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 $N_{ch}$ slots in the sensing-sharing interval is not selected by any cognitive user is given by:

$$p(x) = \binom{N_{ch}}{x} p_{nosed}^x (1 - p_{nosed})^{N_{ch} - x}, \quad 0 \leq x \leq N_{ch}$$
where $p_{\text{nosensed}}$ is achieved from (2.6). The average number of sensing-sharing slots not selected by any cognitive user is:

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

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

$$E[Y] = N_{ch} - E[X]$$ (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 $Ch_{\text{max}}$ 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 $\alpha$ of each channel is:

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

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

$$E[U] = \sum_{u=0}^{E[Y]} u \cdot p(u)$$ (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:

$$p(g) = \binom{E[U]}{g} p_{f}^g (1 - p_{f})^{E[U]-g}, \quad 0 \leq g \leq E[U]$$ (3.6)

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

$$E[G] = \sum_{g=0}^{E[U]} g \cdot p(g)$$ (3.7)
The average number of idle channels detected after certain false alarm probability by $N_{CU}$ cognitive users is:

$$E[H] = E[U] - E[G]$$  \(\text{(3.8)}\)

(b) Miss detection

Moreover, the average number of busy channels detected for the particular value of $Ch_{\text{max}}$ and $\alpha$ 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:

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

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 $N_{CU}$ 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]:

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

$$P_{CU} = \begin{cases} 
\left(\frac{N_{CU}(N_{CU}-1)}{E[J]}ight), & E[J] \leq N_{CU} \\
1, & \text{otherwise} 
\end{cases}$$

(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: $CW_1 = 2 \times N_{CU}$. 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:

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

(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:

\[
p_{\text{success}}(1) = p(1) = \binom{N_{\text{CU}}}{1}(r_1)^1(1 - r_1)^{N_{\text{CU}}-1}
\]

(3.12)

\[
= N_{\text{CU}} r_1 (1 - r_1)^{N_{\text{CU}}-1}
\]

(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 \( p_{\text{success}}(1) \), therefore from the binomial distribution, we can find the average number of successful contention slots or average number of successful cognitive users as:

\[
E[T_1] = CW_1 \times p_{\text{success}}(1)
\]

(3.14)

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

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

(3.15)

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

\[
r_i = \frac{1}{CW_i}, \text{ where } i=2,3,4,\ldots, \text{ and } CW_2 = 2^4, CW_3 = 2 \times CW_2, CW_4 = 2 \times CW_3, \ldots \ldots
\]

(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 increased contention interval, which is described as:

\[
p(s_i) = \left(\frac{E[C_{i-1}]}{s_i}\right)(\eta_1)^{s_i}(1 - \eta_1)^{N_{\text{CU}}-s_i}, \quad 0 \leq s_i \leq E[C_{i-1}], \quad i = 2, 3, 4, \ldots
\]

(3.17)

\[
p_{\text{success}}(i) = E[C_{i-1}] \times r_i \times (1 - r_1)^{E[C_{i-1}]-1}
\]

(3.18)

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

\[
E[T_i] = CW_i \times p_{\text{success}}(i)
\]

(3.19)

and the average number of collided cognitive users are:

\[
E[C_i] = E[C_{i-1}] - E[T_i]
\]

(3.20)
Further, the total number of contention slots $CW_{total}$ are:

$$CW_{total} = \sum_{i=1}^{i} CW_i$$  \hspace{1cm} (3.21)

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

$$E[T_{total}] = E[T_{i-1}] + E[T_i]$$  \hspace{1cm} (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: $CW_{total} = CW_{max}$ 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 $T_{tr}$ is defined as:

$$T_{tr} = T_{cycle} - (T_{idle} + T_{ss} + T_{ct})$$

$$= T_{cycle} - (T_{idle} + 3 \times T_{slot} \times N_{ch} + CW_{total} \times (CR - RTS + CR - SIFS + CR - CTS))$$  \hspace{1cm} (3.23)

where $T_{cycle}$ is the total cycle time, $T_{idle}$, $T_{ss}$ and $T_{ct}$ are idle interval, sensing-sharing interval and contention interval duration, respectively. Since sensing-sharing interval contains $N_{ch}$ number of slots and each sensing-sharing slot have three sub-slots, therefore $3 \times T_{slot} \times N_{ch}$ denotes whole sensing-sharing interval duration. Similarly, $CW_{total} \times (CR - RTS + CR - SIFS + CR - CTS)$ 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 $E(CH_{idle} \times T_{total})$ and the average number of sensed idle channels from (3.5), the amount of time available for the data transmission per cycle interval ($T_{tr}/T_{cycle}$), and the data rate per sensed idle channels $R$. Further, the throughput $T$ for the proposed MAC protocol is given as:
\[ T = \frac{E[\min (C_{\text{idle}} \times T_{\text{total}} , U)] \times T_{\text{tr}} \times R}{T_{\text{cycle}}} \]  

(3.24)

where \( C_{\text{idle}} \) is the number of idle channels that a cognitive user is allowed to use, simultaneously. \( E[T_{\text{total}}] \) 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), \( T_{I} \) is computed from (3.8) since the less idle channels are detected in the false detection and is given as:

\[ T_{I} = \frac{E[\min (C_{\text{idle}} \times T_{\text{total}} , H)] \times T_{\text{tr}} \times R}{T_{\text{cycle}}} \]  

(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:

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

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 ($P_T$) that is required by a cognitive node for transmitting data, 2) reception power ($P_R$) that is consumed by a cognitive user terminal while receiving data, and 3) idle mode power ($P_I$) 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:

$$ (P_R \times T_{slot} + P_T \times 2 \times T_{slot}) \times N_{CU} \times Ch_{max}, $$

where $T_{slot}$ 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:

$$ E[X] \times P_I \times 3 \times T_{slot}. $$

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

$$ E_{T_{ss}} = (P_R \times T_{slot} + P_T \times 2 \times T_{slot}) \times N_{CU} \times Ch_{max} + E[X] \times P_I \times 3 \times T_{slot} \quad (3.26) $$

### 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 $T_{RTS}$ and $T_{CTS}$, respectively and the interval of CR-SIFS (cognitive radio Short-Inter Frame Spacing) between CR-RTS and CR-CTS frame is $T_{SIFS}$. 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:

$$ E_{T_{ct}} = P_T \times T_{RTS} \times \text{total number of collided users} + P_I \times T_{SIFS} \times \text{total number of collided users} + $$
\[ P_i \times T_{\text{CTS}} \times \text{total number of collided users} + P_T \times T_{\text{RTS}} \times E[T_{\text{total}}] + P_i \times T_{\text{SIFS}} \times E[T_{\text{total}}] + P_R \times T_{\text{CTS}} \times E[T_{\text{total}}] + [CW_{\text{total}} - (\text{total number of collided users} + E[T_{\text{total}}])] \times P_i \times T_{\text{slot}} \]

where the total number of collided users is taken from (3.15) and (3.20) and \( E[T_{\text{total}}] \) 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 \((Ch_{\text{idle}} \times E(T_1), E(U))\) and \((Ch_{\text{idle}} \times E(T_{\text{total}}), E(H))\) for the perfect and imperfect sensing, respectively. Therefore, the energy consumption over the information/data transmission interval for the perfect and imperfect sensing is:

\[ E_{T_{\text{tr}}} = P_T \times T_{\text{tr}} \times E[\text{min}(Ch_{\text{idle}} \times T_1, U)] \]  

and

\[ E_{T_{\text{tr},I}} = P_T \times T_{\text{tr}} \times E[\text{min}(Ch_{\text{idle}} \times T_{\text{total}}, H)] \]  

respectively, \( E_{T_{\text{tr}}} \) and \( E_{T_{\text{tr},I}} \) 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:

\[ EE = \frac{T}{E_{\text{total}}} \]  

\[ EE_I = \frac{T_I}{E_{I,\text{total}}} \]

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

\[ E_{\text{total}} = E_{T_{\text{ss}}} + E_{T_{\text{ct}}} + E_{T_{\text{tr}}} \], and

\[ E_{I,\text{total}} = E_{T_{\text{ss}}} + E_{T_{\text{ct}}} + E_{T_{\text{tr},I}} \], 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 $C_{\text{h max}}$, 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 $C_{\text{h max}}$. Moreover, with the increase of $C_{\text{h max}}$ for the chosen value of the probability of false alarm, the number of imperfectly detected licensed channels is more for the higher value of $C_{\text{h max}}$ 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 $C_{\text{h max}}$ 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 $C_{\text{h max}}$. This behavior is well understood from (3.5) which have computed the idle channels detected for a chosen $\alpha$ 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.

<table>
<thead>
<tr>
<th>Simulation Parameters</th>
<th>Numerical Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of licensed channels ($N_{ch}$)</td>
<td>20</td>
</tr>
<tr>
<td>Utilization probability of licensed channels ($\alpha$)</td>
<td>0-1</td>
</tr>
<tr>
<td>Number of sensed channel by each cognitive user ($C_{\text{h max}}$)</td>
<td>2-5</td>
</tr>
<tr>
<td>Number of cognitive users ($N_{\text{CU}}$)</td>
<td>10-30</td>
</tr>
<tr>
<td>Probability of false detection ($P_{\text{m}}$)</td>
<td>0-1</td>
</tr>
<tr>
<td>Cycle time ($T_{\text{cycle}}$)</td>
<td>1 s</td>
</tr>
<tr>
<td>Single slot time ($T_{\text{slot}}$)</td>
<td>9 $\mu$s</td>
</tr>
<tr>
<td>CR-RTS frame duration</td>
<td>24 $\mu$s</td>
</tr>
<tr>
<td>CR-CTS frame duration</td>
<td>24 $\mu$s</td>
</tr>
</tbody>
</table>
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  
\(Ch_{idle}\) | 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 \(\alpha\), 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](image.png)

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

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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 $C_{h_{\text{max}}}$ in the perfect sensing environment. As the utilization probability of licensed channel increases for particular $C_{h_{\text{max}}}$ shown in Fig. 3.2(b), even 10 users can not sense 10 idle channels. For example, with $C_{h_{\text{max}}}=2$ 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 $C_{h_{\text{max}}}$ at a particular value of $\alpha$. 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 $C_{h_{\text{max}}}=2, 3, 4, 5$ which is shown in Fig. 3.2(a) and therefore these values of $\alpha$ 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.
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

![Graph showing the effects of variation of the utilization probability/traffic load of the licensed channels on the number of idle channels detected and number of cognitive users required for all needed idle channels detection.](image)
is of 10 users and not more than that which is the reason that for \( \alpha = 0, 0.1, 0.2 \) the throughput is same. However, as \( \alpha \) 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 \( \alpha \) 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 \( Ch_{\text{max}} \) 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.

![Comparison of analytical and simulated results of the proposed MAC protocol.](image)

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

![Throughput of cognitive network with different licensed channels utilization probability.](image)

**Fig. 3.5** The throughput of cognitive network with different licensed channels utilization probability for $\text{Ch}_{\max} = 2$, $N_{ch} = 20$, $N_{CU} = 10$, 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 ($\alpha$) 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 $C_h_{\text{max}} = 2$, $N_{ch} = 20$, $N_{CU} = 10$ 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 $C_h_{\text{max}}$ where the simulation parameters are $\alpha = 0.5$, $R = 54$ Mbps, $N_{ch} = 20$, $N_{CU} = 10, 20, 30$ and $C_h_{\text{max}} = 2$. 
**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, $N_{ch} = 20$, and $C_{h_{max}} = 2$.

**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 $N_{ch} = 20$.

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.

![Graph showing average idle channel utilization](image)

**Fig. 3.10** The average idle channel utilization with the number of cognitive users for $N_{ch} = 20$ and $\alpha=0.5$ 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.