Chapter 3

Cognitive Cross-layer Multi-channel MAC Protocol

As discussed in chapter 1, a MAC protocol for cognitive networks should support multi-channel operation with dynamic availability of heterogeneous channels. This chapter presents the MAC layer issues in cognitive networks in detail. It also proposes a medium access protocol, named as Cognitive Cross-layer Multi-channel MAC. CCM-MAC is a modification of the MMAC protocol for cognitive networks (MMAC-CR) [39]. Extensive performance evaluation of CCM-MAC is done by simulating multiple scenarios in NS2. The performance evaluation confirms that CCM-MAC ensures high throughput and low value of energy consumed per packet while keeping the average end-to-end delays same.

The rest of this chapter is organized as follows. Sections 3.1 and 3.2 present the literature survey for MAC layer issues and strategies related to cognitive networks. In section 3.4 the proposed protocol is discussed. Section 3.5 presents the results for the proposed protocol. Finally, section 3.6 concludes the chapter.

3.1 Cognitive MAC issues

In cognitive networks, functionality of cognitive cycle is the main challenge of MAC layer. Cognitive cycle builds the spectrum opportunity map and dynamically schedules resources among cognitive users. Furthermore, cognitive cycle allows cognitive users to vacate the selected channel when a primary user becomes active. Cormio and Chowdhury [35] provide a survey of MAC protocols and general classification in cognitive environment. Below are some of the main issues of MAC layer in cognitive networks.

- **Channel Assignment**: In multi-channel environments, channel assignment is critical in achieving high channel utilization. Ideally, it is best to have the traffic equally divided among channels. Cognitive networks work with heterogeneous spectrum bands. Thus, the change in transmission channel also changes the transmission parameters and the rate of data transmissions in cognitive networks. Also, availability of channels is not certain due to primary user activity. This makes the selection of transmission channel from the spectrum holes identified by the spectrum sensing more challenging.
• **Control information sharing**: Control signaling is necessary for every communication protocol. It is much more important in cognitive environment to support transmission coordination and spectrum related information exchange between the cognitive users. It helps in neighbor discovery, spectrum sensing coordination, exchange of local measurements and other control signaling needed between the cognitive users. It can be done in following manner:

  - Common Control Channel (CCC): Portion of spectrum band is allocated for control signaling. CCC can be allocated as in-band CCC or out-of-band CCC depending on whether it shares the data channel or uses a dedicated spectrum, respectively.

  - Time Slot Based: Portion of time slot in all the channels are used for control signaling.

  - Frequency Hopping Sequence: Sequence of frequencies is used for control signaling. Cognitive users hop between these bands for control signaling.

• **Channel Synchronization**: Single channel protocols cannot be directly applied to multi-channel environment because the sender and the receiver have to be operating on the same channel. Here the focus is on the situation where each node is equipped with a single interface, so a node can only listen to one channel at a time. When two nodes are operating on the same channel, we say that their channels are synchronized. Thus, before the actual data transmission, both the transmitter and receiver should synchronize their respective radios to the same channel. The process of node moving from one channel to another is called channel switching. In cognitive networks, channel switching is more frequent as cognitive users must vacate the channel whenever primary user comes back. This requirement make channel synchronization as one of the important feature of cognitive MAC protocol.

• **Medium access control**: When a node transmits a packet onto the channel, the signal reaches all nodes in the transmission range of the sender. If a node receives multiple packets on the same channel at the same time, it cannot properly decode the packet because of interference. Thus, medium access control among the nodes is needed to avoid collision similar to simple wireless MAC strategies.

• **Multi-channel Hidden Node Problem**: In a multi-channel environment with single half-duplex transceiver, a node can only hear RTS and CTS transmitted on the tuned channel. In such case, a node is not able to hear other channel RTS and CTS, which leads to multi-channel hidden node problem. A scenario for the multi-channel hidden node problem is shown in figure 3.1. In the shown scenario node A has a packet for B, so A sends an RTS on Channel 1. B selects Channel 2 for data communication and sends a CTS. After the successful handshake node A and B start data communication. However, during the RTS-CTS handshake of node A and B, node C was busy receiving on another channel, so it did not hear the CTS. Node C might initiate a communication with D on Channel 2 for data communication which will result in collision at node B.
• **Channels Scheduling**: When a node has packets queued for multiple destination nodes with different channels, channels scheduling is needed to schedule the packets on the radio interface based on the operating channel. Some basic approaches for channels scheduling are:

  - Fixed channel scheduling: The simplest method is to schedule channels with fixed period in a round robin manner. This scheme is not suitable where load is different among channels.
  
  - First-in first-out (FIFO): A node switches the channel based on the first packet in the queue. If we schedule packets using FIFO algorithm, in worst case, channel switching could be needed for every single packet which will lead to higher transmission delays.
  
  - Threshold based approach: To minimize the channel switching delay, this method tolerates a packet delay up to a certain bound. A node can stay on a particular channel, until a packet to be sent on a different channel has waited more than the threshold. Then it switches the channel.

### 3.2 Existing Protocols

This section presents some of the cognitive MAC protocols from literature:

• **Dynamic Open Spectrum Sharing (DOSS)** [40]: DOSS uses a busy tone broadcasting based approach for collision avoidance. Whenever a node transmits or receives data on a channel, it also emits a busy tone signal in the corresponding busy tone band. Spectrum sensing support is provided. Packet flow sequence is “REQ → REQ-ACK → DATA → ACK”. **REQ & REQ-ACK**
messages also negotiate about the channel to be used. Whenever a node wants to transmit or receive data on a channel, it senses the corresponding busy tone channel, this ensures that the transmission of the other cognitive users are not mistaken with the primary user activity. The drawback of DOSS is that it requires multiple radio transceivers, and separate frequency bands for the busy tone channel and control channel.

- C-MAC [41]: In C-MAC, all the channels have super-frames containing a beacon period and a data transfer period with the assumption that beacon period is non-overlapping for all the channels. Data transfer period is accessed in TDMA manner by all the users. C-MAC also uses rendezvous channel for control signaling. In this protocol, spectrum switching is not instantaneous which may cause primary user interference. Also, the selection method of non-overlapping beacon periods is not presented in paper.

- HC-MAC [42]: In HC-MAC, each time slot is divided in three parts: contention, sensing and transmission. In contention period, C-CTS, C-RTS are used to reserve a slot for the sensing. In the sensing period, cognitive sender and receiver both sense channels and communicate to get a common free channel, followed by data transfer. In this protocol C-RTS message cannot be received by a node already busy in some communication, and can lead to multi-channel hidden node problem.

- MMAC-CR: MMAC-CR is an improvement of MMAC [43], hence it includes multi-channel operation. Time frame is divided into an ATIM window and a data transfer window. The ATIM window is used to negotiate the channel between transmitter and receiver, it also solves the issue of channel synchronization. It uses the IEEE 802.11 Timing Synchronization Function (TSF) for time synchronization. Packet flow sequence is “Beacon → Scan Result Packet (SRP) → ATIM → ATIM-ACK → ATIM-RES” on control channel and “RTS → CTS → DATA → ACK” on data channels. In MMAC-CR, the transmitter insert a list of its spectral opportunities and queue status in the ATIM frame. The receiver compares this list with its own list and selects the common opportunity for data communication. The selected channel is then inserted in the ATIM-ACK frame. To inform the neighbors of the transmitter that were not able to hear the ATIM-ACK frame, the transmitter sends an ATIM-RES frame, which includes the selected data channel. Nodes that did not send or receive ATIM frame; enter a sleep state for the beacon interval to save energy. This protocol does not provide a silent period for spectrum sensing. The silent period for spectrum sensing insures that the cognitive user’s data is not mistaken as primary user’s data. Also, this protocol suffers from spectrum wastage due to the insertion of the complete list of spectral opportunities and queue status in the ATIM frame.

- Cognitive Radio-EnAbled Multi-Channel MAC (CREAM-MAC) [44]: The CREAM-MAC protocol maintains a Channel Usage List (CUL) and a Free Channel List (FCL). For medium access, it uses “RTS → CTS → RES → Data” sequence flow. RTS, CTS and RES are done on the control
channel. RTS carries the FCL and based on FCL, the receiver selects a channel to be used which is then reserved by a RES message. It uses single transceiver that alternates between monitoring the CCC and the data spectrum bands. It does not provide support for spectrum sensing and channel synchronization.

- **Cognitive-Radio-based Carrier Sense Medium Access with Collision Avoidance (CR-CSMA/CA)** [45]: In CR-CSMA/CA, Prepare-To-Send (PTS) frame is sent before the RTC-CTS mechanism of CSMA/CA for spectrum sensing support. Once other cognitive users receive PTS frame, they keep quiet for the following duration so that cognitive user signal is not mistaken as a primary user signal. This protocol also does not give any information about channel synchronization.

- **Channel Aggregation Diversity (CAD)** [46]: In CAD MAC, cognitive users select a group of channels from the available channels based on sensing results, and select an upper bounded power level for the selected channels. Then, channel aggregation technology is used to simultaneously use the selected channels for data transmission. CAD MAC assumes that all cognitive nodes are synchronized and have the same time slot division as of primary users. This assumption is not practical for more than one kind of primary users.

Summary of these protocols with respect to the issues discussed above is presented in table 3.1. Busy

<table>
<thead>
<tr>
<th>Protocol</th>
<th>Spectrum Access Method</th>
<th>Medium Access</th>
<th>Interface Requirement</th>
<th>Multi-channel Hidden Node</th>
<th>Channel Synchronization</th>
<th>Spectrum Sensing Support</th>
<th>Channel Scheduling</th>
</tr>
</thead>
<tbody>
<tr>
<td>DOSS</td>
<td>Busy Tone Broadcasting</td>
<td>REQ-RQQACK-DATA-ACK</td>
<td>Multiple</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>C-MAC</td>
<td>TDMA Based</td>
<td>TDMA Based</td>
<td>Single</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>HC-MAC</td>
<td>Contention Based</td>
<td>RTS-CTS</td>
<td>Single</td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>MMAC-CR</td>
<td>Contention Based</td>
<td>ATIM Window with RTS-CST</td>
<td>Single</td>
<td>Yes</td>
<td>Partial</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>CREAM-MAC</td>
<td>Contention Based</td>
<td>RTS-CTS</td>
<td>Single</td>
<td>No</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>CR-CSMA/CA</td>
<td>Contention Based</td>
<td>RTS-CTS</td>
<td>Single</td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>CAD MAC</td>
<td>Channel Aggregation Based</td>
<td>RTS-CTS-RES</td>
<td>Single</td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
</tr>
</tbody>
</table>

Table 3.1: MAC Layer Strategies
tone broadcasting based protocols require multiple radio transceivers and separate frequency bands for busy tone channel and control channel. To avoid interference to primary user in TDMA based protocols (like C-MAC), all secondary users should be synchronized and follow the same time-slot division as of the primary user. Thus, for more than one primary user network, TDMA based approach cannot be used. Most of the contention based protocols do not provide a solution to multi-channel hidden node problem. A cognitive MAC protocol which solves all the challenges of cognitive networks is still needed. As discussed in [47], selection of channel at MAC layer will not always give an efficient end-to-end solution. Hence, it is suggested to select channel at upper layers in cognitive networks.

3.3 Background Details

This section discusses the basic assumptions and details about IEEE 802.11 Power Saving Mode (PSM), MMAC [43] and MMAC-CR [39] protocol.

3.3.1 Assumptions

- Total M+1 channels are available to be used by secondary users.
- One channel is used as CCC. Similar to MMAC & MMAC-CRs, only one handshake on the CCC is needed per connection during the beacon interval. Thus, this protocol doesn’t suffer with control channel starvation.
- Channels are non-overlapping, i.e. communication on all the available channels can be done simultaneously.
- Secondary users are capable of dynamically switching their channel.
- Each host is equipped with a single half-duplex transceiver.
- Nodes are synchronized, so that all nodes begin their beacon interval at the same time. We use IEEE 802.11 TSF in our simulations.

3.3.2 IEEE 802.11 PSM

IEEE 802.11 is a widely deployed wireless network standard. It specifies two MAC protocols, called Point Coordination Function (PCF) and Distributed Coordination Function (DCF). PCF only works for infrastructure networks, whereas DCF does not require an infrastructure. DCF is based on a scheme called Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA). A node can save energy by going into sleep mode. In sleep mode, a node consumes significantly less energy compared to idle mode, but cannot send or receive packets. It is desirable for a node to enter the sleep mode only when there is no need for exchanging data. In IEEE 802.11 PSM, time is divided into beacon intervals. Every
node in the network is synchronized by periodic beacon transmissions. Each beacon interval starts with an ATIM window. Each node in the network stays awake in the ATIM window. If node S has buffered packets for node R, it sends an ATIM frame to node R in the ATIM window. When node R receives an ATIM packet, it replies back to node S with ATIM-ACK. Both S and R will then stay awake for that entire beacon interval. If any node has not sent or received any ATIM packets during the ATIM window, it enters sleep mode until the next beacon time to save power.

### 3.3.3 MMAC & MMAC-CR

In MMAC protocol, transmitter also includes its Preferable Channel List (PCL) in the ATIM frame. After receiving the ATIM frame, receiver selects one channel based on the transmitter’s as well as its own PCL. The ATIM-ACK frame notifies the channel to be used in the vicinity of receiver. Similarly, the ATIM-RES (ATIM-Reservation) frame notifies the channel to be used in the vicinity of transmitter. Nodes that have reserved a channel in the ATIM window, communicate with RTS-CTS mechanism in the data window. The sequence of ATIM handshake of these protocols are shown in figure 3.2. In this figure, node S is a transmitter and node R is a receiver. The solid lines show the communication of ATIM frame, ATIM-ACK frame and ATIM-RES frame between the transmitter and the receiver. The dashes lines show the notification of channel to be used in the vicinity of the transmitter and the receiver.

MMAC-CR is discussed in section 3.2. It uses a three way handshake of MMAC protocol to reserve a channel for data communication. In MMAC-CR, the transmitter insert a list of its spectral opportunities and queue status in the ATIM frame. This protocol does not provide a silent period for spectrum sensing. The silent period for spectrum sensing insures that the cognitive user’s data is not mistaken as primary user’s data. Also, this protocol suffers from spectrum wastage due to the insertion of the complete list of spectral opportunities and queue status in the ATIM frame.

### 3.4 Proposed MAC Protocol

This section discusses the proposed MAC protocol, CCM-MAC. This protocol is based on the concept of IEEE 802.11 PSM. The proposed protocol minimizes the overhead by supporting channel as-
signment at routing layer. This way it reduces the size of an ATIM frame. It also reduces the three way handshake of MMAC-CR to two way handshake as ATIM-RES frame transmission is not necessary when channel assignment is done at routing layer. CCM-MAC protocol also provide full spectrum sensing support by providing silent period for spectrum sensing. Subsections below describe the features of the proposed protocol in details.

3.4.1 Channel Assignment

Channel selection in an optimized MAC protocol may provide best channel, power and rate assignment for a particular link; but such an assignment can be inefficient for the end-to-end path. Hence, selection of channel is done at routing layer, as discussed in chapter 2. The channel selection rule for a cross layer protocol is shown in equation 3.1. Node \( j \) selects channel \( m \) from the spectrum opportunities which minimizes the cost function \( C' \), and tunes its receiver radio to the selected channel.

\[
C' = \left\{ w_1 f_{\text{norm}} \left( \frac{P_{\text{avg}}^m}{B_m} \right) + w_2 f_{\text{norm}} \left( \frac{1}{B_m} \right) \right\}
\]  

(3.1)

where \( P_{\text{avg}}^m \) is the average of transmit power required by neighbors to transmit packet to node \( j \) and \( B_m \) is bandwidth of channel \( m \). Here \( w_1, w_2 \) are the coefficients which decide the weights for each component in the cost function. As all these parameters are in different scales, we use normalization function \( f_{\text{norm}}(x) \) to scale them to range \( [x_{\text{min}} - x_{\text{max}}] \) as shown in equation 3.2.

\[
f_{\text{norm}}(x) = \frac{x - x_{\text{min}}}{x_{\text{max}} - x_{\text{min}}}
\]

(3.2)

\( f_{\text{norm}}(x) \) will have values between zero and one. From equation 3.1, it is clear that each node selects a channel which minimizes average transmit power from neighbors and has better channel bandwidth.

3.4.2 Medium access control

In CCM-MAC, ATIM and ATIM-ACK messages are used to reserve channel for medium access and collision avoidance. ATIM and ATIM-ACK message transmissions are done on control channel. ATIM message contains the value of selected channel for transmission. Receiving node confirms the reservation of same channel in ATIM-ACK message. Nodes that do not exchange ATIM messages go to sleep mode for the beacon interval to save power. After the ATIM window, data transmissions follow the RTS-CTS mechanism of IEEE 802.11 to avoid collisions in data window. The sequence of message transmission for channel reservation and data transmission is shown in figure 3.3.

The complete list of spectrum opportunities and queue status are not transmitted in ATIM message (as done in MMAC-CR protocol), which decreases the overhead of transmission. Also, ATIM-RES message is not required, as the ATIM message notifies the transmission channel in the vicinity of sender.
3.4.3 Spectrum sensing support

Unlike MMAC & MMAC-CR, the proposed CAM-MAC protocol provides spectrum sensing support by reserving a slot for fast spectrum sensing (SS) in every ATIM window. In SS period, cognitive users will not transmit or receive any messages. Hence, primary user data will not be mistaken as cognitive user data in spectrum sensing. The nodes randomly select one of the channels to perform a fast scan. Based on the result of fast scan Spectral Image of Primary users (SIP) vector is updated. SIP vector has three kinds of entries:

1. Channel $c$ is free from primary user activity ($SIP[c] = 0$).
2. Channel $c$ is occupied with primary user activity ($SIP[c] = 1$).
3. The spectral image of channel $c$ is uncertain ($SIP[c] = 2$).

Spectrum sensing periods of ATIM window also include the C mini-slots which are used to broadcast results of spectrum sensing. This mini-slot process of learning network-wide spectrum opportunities is also used in [48] and [49]. If primary user activity on channel $c$ is uncertain, then a fine scan is performed during the data window by nodes that do not have any data transmission scheduled for the beacon interval.

3.4.4 Other details

In CCM-MAC, the ATIM window handshake provides a solution to channel synchronization and multi-channel hidden node problem. Common control channel is used for control information sharing.
As only one handshake on CCC is needed per connection during the beacon interval, control channel starvation problem does not arise.

Channel scheduling follows the threshold based approach to minimize the channel switching delay. Once buffered packet count for any channel reaches the specified threshold, packets with that channel are transmitted first.

### 3.5 Performance Evaluation

In this section, we evaluate the performance of CCM-MAC by means of simulation performed in NS2. It is evaluated across multiple scenarios and a comparative analysis is done against MMAC-CR protocol. Primary user activity on the spectrum band is modeled as an alternating sequence of ON and OFF periods, where ON and OFF denote that the spectrum band is occupied and unoccupied by primary users, respectively. ON and OFF periods are exponentially distributed with rate $\alpha$ and $\beta$, respectively. For transient period elimination and calculating stopping criterion of simulation, batch mean technique is used. Stopping criterion gives the mean values of the parameters, which remain unchanged even if simulation is run for larger period. The simulation parameters are listed in table 3.2.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spectrum band (GHz)</td>
<td>2.4-2.5</td>
</tr>
<tr>
<td>Number of channels</td>
<td>11</td>
</tr>
<tr>
<td>Number of primary users</td>
<td>10</td>
</tr>
<tr>
<td>Primary user transmission range (m)</td>
<td>300</td>
</tr>
<tr>
<td>$\alpha$</td>
<td>0.5</td>
</tr>
<tr>
<td>$\beta$</td>
<td>0.5</td>
</tr>
<tr>
<td>Secondary user interference range (m)</td>
<td>100</td>
</tr>
<tr>
<td>Packet size (kb)</td>
<td>1024</td>
</tr>
<tr>
<td>Traffic data type</td>
<td>CBR-UDP</td>
</tr>
<tr>
<td>Initial energy of nodes (J)</td>
<td>1500</td>
</tr>
<tr>
<td>Simulation run time (s)</td>
<td>1000</td>
</tr>
<tr>
<td>Area size (m X m)</td>
<td>500 X 500</td>
</tr>
<tr>
<td>Beacon Interval ($T_{BI}$)</td>
<td>100 ms</td>
</tr>
<tr>
<td>$CW_{min}$</td>
<td>15</td>
</tr>
</tbody>
</table>

Table 3.2: Simulation Parameters
Figure 3.4 to 3.6 show performance of CCM-MAC and MMAC-CR with respect to the throughput, average delay, and energy consumed per packet by varying traffic load. It is observed from figure 3.4 that the throughput achieved in CCM-MAC is higher by at least 24%. This improvement is obvious because complete PCL/SRP is not transmitted in CCM-MAC. ATIM-RES message is also not needed in CCM-MAC. Figure 3.5 shows that the average delay is almost the same for both the algorithms in all the user load values. This implies that the increase in throughput is not deteriorating the delay performance.
Figure 3.6 shows that the energy consumed per packet is also low for CCM-MAC. The difference in energy consumed per packet is approximately 0.03J. Energy consumption is reduced because CCM-MAC selects a channel which minimizes transmit power.

![Energy Consumed Per Pkt (J) vs Traffic load (kbps)](image)

**Figure 3.6: Energy consumed per packet by varying traffic load**

The study of energy and time consumption done in idle, sleep, transmit and receive state in different kind of nodes (transmitter, receiver and idle nodes) is shown in figure 3.7. It is clear from figure 3.7 that the idle nodes save energy by entering sleep state for most of the time. The main contributor to energy consumption is the receive state. This is because nodes also receive packets that are not destined for them. This energy consumption can be reduced by increasing the number of channels.

Figure 3.8 shows throughput achieved by users with respect to the ATIM window size. For analyzing the effect of ATIM window size, the number of users is considered as 50. It is clear from figure 3.8 that for every ATIM window size throughput of CCM-MAC is better than MMAC-CR protocol. It can be noted that if the size of ATIM window is too small then the number of successful ATIM handshakes will be less than the number of channels available for cognitive users. In such situations, throughput of system will be reduced. But if ATIM window size increases more than a certain value then spectrum bandwidth is wasted due to the long ATIM window size. Thus, very large ATIM window size also limits the throughput performance. It can be observed that the size of ATIM window affects the performance of protocol and should be selected carefully. Figures 3.8 also shows that the required value of ATIM window size increases with the increase in number of channels. As seen in figure 3.8, the required size of ATIM window is 5 ms for 10 channels and 10 ms for 20 channels.
Figure 3.7: Distribution of energies and time consumed by receiver, transmitter and idle node
3.6 Chapter Summary

This chapter proposes a MAC layer protocol, CCM-MAC, for multi-channel cognitive networks. This protocol can be used in any cognitive network. Extensive performance evaluation of CCM-MAC is done by simulating multiple scenarios in NS2. As shown in the performance analysis, ATIM window size should be selected based on number of channels available to get better results. The performance evaluation confirms that as compared to MMAC-CR, CCM-MAC ensures high throughput and low value of energy consumed per packet while keeping the average delays performance unchanged.