppose that the primary user remains active at 50% of the time ($\alpha = 0.5$) and have set the PU's transmit power $\mathrm{P_t} = 1$. Fig. 7.2(a) illustrates the distribution of conditional probabilities $f_0(\xi)$ and $f_1(\xi)$ corresponding to the different values of detected energy by sensing detector in the particular number of samples. Moreover, these distributions are used for the computation of $\gamma_\mu(\xi)$ for different detected energy values in a particular interval as shown in Fig. 7.2(b) and three regions have been recognized for the parameter $\gamma_\mu(\xi)$, namely, $\gamma_\mu(\xi) > 1$, $\gamma_\mu(\xi) = 1$ and $\gamma_\mu(\xi) < 1$. In Fig. 7.2(b), when $\gamma_\mu(\xi) > 1$ represent that the probability of the PU to be idle is higher than that of being active otherwise, $\gamma_\mu(\xi) < 1$. The power and rate is adapted according to the channel gains and the sensing information. Moreover, the higher power levels are used by secondary user's when the probability of primary user being inactive is significantly more (higher values of $\gamma_\mu(\xi)$) in comparison to the case for which $\gamma_\mu(\xi)$ is less. We have considered the bit-error-probability $10^{-2}$, $10^{-4}$ and $10^{-6}$ for the adaptive rate and power transmission policy for these two cases: ($\gamma_\mu(\xi) > 1$ and $\gamma_\mu(\xi) < 1$).

For the Rayleigh fading environment or Nakagami-*m* distribution with *m* = 1, Fig. 7.3(a) and Fig. 7.3(b) shows the variation of Lagrangian parameter $\lambda$ and Ergodic channel capacity with $Q_{\mathrm{int}}$ for the adaptive power and adaptive rate and power transmission policy, while considering the sensing information metric available at the cognitive user. The simulation results in Fig. 7.3 are presented for the value of parameter $\gamma_\mu(\xi) < 1$. Moreover, Fig. 7.3(a) shows the optimum value of Lagrangian parameter for the given $Q_{\mathrm{int}}$ and $\gamma_\mu(\xi)$, which satisfy (7.20) and provides the adaptation in transmit power needed for Rayleigh fading channel. It is clear from Fig. 7.3(b), that as the interference tolerance ($Q_{\mathrm{int}}$) at primary receiver increases, the capacity of secondary user increases due to the increase in transmit power of the secondary user. The Ergodic capacity of adaptive rate and power transmission policy is less in comparison to that of the adaptive power transmission policy since there is additional constraint on target BER in former policy. In addition to this, as the required BER decreases, the Ergodic capacity of the system is less as depicted from Fig. 7.3(b). For example, the capacity for $P_b$ of $10^{-6}$ is less than that for $P_b = 10^{-2}$ due to the more strict constraint on the required error rate.

In Fig. 7.4(a) and Fig. 7.4(b), we have considered the value of the parameter $\gamma_{\mu}(\xi) > 1$ which shows that the probability of the primary user being active is more than being inactive and it leads to increase in the transmit power, consequently results the increase in capacity of the secondary user in comparison to the capacity that is shown in Fig. 7.3(b) where $\gamma_{\mu}(\xi) < 1$. Further, without considering the sensing information available at the secondary user, the capacity variation with $Q_{\text{int}}$ presented in Fig. 7.5 have been validated with Fig. 3 of [163], which is the case when only the average interference power constraint is considered. The effect of average interference power constraint $Q_{\text{int}}$ on the capacity and Lagrangian parameter $\lambda$ in Nakagami-$m$ fading environment with $m = 2$ that is for the Rician fading channel for the adaptive power and adaptive rate and power transmission is shown in Fig. 7.6(a) and Fig. 7.6(b) for the case when $\gamma_{\mu}(\xi) < 1$. Moreover, for the adaptive power and adaptive rate and power transmission policy and the comparison of the capacity for three cases of BER that is $10^{-2}$, $10^{-4}$ and $10^{-6}$ is presented in Fig. 7.6(b).

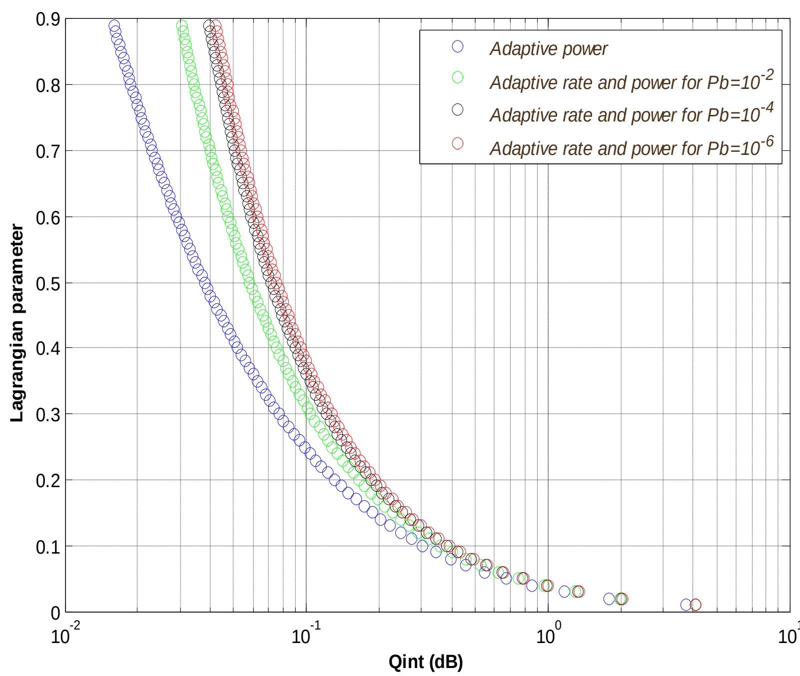



(a)

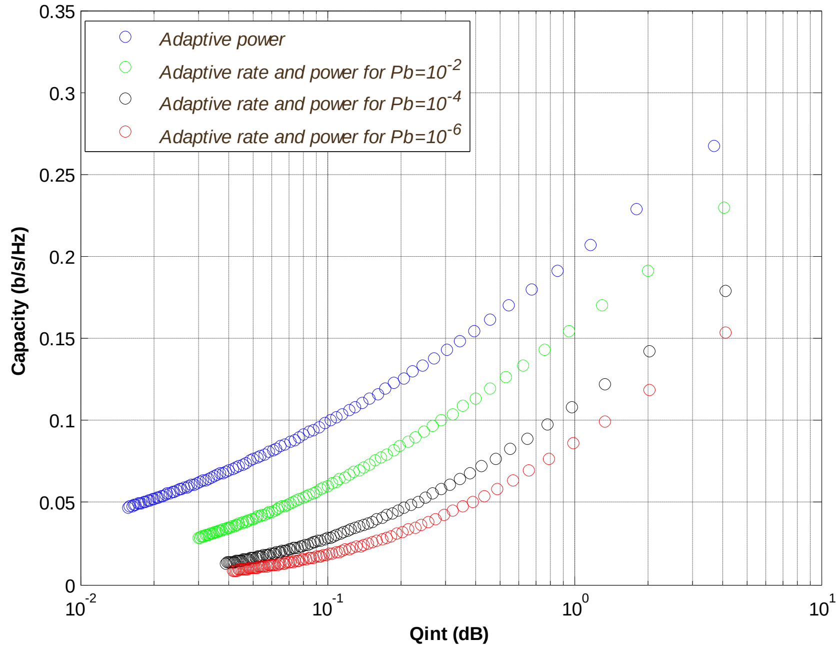



(b)

**Fig. 7.3** The response of primary receiver interference power constraint for the adaptive power and adaptive rate and power transmission policies in the Rayleigh fading channel for M-QAM modulation and $\gamma_{\mu}(\xi) = 0.8$ over (a) the Lagrangian parameter, and (b) Ergodic channel capacity.




(a)




(b)

**Fig. 7.4** The response of primary receiver interference power constraint for the adaptive power and adaptive rate and power transmission policies in the Rayleigh fading channel for M-QAM modulation and $\gamma_{\mu}(\xi) = 1.2$ over (a) the Lagrangian parameter, and (b) Ergodic channel capacity.

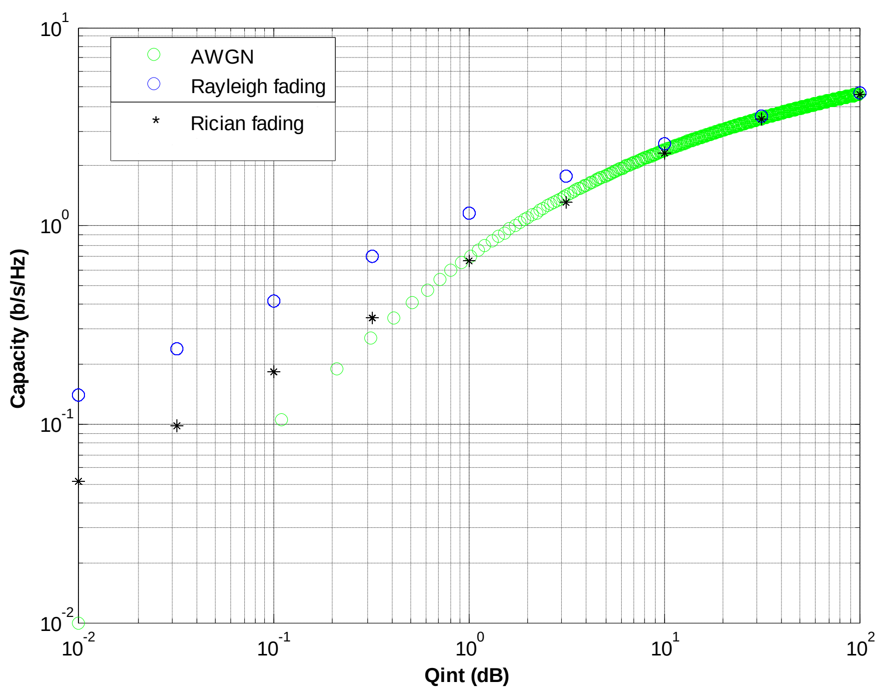
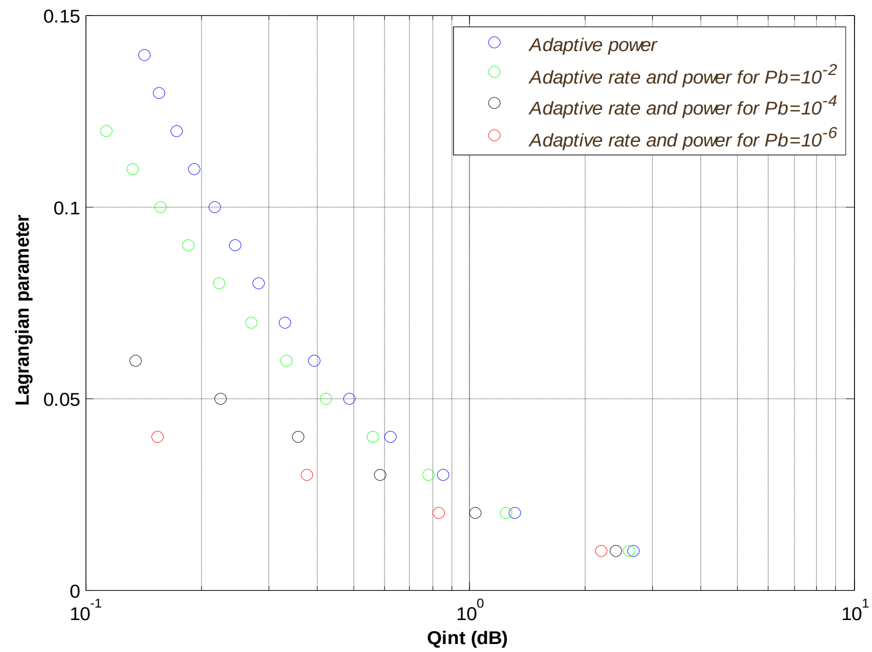
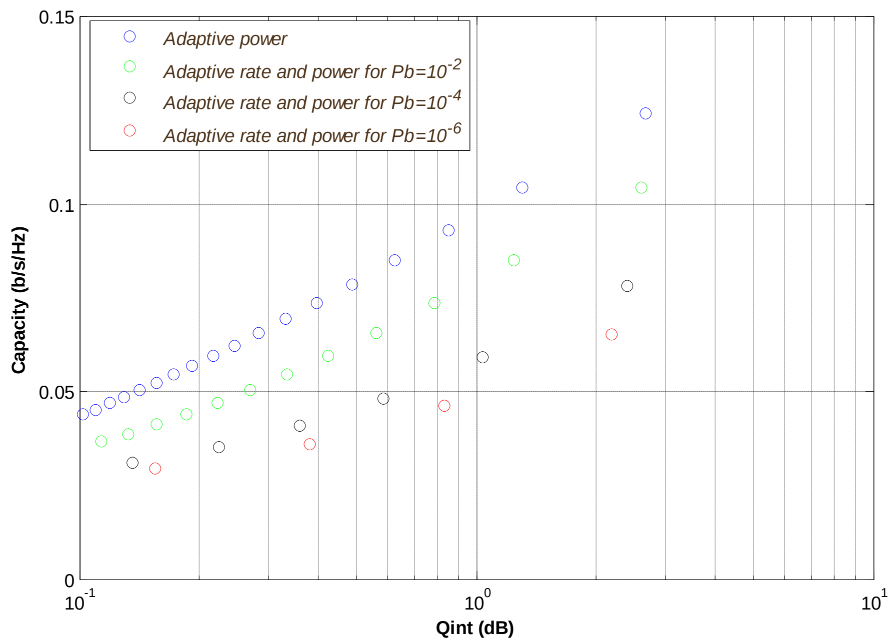



**Fig. 7.5** The capacity under the average interference-power constraint as reported in [163].



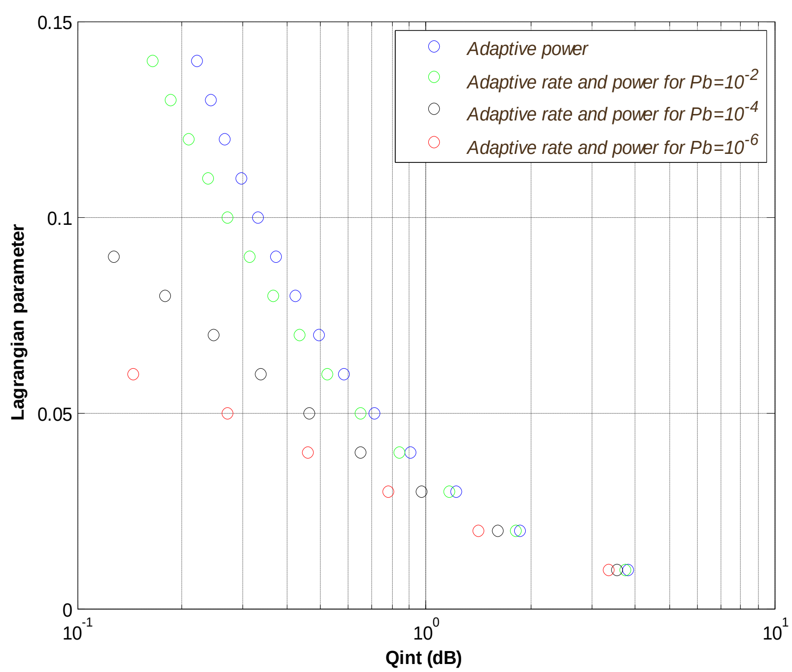

(a)



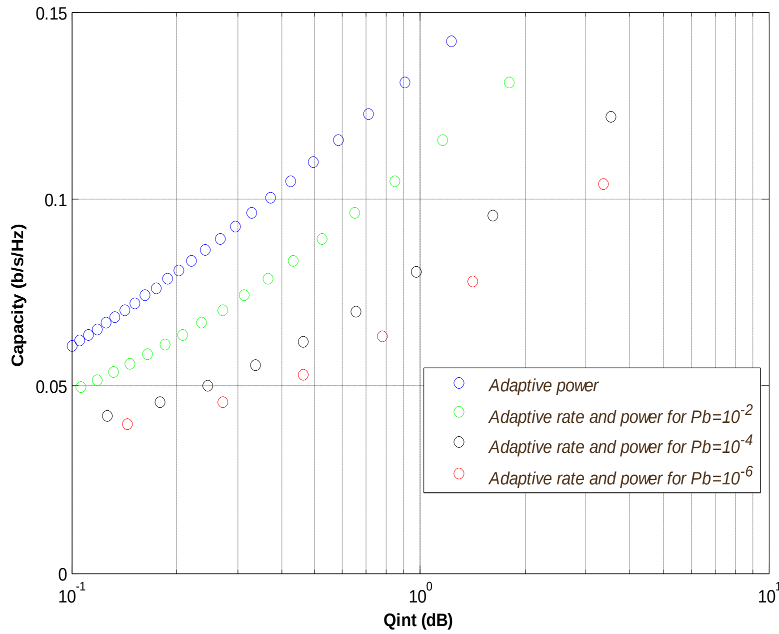

(b)

**Fig. 7.6** The response of primary receiver interference power constraint for the adaptive power and adaptive rate and power transmission policies in the Rician fading channel for M-QAM modulation and $\gamma_{\mu}(\xi) = 0.8$ over (a) the Lagrangian parameter, and (b) Ergodic channel capacity.

Further, in Fig. 7.7(a) and Fig. 7.7(b) the Lagrangian parameter and capacity in Rician fading environment (Nakagami-*m* distribution with $m$ = 2) for $\gamma_{\mu}(\xi) > 1$ is presented. However, the comparison of Fig. 7.6(b) with Fig. 7.7(b) reveals that the significant enhancement in the capacity is due to the higher power adaptation of the secondary transmitter. Moreover, the capacity comparison between Rayleigh and Rician fading environment demonstrate that the capacity of cognitive radio network for later case is less than that of former for a given $Q_{int}$. The reason lies in the fact that severe primary channel Rayleigh fading has given advantage to the secondary transmitter to increase its transmission power while keeping interference power constraint constant in comparison to the Rician fading channel with $m = 2$, which is less severe due to the presence of line-of-sight (LOS) component. Moreover, Fig. 7.8(a) and Fig. 7.8(b) shows the adaptation in the constellation size according to the channel gain ratio of the secondary-to-primary user and average interference power for different BER, respectively. It is also clear from Fig. 7.8(a) and Fig. 7.8(b) that the number of bits per symbol or the constellation size of modulation technique increases as the channel gain ratio of the ST to PR increases, or the average interference power limit at PR increases for the chosen BER. Thus significantly better channel conditions of the secondary link leads to the adaptation of higher modulation format.

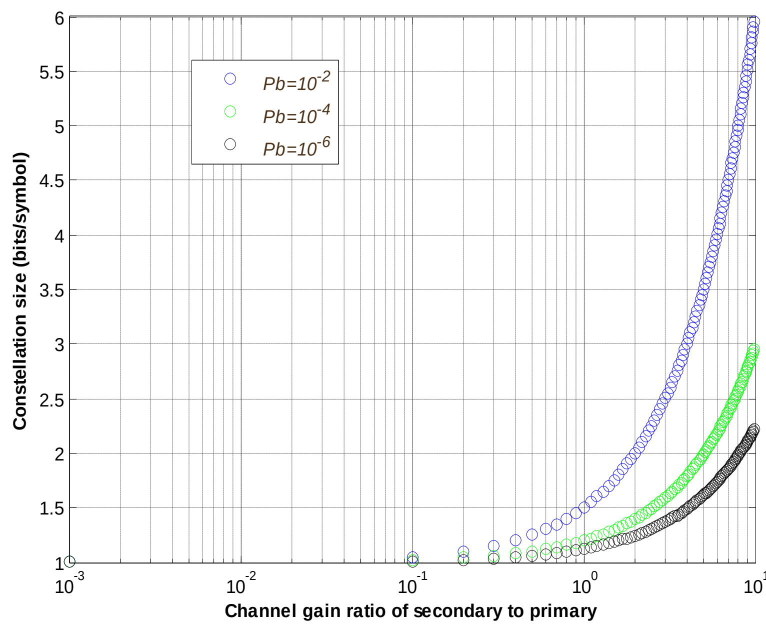



(a)

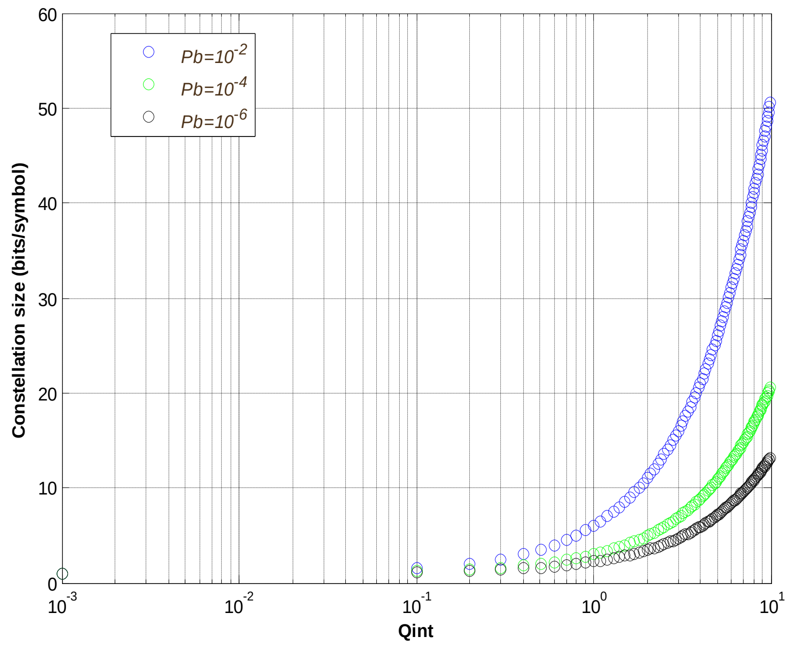



(b)

**Fig. 7.7** The response of primary receiver interference power constraint for the adaptive power and adaptive rate and power transmission policies in the Rician fading channel for M-QAM modulation and $\gamma_{\mu}(\xi) = 1.2$ over (a) the Lagrangian parameter, and (b) Ergodic channel capacity.




(a)




(b)

**Fig. 7.8** The constellation size adaptation (a) according to the signal-to-noise power ratios of secondary-to-primary user for $Q_{int} = 0dB$, and (b) with the interference power constraint, for the given signal-to-noise power ratios (10dB) of secondary-to-primary user for adaptive power and rate transmission policy with $P_b = 10^{-2}$, $10^{-4}$, and $10^{-6}$.

## 7.6 Conclusion

In this chapter, we have considered a spectrum-sharing concept for the cognitive radio system where the secondary user's transmit power and rate can be adjusted based on the sensing information of the primary user and secondary user's as well as secondary-to-primary user's fading environment. In addition to this, the spectrum-sharing system has been operated under the average interference power constraints of the PR. In this context, we have demonstrated the Ergodic capacity of the cognitive radio communication system with power and rate adaptation policy in different fading environments for chosen BER. Since the Nakagami-*m* distribution is fit for both the Rayleigh and Rician fading distribution by varying the fading parameter, therefore the Ergodic capacity for both these distributions have been presented. In addition to this, the numerically simulated results for the Ergodic capacity are presented for both the adaptive power and adaptive rate and power transmission policies, which reveal that the adaptive power transmission has more capacity than that of the adaptive rate and power transmission policy at the cost of BER. Moreover, we have demonstrated that the sensing parameter knowledge has provided an opportunity to control the secondary user's transmission parameters such as rate and power according to different primary user's activity levels observed by the sensing detector. However, the secondary transmitter can adapt different modulation by varying the value of $M$ in $M$-QAM according to the channel conditions, BER and interference constraints. Further, it is also illustrated that the capacity in case of Rician fading environment is less as compare to that of Rayleigh fading because of LOS component present in the ST to PR has provided more prominent effect on the capacity of secondary user in comparison to that present in ST to SR link.

# Chapter 8

## Conclusion and Future Scope

With an explosive demand of the wireless broadband services, the future wireless system will witness a rapid growth of high data rate applications with very diverse quality-of-services (QoS) requirements. To support such applications under the limited resources and harsh wireless channel conditions, the dynamic resource allocation which achieves both the higher system spectral efficiency and better QoS has been identified as one of the most promising techniques. Since, the frequency allocation performed by the regulatory bodies have allocated different spectrum to various services through static/fixed spectrum allocation strategy in order to avoid the interference and collision, which reveals that most of the frequency bands have already been assigned. However, at certain time or space, some of the allocated spectrum to specific services is unutilized and other user/service provider cannot use this unutilized spectrum. This unutilized spectrum of certain service provider/licensed user is called the spectrum white space or spectrum hole and is wastage of the natural resource. Due to the spectrum scarcity created by the fixed spectrum allocation, some new services wanted to enter the communication world might not get enough spectrum for their functioning. Therefore, the limitations of aforementioned fixed spectrum allocation based scheme have been mitigated by cognitive radio technology which uses dynamic spectrum access (DSA) and opportunistic spectrum access (OSA) schemes for the spectrum access/ allocation. The cognitive radio is a promising wireless communication technology geared to solve the spectrum scarcity problem by opportunistically identifying the unused portions of the spectrum, which observe, learn, optimize, intelligently adapt to achieve optimal frequency band usage and establish the communication, while ensuring that the licensed or primary users of the spectrum are not affected. It is able to operate in multiple frequency bands and maximizes the utilization of limited radio spectrum while accommodating the increasing number of services and applications in the wireless communication systems.

Since the cognitive radio technology is still evolving, therefore in this thesis we have proposed the efficient method for spectrum sharing in the cognitive radio communication system. Firstly, a critical study of the state -of -the- art in cognitive radio technology is discussed. Further, the multichannel cooperative distributed medium- access control (MAC) protocol for cognitive radio network has been explored. The thorough study of existing distributed cognitive radio MAC protocol has set the guideline for the proposal of novel cognitive radio MAC protocol. We have implemented the back-off algorithm in cognitive radio MAC protocol for contention solving and reserving the idle licensed channels for data transmission. In the proposed control channel MAC protocol, the cognitive users share the sensing results with each other and implementation of back-off algorithm in the protocol has enhanced the throughput of cognitive radio users in comparison to the existing self-scheduling multi channel (SMC) MAC protocol. The proposed MAC protocol has flexible contention interval depending on the number of cognitive users in comparison to the fixed contention interval in SMC-MAC. Furthermore, the practical scenario of imperfect sensing has been considered in the proposed MAC protocol and degradation in the performance due to sensing error has further been presented. Moreover, the perfect and imperfect sensing effect on the throughput and energy efficiency of the cognitive radio network is shown. The false alarm which occurs due to the imperfect sensing has affected the system performance of cognitive radio network by missing the opportunities of spectrum use in comparison to the perfect sensing, as demonstrated in the simulation results. In addition to this, the energy efficiency of the proposed system has been computed and compared. The performance of the MAC protocol for different licensed channels utilization probability has been simulated and presented. The simulation results have illustrated that throughput and energy efficiency of the proposed MAC protocol in the false alarm scenario is less as compared to that of the perfect sensing scenario. Moreover, miss-detection which also occurs due to imperfect sensing has resulted interference to the primary users and has been shown through the simulation results. Further, since we know that bandwidth is one of the most important commodities for communication system therefore we have presented a novel technique to minimize the bandwidth wastage in the proposed cognitive radio MAC protocol. The bandwidth wastage in the cooperative distributed MAC protocol has been minimized by transmitting data of the cognitive users over the idle licensed channels, which are unutilized in the sensing-sharing and contention interval. The proposed technique has significantly enhanced the throughput of the cooperative distributed network. Moreover, we concern about maximizing the energy efficiency of cognitive radio terminal and have obtained the optimum transmit power for the cognitive terminal at which energy efficiency is maximum. We have considered different scenarios of channel conditions at different channel gain and have maximized the energy efficiency of the cognitive radio terminal along with considering primary user’s channel status.

Further, we have proposed a novel frame structure for cognitive radio users which minimizes the data loss rate and eliminates the sensing-throughput trade-off in the conventional cognitive radio network. The proposed frame structure is compared with the earlier proposed frame structures and has provided the significant improvement in the throughput and reduction in data loss rate of the cognitive radio user. Thus, the data loss rate has been minimized by dividing the transmission time into small segments, which consist of multiple sub-frames. Therefore, in the proposed frame structure, the primary users are adequately protected against the harmful interference by the cognitive user’s transmission in the same frequency band. Finally, the fading environment effect on the channel capacity of cognitive radio communication system is considered under average interference power constraint with two different adaptation policies namely power adaptation and rate and power adaptation for multilevel quadrature amplitude modulation. The data rate and power of cognitive radio transmitter is varied based upon the sensing information and channel state information of the cognitive radios link. The channel capacity is maximized for these two policies by considering the Lagrange optimization problem for average interference power constraint. In this context, the Ergodic capacity of the cognitive radio communication system with power and rate adaptation policy in different fading environment for chosen BER is demonstrated in this thesis. Since the Nakagami-*m* distribution is fit for both the Rayleigh and Rician fading distribution by varying the fading parameter, therefore the Ergodic capacity for Nakagami-*m* fading is computed from which capacity is derived for Rayleigh and Rician fading channels. In addition to this, the numerically simulated results for the Ergodic capacity are presented for both the adaptive power and adaptive rate and power transmission policy, which reveal that the adaptive power transmission has more capacity than that of the adaptive rate and power transmission policy at the cost of BER. Moreover, we have demonstrated that the sensing parameter knowledge has provided an opportunity to control the secondary user’s transmission parameters such as rate and power according to different primary user’s activity levels observed by the sensing detector. However, the secondary transmitter can adapt different modulation by varying the value of $M$ in $M$-QAM according to the channel conditions, BER and interference constraints. Further, it is also illustrated that the capacity in case of Rician fading environment is less as compare to that of Rayleigh fading because LOS component presence in the cognitive radio transmitter to primary receiver has provided more prominent effect on the capacity of cognitive radio user in comparison to that present in cognitive radio transmitter to its receiver link.

The METIS (Mobile and wireless communications Enablers for the Twenty-twenty (2020) Information Society) project for 5$^{th}$ generation technology has been initiated which will use the cognitive radio technology for providing spectrum and energy efficient communication to the users. This project is proposed to be deployed till 2020. The attractive feature of 5G technology [185-187] is that it is built on the existing 4G and 3G technologies and therefore shares resources of these technologies. Heterogeneous networks support may provide a larger set of available resources than individual network, allowing users of 5G to seamlessly connect, at any time and any place, to the access technology that is most suitable according to some user/operator specified criteria. Cognitive radio technology inter-connects heterogeneous networks to satisfy all user's need and is suited as 5G terminal by using networks of different characteristics and technologies under same platform. In addition to this, the cognitive radio for green communication and its security issues are also the future directive in this field. In cognitive radio network, along with tradition security issues some unique security attacks occur [188]. Malicious users can attack the distributed systems and jam the control channel of cognitive radio network. Further, malicious users may pretend to be like primary users and deprive the cognitive users from getting the channel which is called primary user emulation attack. However in spectrum sensing data falsification attack, a set of malicious users report false results which affects cooperative sensing decision. Therefore, it is required to achieve the security in cognitive radio network during spectrum sensing and spectrum allocation process. Further, since the decision of sensing a channel is made by MAC layer and is passed to the lower layer, later which further communicates to the MAC layer with the sensing results. Moreover, scheduling and power control determine link capacities which affects routing [189]. Thus, various layers should communicate with each other in cognitive radio network to make the joint decisions on accessing a channel, power control, scheduling and routing. Therefore, an effective cross layer optimization scheme for cognitive radio network is an important directive for the future research. In addition to this, besides a long-term interdisciplinary effort to tackle the problem of building and deploying large-scale cognitive radio networks that meet the future growing demands of spectrum by our society, we believe that there is a need for an immediate research effort in the area of cognitive radio testbeds and its infrastructure. Such an effort would be of immediate benefit to the society and provides an excellent starting for a broader cognitive radio network research program.

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