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.