CHAPTER 4

CROSS LAYER BASED THROUGHPUT OPTIMIZATION IN COGNITIVE RADIO NETWORKS WITH EFFECTIVE CHANNEL SENSING SCHEMES

4.1 INTRODUCTION

The demand for new wireless services and applications as well as the number of users demanding these services are steadily increasing. This growth is ultimately constrained by the available frequency spectrum. According to current frequency allocation policies, fixed frequency band is being allocated to different wireless services to eliminate interference between them. The prime radio frequency spectrum (less than 3 GHz) is already exclusively assigned and the deployment of new wireless services is restricted to either the overpopulated license free ISM bands or bands located above 3 GHz. However a number of studies have shown that about 90% of the prime radio spectrum is significantly underutilized. In many bands, spectrum access is a more significant problem than the physical scarcity of spectrum, due to legacy command-and-control regulation that limits the ability of potential spectrum users to obtain such access (Arienzo 2009, Akyildiz et al 2008, Akyildiz et al 2006, Ben Lataief and Zhang 2006). To achieve a better utilization of the licensed radio spectrum, the FCC has recently suggested a new concept/policy for dynamically accessing the spectrum, referred to as Cognitive Radio, enabled by the software-defined radio technology. Cognitive radio is viewed as a novel approach for
improving the utilization of the electromagnetic spectrum (Demestichas et al 2009, Khalife et al 2009 and Stevenson et al 2009). CR techniques provide the capability to use or share the spectrum in an opportunistic manner. Dynamic spectrum access techniques allow the cognitive radio to operate in the best available channel. Therefore the main functions of CR technology are (Akildiz et al 2006),

- Spectrum sensing: Detecting unused spectrum and sharing the spectrum without harmful interference with other users.

- Spectrum management: Capturing the best available spectrum to meet user communication requirements.

- Spectrum mobility: Maintaining seamless communication requirements during the transition to better spectrum.

- Spectrum sharing: Providing the fair spectrum scheduling method among coexisting next generation users.

In this work designing a cross layer based MAC protocol for the CR network to maximize the throughput is considered as the main aim, which is made possible with efficient sensing algorithms. Hence this work concentrates only on the spectrum sensing aspect of the CR network and not on the other functionalities mentioned above. In a CR scenario, various spectrum sensing techniques are used by the secondary users to scan the licensed spectrum band of the PR users to determine the spectrum holes. These are then intelligently used by the CR users, for their own transmission without causing interference to the PR users. The dynamically changing spectral usage scenario necessitates the design of a suitable MAC protocol for the CR network. A number of cognitive radio MAC protocols have been proposed in the recent past. Hsu et al (2007), have proposed a statistical
channel allocation cognitive MAC protocol, based on Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA). Decision making for channel access is based on the spectrum usage statistics. For each transmission, the sender negotiates with the receiver on transmission parameters through Cognitive RTS/Cognitive CTS exchange over the control channel. However, collisions necessitate frequent re-negotiations. Dynamic open spectrum sharing MAC proposed by Ma et al (2005) allows nodes to adaptively select an arbitrary spectrum for the incipient communication, subject to spectrum availability. High spectrum utilization is achieved without relying on any infrastructure and the hidden terminal /exposed terminal problems are avoided by including the tri band (Busy tone band, Control Channel and Data band) approach. However, the device cost is increased due to the need for multiple transceivers.

The synchronized MAC proposed by Kondareddy et al (2008), is applicable for heterogeneous environments where channels have different bandwidths and frequencies of operation. The use of a common control channel is avoided in the protocol and a solution to issues like denial of service attacks and multi-channel hidden problem is provided. Better connectivity and higher throughput are obtained with a requirement that all the nodes in the network are to be synchronized. Le and Hossain (2008) have proposed opportunistic spectrum access MAC, where time is divided into beacon intervals and all the secondary users are synchronized. Each beacon interval consists of a channel selection phase, a sensing phase and a data transmission phase. Four-way handshake mechanism as in IEEE802.11 CSMA/CA protocol is used for data transmission. Uniform Channel Selection/Spectrum Opportunity-Based Channel Selection is employed. The system throughput increases with the number of secondary flows until reaching a maximum value and then slightly decreases.
Su and Zhang (2008) propose a cross-layer based MAC protocol, where two transceivers are used, one operates over a dedicated control channel and the other can be tuned to any one of the licensed channels on being found idle. Random sensing policy and negotiation-based sensing policy are proposed for spectrum scanning. Throughput and packet transmission delay are analyzed for CR networks using probability concepts and queuing theory. In (Ben Lataief and Zhang 2009), co-operative channel sensing using cognitive relays is discussed, where each relay makes a one bit decision about the channel and forwards to a common receiver which fuses all the decisions based on AND / OR / Majority logic. Protection of decision information using space time codes is also investigated.

The contribution in this work lies in analysing the effect of interferences on the primary communication link and its subsequent impact on the secondary users’ throughput in a CR scenario. In any wireless channel, interferences are unavoidable and these reduce the Signal to Interference and Noise Ratio (SINR) of the link. This in turn will have an impact on the effective spectrum sensing by the secondary users leading to misdetection. Misdetection is the case when a busy channel is identified to be an idle one by the CR network, due to the adverse effect of interference on the primary link. In the case of misdetection, the secondary users transmit their information via a particular band assuming that the primary user is not utilizing it. But in reality, the primary user will be using the band albeit with a low SINR. In this situation the primary user and the secondary user both cause interferences to one another. To combat such effects, interference analysis and it’s mitigation are very essential. Herein, the interferences to a given primary user’s receiver are modelled and their impact is analysed.

Further, an attempt is made to adaptively increase the throughput of the secondary users and hence that of the CR network by employing rate
adaptation techniques on the secondary users’ data transmission with a novel cross layer based MAC protocol. Further a simple idea to maximize the throughput of the secondary network based on the time series prediction technique using the backpropagation neural network technique is also implemented.

4.2 OVERVIEW OF SYSTEM

The system model considered for the study is shown in Figure 4.1. The primary users’ transmitter and receivers are considered to be in fixed positions. The secondary nodes are assumed to be distributed randomly within the area. The interference range shown in the figure is the area around a given secondary node within which it can cause harmful interference to the primary nodes. This can happen under misdetection of spectrum availability by the secondary node. The detection range is that area around a given secondary node within which it can detect the presence of any active primary user. For every secondary user, its detection range is maintained comparatively larger than its interference range so as to minimize the interferences from a secondary node to any of the primary receiver. This is achieved by controlling the secondary users transmit power level to be always lesser than that of the primary transmitter. Hence it can interfere only over a smaller range while being able to detect the presence of primary users over a wide range. Thus, the secondary user in spite of using an idle portion of the licensed frequency band ensures that, it in no way poses interference threat to the primary user.
Figure 4.1 System model

The interference range and the detection range are uniquely defined for each secondary user in the primary-secondary co-operative network. The interference range, $D_r$, as depicted in Figure 4.1 is estimated based on the following condition,

$$I_t = \frac{P_{PL}(R_d)}{P_{SL}(D_r) + P_b}$$  \hspace{1cm} (4.1)

where $I_t$ is the minimum SINR needed at the primary receiver, $P_{PL}(R_d)$ and $P_{SL}(D_r)$ are powers received from the primary transmitter and the interfering secondary transmitter respectively, inclusive of the path loss and $P_b$ is the power of background interference.

The detection (sensing) threshold, which is the minimum SINR at which the primary signal may still be accurately detected by the cognitive radio, is expressed as
where $P_{PL}(B_r)$ is the primary transmitter power received by secondary user inclusive of path loss and $N_c$ is channel noise power. $B_r$ is the maximum distance between primary transmitter and secondary user. In Figure 4.1 these parameters are shown for one secondary node. Similarly these parameters can be defined for every other secondary node in the network (Su and Zhang 2007). This helps the secondary user to estimate it’s interference effect on the primary receiver and hence adjust its transmission strategy (access policy and/or transmit power) accordingly. In wireless networks, transmission power defines the network topology and determines the network capacity (Ren et al 2009). The transmission power of secondary user not only determines its communication range but also affects its usage of idle spectrum. A secondary user can use a higher power to reach it’s intended receiver, only when the primary user band it is using is inactive within its interference region. Optimal power control in cognitive radio systems thus requires careful analysis of the impact of secondary user transmission power on the primary user’s receiver.

4.3 SPECTRUM SENSING AND THE MAC PROTOCOL

The key requirement envisaged as one of the basic features of any cognitive radio is that it must be able to accurately sense the spectrum holes. Spectrum holes are the bands of frequencies licensed to a primary user, that are not currently utilised by that user at a particular time and at a specific geographic location. It is therefore required that the secondary users appropriately decide when and which channel they should tune to in order to communicate among themselves without affecting the communication among the primary users. For this the secondary users must either continuously or
periodically scan the radio spectrum to identify the spectrum holes and sense their status.

### 4.3.1 Spectrum Sensing Schemes

In this work, two channel sensing schemes namely the Fusion based Arbitrary channel Sensing Scheme (FASS) and the Enhanced Intelligence based channel Sensing Scheme (EISS) are developed by combining the RSP and NSP proposed in (Su and Zhang 2008) with that of the majority fusion technique proposed in (Ben Letaief and Zhang 2009), and incorporating a novel rate adaptation algorithm.

In cognitive radios, channel sensing and data transmission cannot be carried out simultaneously and hence each secondary user is required to be equipped with two transceivers. These are called the control transceiver and the data transceiver respectively. To communicate among themselves, the secondary users have a small chunk of frequency spectrum allocated to them. This frequency band is called control channel. This control channel is time slotted with equal period and is divided into two parts namely the sensing/reporting phase and the contending phase. The reporting slot is further divided into smaller mini-slots corresponding to the number of licensed channels in the network.

In the FASS, the secondary users sense the channels independently and there is a chance that a single channel gets sensed by more than one secondary user, as in the case of RSP. The secondary users share their one bit decisions regarding the primary channels’ status in the corresponding mini-slots representing the licensed channels over the control channel. The primary channel sensed by more than one CR user is considered as free, only when all those CR users sense it to be free. This is a kind of co-operative sensing with AND logic and is highly conservative, because the fading and multi path
effects may result in different CR users experiencing different channel conditions and hence they may not be able to make correct decision about the channel status. To overcome this, in the proposed work, another co operative sensing scheme based on majority rule is used. To enable this, the sensing/reporting slot of the time slotted MAC protocol is modified such that the mini slot representing the primary channel is further divided into micro slots as shown in Figure 4.3b and the secondary users sensing the same channel are allowed to transmit their decision on their individual micro slots. Based on these decisions the majority fusion is done at the control transceivers of the secondary users, which are assumed to be working synchronism among themselves. Further, by making decisions based on majority fusion, the number of unused channels perceived by the secondary user will increase and thus is expected to improve the overall network performance in terms of spectrum utility and hence the network throughput.

The Enhanced Intelligence based channel Sensing Scheme is similar to that of the Negotiation based sensing policy of (Su and Zhang 2008) with the enhancement realized by the rate adaptation techniques. In this policy the secondary users have an idea of the channels that have already been sensed by other secondary users and select a new channel that has not yet been sensed. This is possible because the secondary users overhear the RTS/CTS packets of the secondary user transmissions on the control channel which contain information about the channels that have already been sensed. Herein, the number of licensed channels which are sensed by the secondary users in the $(t+1)^{th}$ time slot is considered to be always larger than or equal to that in the $t^{th}$ time slot for any value of $t$. Hence if the number of secondary users is larger than or equal to the number of licensed channels, all the licensed channels can be eventually sensed by using this policy. It is intelligent because each secondary user senses a new channel in each time slot.
The primary channel status is modeled using a Markovian state diagram as shown in Figure 4.2, where transition happens between two states at any given time slot. When the primary users are occupying a channel it is said to be busy (ON state/1), else it is said to be idle (OFF state/0) (Urgoankar and Neely 2009). Hence, a primary user’s channel usage may be viewed as a Markovian random process. The probability that a channel goes from ON state to OFF state is ‘$\alpha$’ and the probability that it goes from OFF state to ON state is given by ‘$\beta$’. The probability that the channel remains in the ON state is ‘1-$\alpha$’ and the probability that the channel remains in the OFF state is ‘1-$\beta$’. Thus, the primary users’ channel utilization factor, $\gamma$, is given as

$$\gamma = \frac{\beta}{\alpha + \beta} \quad (4.3)$$

![Figure 4.2 Primary user’s channel usage model](image)

From the probability transition matrix of this Markovian chain, the relationship between the number of secondary users and the probability that they can sense a given number of primary channels can be found and it is seen that the probability that all the channels are sensed by the secondary users depends on the number of secondary users. The more the number of secondary users, the more likely a larger number of channels is sensed. When the number of secondary users is large enough, they can sense all of the idle
licensed channels even using a simple random channel sensing scheme (Su and Zhang 2007).

In FASS, it is ensured that the channels are correctly sensed whereas in EISS it is ensured that all the channels are sensed. The channel sensing schemes may be selected as per the application requirements.

4.3.2 Cross Layer based Rate Adaptive MAC protocol with Interference Constraints

Cross layer design has been in focus over the past decade more so in the field of cognitive radios as it is found to improve the performance of wireless networks. The inter-layer coupling among/between the layers of the protocol stack can be exploited for optimization of QoS parameters such as the data rate, throughput, delay constraints, overall fairness etc. In this work, the spectrum sensing in the physical layer is integrated with packet scheduling at the MAC layer as in (Su and Zhang 2008). However the dynamic channel allocation and rate adaptation for secondary user transmission is additionally subjected to interference constraints which have not been considered in (Su and Zhang 2008).

The primary and secondary users are assumed to be synchronized within their respective groups. The secondary users are also assumed to be working in synchronism with the primary receivers. This synchronism is realized by having the control channel and the licensed channels equally time slotted. In the reporting phase of the time slot, the secondary users perform the process of channel sensing according to the sensing scheme and report the same. In the contending phase, they are allocated the unused frequency band based on the interference range constraints of a secondary node with respect to a primary receiver.
Referring to Figure 4.3a during the reporting phase, the data transceiver sense the channel say ‘j’ and makes a decision on the channel according to the channel sensing scheme. If it finds the j\textsuperscript{th} channel to be idle, it informs the control transceiver which in turn transmits a beacon in the respective mini-slot. The control transceivers of the secondary users are also listening on the control channel and when a secondary control transceiver receives a beacon at the k\textsuperscript{th} mini-slot, where k=j, the already stored number
gets updated and also the list of the unused channels. Thus in the reporting phase, the secondary users sense the licensed channels and report the channel state by sending beacons in the corresponding mini-slots and thereby share the respective channel state information in a distributed fashion. As the control channel has a very narrow bandwidth the cognitive users exchange only a single bit information regarding the status of the channel sensed by them.

To understand the working during the contending phase, consider two secondary nodes, $A_{CR}$ and $B_{CR}$. Assume that $A_{CR}$ wants to transmit data to $B_{CR}$. $A_{CR}$ initiates transmission following a contention-based algorithm such as the p-persistent CSMA protocol to access the control channel to negotiate with $B_{CR}$. $A_{CR}$ continuously listens to the control channel and waits until it becomes idle. Then it transmits the RTS packet with a probability ‘$p$’ (Tanenbaum 2009). Upon receiving this RTS packet, which contains information about the channel sensed by $A_{CR}$, the control transceiver of $B_{CR}$ will update the channel it should sense in the upcoming time slot, according to the channel sensing scheme and sends a CTS packet to the source node $A_{CR}$. When $A_{CR}$ receives this CTS packet, which also contains the information about the channel sensed by $B_{CR}$ it also updates the channel that it will sense according to the channel sensing scheme. If this RTS/CTS packet exchange is successful, it is concluded that the contention is succeeded, that is, the $A_{CR}$ has acquired the channel for communicating with $B_{CR}$.

The control transceiver of $A_{CR}$ sets a flag $s=1$. The data transceiver of $A_{CR}$ transmits the data packets to $B_{CR}$ via the channel allocated to them temporarily based on the interference constraints and resets the ‘$s$’ flag for the next consecutive time slot. The secondary users transmit data packets in the time slot following the one in which they successfully exchanged RTS/CTS packets with their destination secondary users. Thus, in the contending slot, the cognitive users use their control transceivers to negotiate or discuss
among themselves about the possible data channels by exchanging RTS/CTS packets over the control channel and then perform the actual data transmission using the respective data channels among themselves. Thus, an idle licensed channel is an opportunity to a pair of secondary users if they can communicate successfully without violating the interference constraint.

In this thesis, it is further noted that, if the bandwidth allocated to secondary users for transmission over an idle primary channel is uniform, the throughput obtained is much lower than that estimated theoretically from equations derived under ideal conditions. This problem is overcome in this work by proposing interference based rate adaptation algorithm for the secondary users, executed at the control transceivers of the secondary users after the reporting phase, when they have acquired knowledge about the idle channels.

On finding a channel to be idle, the secondary user must estimate the distance between itself and the relevant primary user to confirm if the primary user licensed to use that band falls outside its interference range. If so, the secondary user can use the channel for data transmission as it will not cause any harmful interference to the primary receiver, else it should refrain from using the channel. Also depending on this distance, the transmit power of the secondary user is fixed. To start with, it sends the RTS packet to its intended secondary receiver node with an arbitrary rate indicated in the rate field. On receiving the RTS packet at specific signal strength, the secondary receiver node will have an idea about the nature of the channel, inclusive of the interference constraint. Depending on its estimation of the channel characteristics, it will decide the data rate possible for further communication between them and will in turn acknowledge the reception of RTS packet by sending a CTS packet to the source secondary node. The CTS packet will contain information about transmission rate that will ensure successful transmission between them for the current channel status. When the
transmitter receives the CTS packet, it will use the specified rate in the CTS for further data transmissions.

Figure 4.4 shows the flowchart for the rate adaptation algorithm used in the MAC protocol. The basic idea here is to reduce the impact of misdetection. Thus, this is a kind of indirect interference mitigation technique.

(a) Flow chart depicting operation at secondary transmitter

**Figure 4.4 (Continued)**
Since cognitive radio is defined on a software platform, it can adaptively change its transmission parameters such as the frequency, transmit power, modulation technique, data rate etc. Here the rate adaptation scheme is used to maximize the throughput utilizing the available resources such as the power and bandwidth, efficiently. When the idle primary channel is found to
be more prone to interference and fading effects thus resulting in a low SINR, a very low rate data will be transmitted through that channel. But when the channel is found to be very good with negligible interference, information is sent at a higher data rate. This technique is expected to enhance the throughput of the cognitive network when compared to the throughput obtained under uniform low data rates.

### 4.3.3 Network Throughput Analysis

The cognitive radio network throughput is defined here in terms of the number of unused primary channels as perceived by the cognitive users and the bandwidth (data rate) allocated to each of these unused licensed channels, rather than in terms of the number of packets. Also, the throughput equations are defined based on the channel sensing schemes. This emphasizes the importance of a proper spectrum sensing scheme.

The throughput of the cognitive network based on the simple arbitrary sensing scheme, $\eta_{ASS}$, is given by

$$
\eta_{ASS} = \frac{R \cdot U_{ASS} \cdot T_{CP}}{T_o}
$$

(4.4)

where $R$ is the data rate of each cognitive user and $U$ is the number of unused channels as perceived by the secondary users and is denoted as $U_{ASS}$ and $U_{ISS}$, in ASS and in ISS respectively. The data transmission among the secondary users starts immediately after the sensing slot and continues for the entire contention period in every time slot. $T_{CP}$ and $T_o$ are the time durations of the contending phase and the whole time slot respectively.
Similarly, for the case of ISS the throughput is obtained as

$$\eta_{ISS} = \frac{RU_{ISS}^{TCP}}{T_0}$$  \hspace{1cm} (4.5)

The above equations obtained from (Su and Zhang 2008) assume there is accurate channel sensing, since ideal (no interference) conditions are assumed, which may be unrealistic.

### 4.3.4 Interference Modeling

Interference plays an important role in characterizing the system performance in any communication network especially in the case of networks that operate in a wireless environment. In the case of cognitive radio wireless networks, this interference affects both the primary as well as the secondary users’ networks either directly or indirectly. Hence statistical modeling of the interference and its analysis would help to a greater extent in mitigating these effects to improve the overall performance of the cognitive system.

To any given primary user, another primary user and cognitive user can cause interferences (Salameh et al 2009). These interference powers are statistically characterized. The stochastic models for PR-to-PR and the CR-to-PR interference under a Rayleigh fading channel model are constructed and the variance or the total interference power at the primary receiving node is obtained for a path loss exponent corresponding to a relatively lossy environment. The characteristic function of this random process, that is, aggregate interference at the PR receiving node, is obtained, from which its variance or power is estimated. The estimation is done for a terrain with path loss exponent 4, as follows. The primary user to primary user interference is given as
\[ \sigma_{\text{PR-PR}}^2(i) = \left[ \pi \gamma_i \rho_i / 3 \right] \left[ 2P_o(i) \exp\left(-\pi \gamma_i \rho_i (b_i)^2 \right) \right] \left( b_i / d_o(i) \right)^{-\delta} \] (4.6)

The cognitive user to primary user interference is given as

\[ \sigma_{\text{CR-PR}}^2(i) = \left[ \pi \gamma_i \rho_i / 3 \right] \left[ 2P_o(i) \exp\left(-\pi \gamma_i \rho_i (b_i)^2 \right) \right] \] (4.7)

The parameters in these equations are defined as follows

\[ \gamma_i \] - i\textsuperscript{th} primary users channels’ utilization given by

\[ \gamma_i = \frac{\rho_i}{\rho_i + \rho_t} \] (4.8)

\[ \rho_i \] - mean number of primary users per unit area

\[ P_o(i) \] - path loss of the i\textsuperscript{th} channel

\[ d_o(i) \] - reference distance between a given transmitter and receiver

Here, ‘i’ refers to the channel other than that used by the primary user under consideration. The total interference that accumulates at the reference primary receiver is thus given by

\[ \sigma_{\text{total}}^2 = \sigma_{\text{PR-PR}}^2(i) + \sigma_{\text{CR-PR}}^2(i) \] (4.9)

The signal power of the primary user is given by

\[ S = \delta |h(t)|^2 P_p \] (4.10)

where h(t) is the channel impulse response, \( \delta \) is the average channel power gain, \( P_p \) is the normalized transmit power of the primary user. The radio
propagation between any two primary nodes is assumed to be affected by slow flat fading channels. The signal to interference ratio is now derived as

$$\beta = \frac{S}{\sigma^2_{\text{total}}}$$ (4.11)

The secondary users can detect the presence of primary users when the SIR of the primary link is greater than a given sensing threshold, $\gamma_r$. The probability of erroneous sensing is

$$P(\text{error in sensing}) = P_e = P(\beta < \gamma_r) = 1 - \exp(-\gamma_r / \delta)$$ (4.12)

which gives the probability that a primary link’s SIR is less than the sensing threshold that results in erroneous sensing (Simeone et al 2007). Taking into account this probability of erroneous sensing due to interference, the throughput equations would be modified as follows. For the case of ASS,

$$\eta_{\text{ASS, INT}} = (1 - P_e) \eta_{\text{ASS}}$$ (4.13)

Following a similar kind of analysis for ISS,

$$\eta_{\text{ISS, INT}} = (1 - P_e) \eta_{\text{ISS}}$$ (4.14)

These are the actual throughputs that can be achieved considering the impact of misdetection due to interferences.

After the majority fusion technique is incorporated along with rate adaptation, the throughput equations get modified as

$$\eta_{\text{FASS, Rate}} = \frac{R_{\text{Adapted}} U_{\text{FASS}}^T C_P}{T_0}$$ (4.15)
for the case of Fusion based ASS and, for ISS with rate adaptation (EISS),

\[ \nu_{EISS\_Rate} = \frac{R_{Adapted}^{U_{ISS}} T_{CP}}{T_0} \]  

(4.16)

The average rate \( R_{Adapted} \) is obtained according to the algorithm discussed in section 2.2.

4.3.5 Performance Results and Discussion

A cognitive radio network scenario similar to that in Figure 4.1 was simulated using MATLAB 7.0. In the simulation 10 primary users are considered. The primary users are assumed to be stationary. The number of secondary users is taken up to 20. The secondary nodes are randomly distributed and form an ad hoc network with distributed control. The terrain is considered to be having a path loss exponent value of 4. The wireless channel is modelled with Rayleigh fading and log normal shadowing effect. A saturated network is considered wherein all the secondary users are assumed to be ready with data to transmit. Time duration of the slot is considered as 1.89 ms which includes the contending phase and reporting phase. The primary users’ channel utilization factor is taken to be 0.2. The data rate of each channel is uniformly taken as 1 Mbps. Figure 4.5a shows the throughput obtained from theoretical analysis and Figure 4.5b shows the throughput obtained from the simulation of simple ASS. Here throughput is defined as the total data rate perceived by the network, that is, the aggregate throughput of the network. It is clear from these performance curves that with misdetection, the cognitive users get a false notion that they are achieving a greater throughput than what is actually realized.
Figure 4.5a Throughput performance of simple Arbitrary Sensing Scheme for CR Network with and without interference constraint using analysis for $\gamma=0.2$

Figure 4.5b Throughput performance of simple Arbitrary Sensing Scheme for CR Network with and without interference constraint using simulation for $\gamma=0.2$
The throughput obtained using analysis and simulation for the Intelligence based sensing policy with the same parameters are shown in Figures 4.6a and 4.6b respectively. Here again a similar observation is made as for the case of ASS. This proves that throughput estimation without considering interference constraints gives a false notion of improved performance. Further comparing the throughputs of the two spectrum sensing schemes, it is observed that the throughput is improved in ISS compared to simple ASS since ISS makes sure that a primary channel is sensed by only one secondary user and also that the number of channels sensed by the secondary users is higher.

Figure 4.6a Throughput performance of Intelligent Sensing Scheme for CR network with and without interference constraint using analysis for $\gamma=0.2$
Figure 4.6b  Throughput performance of Intelligent Sensing Scheme for CR network with and without interference constraint using simulation for $\gamma=0.2$

A majority fusion based ASS is then simulated with five primary nodes and up to 20 secondary nodes with same parameters. The system model generated using MATLAB 7.0 for this scenario is shown in Figure 4.7.
Figure 4.7 Simulation Scenario of Cognitive Radio Users with Primary Users

With the use of fusion technique which exploits the cooperation among secondary users about sensed results, the probability of misdetection will be reduced. Also the MAC protocol integrates the rate adaptation on each perceived free channel thereby significantly improving the aggregate network throughput. The data rates used for rate adaptation are 1Mbps, 2Mbps, 5.5Mbps and 11Mbps. A link which is estimated to have low SNR uses lower rates for transmission while that with high SNR uses relatively higher rates. The throughput results obtained are shown in Figure 4.8 for different values of utilization factors and compared with simple ASS operating with fixed rate of 1 Mbps. Figure 4.9 gives the corresponding results for Enhanced intelligence based sensing scheme with rate adaptation.
Figure 4.8 Comparison between Fusion based Arbitrary Sensing Scheme with Rate adaptation and simple ASS for different utilization factors

Figure 4.9 Comparison between Enhanced Intelligence based Sensing Scheme and simple ISS for different utilization factors
The throughput comparison suggests that the proposed FASS and EISS show significantly improved performance because of the rate adaptation compared to fixed rate. It is further noted that the lower utilization factor of primary network translates to improved performance of the secondary users’ network. The FASS scheme primarily focuses on correctly sensing the idle channel using majority fusion technique along with rate adaptation and hence shows an improved throughput compared to the EISS scheme. The primary focus of EISS scheme is to sense all the primary channels and do the rate adaptation and hence the throughput tends to saturate once the number of secondary users exceed the number of available primary channels as shown in Table 4.1.

**Table 4.1 Throughput for \( \gamma=0.2 \) and \( n=5 \)**

<table>
<thead>
<tr>
<th>Number of secondary users</th>
<th>Throughput in (Mbps)</th>
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<tbody>
<tr>
<td></td>
<td>FASS</td>
<td>EISS</td>
</tr>
<tr>
<td>2</td>
<td>6.50</td>
<td>3.167</td>
</tr>
<tr>
<td>4</td>
<td>9.75</td>
<td>6.85</td>
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<tr>
<td>6</td>
<td>11.99</td>
<td>8.667</td>
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<tr>
<td>8</td>
<td>13.01</td>
<td>8.667</td>
</tr>
<tr>
<td>10</td>
<td>14.02</td>
<td>8.667</td>
</tr>
<tr>
<td>12</td>
<td>15.00</td>
<td>8.667</td>
</tr>
<tr>
<td>14</td>
<td>15.80</td>
<td>8.667</td>
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<td>16.25</td>
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<td>20</td>
<td>18.00</td>
<td>8.667</td>
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4.4 NEURAL NETWORK BASED THROUGHPUT MAXIMIZATION

The basic idea in this component of the work is to maximize the throughput of the cognitive network by predicting the primary channel availability and thereby increasing the data transmission time available for the secondary users. This is done based on the time series prediction technique using the back propagation neural network (Refenes et al 1992). If spectrum sensing is carried out very frequently there is unnecessary wastage of time. On the other hand, if it is done infrequently, some spectrum opportunities might be missed out (Ma and Ye Li 2008, Pei et al 2007).

Once the secondary user has acquired a primary channel for data transmission, if it is possible to predict the duration of the primary channel availability based on the history of channel status transition, then that primary channel need not be sensed for the predicted duration. This results in a corresponding increase in the duration of the contending phase or the data transmission time available for the secondary users and hence the throughput of the cognitive network improves. In this work the prediction based spectrum sensing using backpropagation neural network is employed in the simulated cognitive network and the throughput is compared with that of conventional spectrum sensing. The duration of primary channel availability is predicted using backpropagation neural network model shown in Figure 4.10. This is a three layer architecture consisting of input, output and hidden layers. The weighted connection from input to hidden and from hidden to output are given by matrices $u_{ij}$ and $v_{jk}$ respectively.
Figure 4.10 Backpropagation neural network model

The time series vector of 100 values that denote the time slot for which specific primary channel was free prior to the observation is given as input. Once the secondary user starts transmitting over that channel, based on this input and approximate target values, the time duration for which the channel will be free is found out. For these numbers of time slots, this specific channel need not be sensed and hence need not be allocated a mini slot duration for sensing information transfer. This can increase the contention period, however synchronization aspects due to elimination of corresponding mini slots need to be taken care of. The specifications of backpropagation algorithm employed in the simulation are given in the Table 4.2. Figure 4.11 illustrates the convergence of the back propagation algorithm during its training phase. Once it gets appropriately trained, it gives the correct output. In the hidden layers the main operation that take place is the autocorrelation analysis of the input time series that is very vital for predicting or forecasting the required value (Lin et al., 1995).
Table 4.2 Specifications of backpropagation algorithm employed in simulation

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of layers</td>
<td>Three (one input, one hidden, one output)</td>
</tr>
<tr>
<td>Number of input neurons</td>
<td>50</td>
</tr>
<tr>
<td>Number of output neurons</td>
<td>1</td>
</tr>
<tr>
<td>Transfer function at the hidden layer</td>
<td>Tan-sigmoid</td>
</tr>
<tr>
<td>Transfer function at the output layer</td>
<td>Linear</td>
</tr>
<tr>
<td>Learning rate</td>
<td>0.02</td>
</tr>
<tr>
<td>Tolerable value of error</td>
<td>$10^{-3}$</td>
</tr>
</tbody>
</table>

Figure 4.11 Convergence of the backpropagation neural network

The throughputs obtained with prediction based spectrum sensing and that of the conventional periodic spectrum sensing when there are ten
primary channels and the channel utilization factor is considered to be 0.6, are compared for the RSP and the NSP and shown in Figures 4.12 and 4.13 respectively. It is observed that the throughput is marginally improved by using the neural network based idle time prediction technique under both the sensing policies.

![Figure 4.12 Throughput under Random Sensing Policy](image1)

![Figure 4.13 Throughput under Negotiation based Sensing Policy](image2)
4.5 SUMMARY

In this work, a novel interference based rate adaptive MAC protocol is proposed for cognitive radio networks with FASS and EISS and the throughputs are analyzed. Sensing a channel effectively in the presence of interference is observed to significantly affect the throughput of the CR Network. A system model is evolved and the novel rate adaptation algorithm including interference constraints is implemented and found to significantly improve the throughput of the cognitive network. The following important inferences are drawn from the performances obtained.

- Throughput realized for secondary network is dependent on probability of misdetection which in turn is indicated by the interferences in the network.

- ISS shows improved throughput compared to ASS and saturates when the number of secondary users exceeds the number of primary channels.

- Rate adaptation improves the performance of both FASS and EISS, but is significant for FASS due to majority fusion.

- Idle time prediction when implemented results in marginal improvement in throughput at the cost of protocol structure modifications.