A QoS provisioning MAC protocol for Cognitive Radio Network

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Abstract—Recently cognitive radio has been envisioned to solve the problem of spectrum scarcity and spectrum under-utilization. A cognitive radio performs communication by selecting a channel on an opportunistic basis. Thus the implementation of a cognitive radio for real-time application faces the challenge of sharing of a constantly varying sporadically available channel among multiple users. To this end we propose an energy efficient medium access control scheme for single-hop cognitive radio network (QCR-MAC) which provides four levels of QoS support with complexity equivalent to that of a single transceiver node. The scheme imparts QoS through the usage of different interframe spaces, which allows different priorities of a contention by packets from different applications. Two different channel access etiquettes are used according to the type of channel and data traffic. One spectrum etiquette favours stream based real-time data transfer while another favours bursty traffic. The protocol utilizes a beacon based structure for information interchange and thus allows contentions to be distributed on different channels whilst mitigating the control channel saturation problem. Simulation results shows the effectiveness of the proposed scheme over an existing similar work.

Index Terms—Cognitive Radio, QoS, Medium access control, Spectrum sharing, Distributed contention

I. INTRODUCTION

The ever growing market of wireless devices has resulted in depletion of available usable spectrum. Technological advancements are pushing the operating frequency bands to move towards higher frequency bands (≥60 GHz) which require line of sight operation due to high attenuation; and thus requires higher power for operation. The usable bands in the sub 2 GHz range are over crowded. A survey done by FCC has shown that more than 70% of the frequency bands are under-utilized over a given place and time [1]. Therefore there exist a paradox between the shortage of the available frequency spectrum and its under-utilization. Cognitive radio (CR) based dynamic spectrum access techniques have been proposed to mitigate such paradox by opportunistically utilizing the channels, whenever they are free from incumbent users [2]. Cognitive radio realizes a hierarchical structure for spectrum usage. The incumbents are designated as primary users (PU) while cognitive radio users as secondary users (SU). A SU performs its own communication only when the channel is sensed free from any incumbents. A SU provides guarantee on the maximum interference it causes to the primary users [3]. Therefore a secondary user should abort its communication whenever an incumbent is sensed on the channel [4]. For the proper functioning of a cognitive radio, the system has to accomplish three important tasks: Spectrum Sensing, Channel Selection, and Spectrum Sharing [7]. Spectrum sensing involves detection of spectral holes in the channel for opportunistic utilization; channel selection involves making a decision on the selection of channels which satisfy constraints of a given communication; and spectrum sharing involves the task of sharing a given communication media among multiple CR users. Various work has been done on spectrum sensing [4]–[6], which requires co-operation between secondary users to avoid false alarms [5]. Literature work done in [8]–[14] reports efficient channel selection techniques. Several approaches have been taken towards the development of efficient spectrum sharing scheme [18]–[27]. The efficiency of a medium access control scheme depends upon the number of channels used in the system, number of secondary users, number of primary users, load on the network, quality of service parameters etc. Literature work done in [15, 16] provides a survey of spectrum sharing techniques. For the proper operation of a media access, nodes exchange control packets over a common signalling channel called as control channel. On the basis of usage of control channel, media access can be classified into two categories: control channel based and control channel-less media access schemes [16]. A control channel based medium access scheme utilizes a dedicated control channel for exchange of control packets [21]–[27]. As the number of nodes in the network increases, the amount of contention increases and thus control channel may become saturated; limiting the number of data exchange between nodes. To avoid control channel as bottleneck, control channel-less based media access schemes are proposed which does not utilize control channel for control packet exchange. Control channel-less media access scheme generally utilizes a predefined hopping sequence of channels over which all nodes in the network hop periodically [17]–[20]. Thus a node which wants to communicate with another node, follows the hopping sequence of the receiver node. The usage of hopping sequence requires complex calculations along with tight synchronization. Therefore nodes in such network synchronize more frequently and in turn cause bandwidth wastage and loss of energy.

An important objective during the operation of a network is to ensure a minimum grade of service to real time applications like voice or video. In a traditional network, all devices are
allocated with equal priority to access the resources. If the total demand of resources by traffic from overall nodes in the network exceeds the available resources, then the throughput of all nodes is equally reduced [29, 30] thus impacting the user experience on different levels to different application. For example, a second delay is tolerable for web browsing while the same delay is not acceptable for voice or video application. To mitigate such adverse effects of resource equalization, traffic from different application is prioritized into different levels and managed by different policies. Thus quality of service is defined as the ability of the system to provide a guarantee on assured grade of service. Quality of service generally consists of service latency, signal-to-noise ratio, response time, bandwidth etc. Traditional Wi-Fi network implements QoS support by providing Wi-Fi Multimedia (WMM) [30] profile (802.11e).

The cognitive radio operation over multi-channel allows multiple CR users to perform simultaneous communication thus improving the throughput of the system. But this improvement comes at the cost of multi-channel hidden terminal problem. The multi-channel hidden terminal problem arises from missed channel usage information. An example would be- nodes A and B operating over a channel i while another node pair C and D operates simultaneously over channel j. Since A and B were operating over channel i, they don’t know about the usage of channel j and may accidentally use the channel j. This problem is called as multi-channel hidden terminal problem. Temporal synchronization and three way handshakes are generally used to mitigate the problem of multi-channel hidden terminal problem [15, 16]. Another problem in cognitive radio network consisting of mobile nodes is of energy management. This is because of the fact that mobile nodes have limited energy and may require a recharge over a period of time. Operation over a long period of time may involve dying of intermediate nodes leading to network partitioning [9]. Therefore techniques should be used to ensure that nodes conserve energy whenever wherever possible. An example of energy conservation in Wi-Fi is power saving mode (PSM) operation [28].

Considering all the factors and limitations of a control channel, we have proposed a MAC scheme (QCR-MAC) for single-hop cognitive radio network which provides four levels of quality of service to an application running on a node with single transceiver. Two different spectrum access etiquettes are used depending upon the type of channel and data traffic. One spectrum etiquette favours uniform stream based data transmission while another favours bursty data traffic. The time period of channels are overlapped in such a way that there is minimal throughput loss. The throughput loss is further prevented by using non-overlapping distribution of quiet periods for in-band and out-of-band spectrum sensing.

The rest of the paper is organized as follows. In Section II we model the system by providing details about the network, QoS access categories, distribution of the quiet periods, channel model and their classification. Section III provide details about QCR-MAC design and its working. It also provide details about the initialization of the network along with multiple types of data transfer. Performance analysis is done in Section IV and the paper concludes in Section V.

II. SYSTEM MODEL

A. Cognitive Radio Network

The system consist of a distributed ad-hoc cognitive radio network (CRN) comprising N secondary users and Z primary users. All N secondary users are assumed to be at single-hop distance to each other. Each secondary user is also assumed to be equipped with a single half-duplex transceiver i.e. nodes can either transmit or receive but not simultaneously. An ideal spectrum sensing scheme is used at physical layer which utilizes quiet period for sensing purposes. A common control channel is used as a physical media for exchanging control packets. The common control channel can be a dedicated channel or one of the primary channels with low incumbent activity [17]. We consider that the system operates in a heterogeneous channel environment consisting of C channels, each having bandwidth B_i, ∀i ∈ C.

B. QoS Access Category

For the purpose of QoS, the system need to identify and prioritize the packets based upon the application which generated it. We utilize the packet marking scheme i.e. each packet is marked individually for its priority [32]. We define four types of priorities (access categories) similar to WMM [30] as shown in Table I. We assume that an application executing on a secondary user is capable of marking the packets by a separate field in the packet header. If applications are unable to do so, then a traffic classifier is used for packet marking at lower layers [31].

### Table I

<table>
<thead>
<tr>
<th>Access Category</th>
<th>Description</th>
<th>Marker</th>
</tr>
</thead>
<tbody>
<tr>
<td>Voice priority</td>
<td>Highest priority, Low latency</td>
<td>0</td>
</tr>
<tr>
<td>Video priority</td>
<td>Second highest priority, Video can buffer if needed</td>
<td>1</td>
</tr>
<tr>
<td>Best Effort priority</td>
<td>If no QoS mentioned, or burst mode traffic like web surfing</td>
<td>2</td>
</tr>
<tr>
<td>Background priority</td>
<td>Lowest priority, print jobs, no strict latency</td>
<td>3</td>
</tr>
</tbody>
</table>

![Fig. 1. 2 state markov chain model for channel availability](image-url)
C. Channel Model

The availability of a channel depends upon the activity of primary users on that channel. To simplify the analysis of the system, we assume that a channel is occupied if there is a primary user present on that channel and vice-versa. Therefore all the \( C \) channels in the system can be modelled as ON-OFF source depending upon the presence or absence of a PU respectively. We model the channel as two-state markov chain as shown in Figure 1. The parameters \( \alpha \) and \( \beta \) represents the probability of transition of primary user on the given channel from ON to OFF state and OFF to ON state respectively. The probability that a channel will be available at a given time slot is given by

\[
P_i = \frac{\alpha_i}{\alpha_i + \beta_i} \quad \forall i \in C'
\]

where \( C' = \{1..C\} \).

D. Channel Classification

The channels used in the system are classified into two types: Control channel and Data channel. A data channel is a channel onto which nodes perform data exchange. Data channels are further divided into two types of channels: Reservation based channels (RBC) and Contention based channels (CBC) (shown in figure 2). A reservation based channel employs reservation of the time-slots ahead of time for data transfer while a contention based channel perform contention whenever a data transfer is required. A reservation based channel allows implementation of higher priority stream based data transfer service (like voice or video). The system comprises of a non-hopping network where nodes resides on a channel as long as that channel is free or a node wants to switch to another channel for some reason. The channel onto which a node resides is called as home channel while all other channels w.r.t. it are termed as foreign channels. The node itself is called as home node for home channel, while all other node residing on foreign channel are called as foreign node. A representative from each channel is selected to broadcast the information about the nodes, channel condition etc. onto a common signalling channel (control channel). The representative is termed as representative node (RN) and is selected periodically depending upon the current load of traffic on nodes. A relatively less busy node is selected among the group of all nodes in a home channel as RN. A control channel is a channel which is used for periodic exchange of beacons among RN. A control channel may also be used as a media for data exchange similar to CBC.

E. Quiet Period Distribution

For proper sensing, all CR users stop their communication during quiet period so that nodes can detect the transmissions from incumbents. Since nodes in network perform sensing periodically, the quiet period are designed to be periodic in nature. Two types of sensing is performed: In-band and out-of-band. In-band sensing involves detection of incumbents by home nodes on home channel while out-of-band sensing involves detection of incumbents by nodes on foreign channel. The quiet periods are distributed on all channels such that they do not overlap. This allows in-band and out-of-band sensing to be performed effectively without any throughput loss. To perform sensing, a node should know the distribution of the quiet period on home/foreign channels.

III. QCR-MAC Design

The system is divided into fixed length time frames called as superframes as shown in Figure 2. The superframes of all data channels are overlapped and synchronized over time with each other. The end of the control channel beacon of control channel is overlapped and synchronized with the start of home channel beacon of a data channel. The superframe of control channel is composed of three separate intervals: Control channel beacon (CCB), data transfer and quiet period. A CCB has time-slotted architecture, where the size of CCB equal to the number of channels used in the system. Therefore number of time-slots equals number of channel used in the system+2 \((C+2)\). The additional 2 slots allows a new node to join the network. During CCB, RN from all data channels transmit their beacon on their respective slot. The beacon contains the information about the channel SNR, home nodes on that channel, quiet period distribution etc. At the end of CCB, all RN know about the home channels of all other nodes in the network including the distribution of quiet periods and channel conditions. During quiet period of the control channel, all home nodes on control channel stop their communication and perform in-band sensing. If a control channel is also used as data channel, then it consist of one more separate field: home channel information beacon (discussed later).

A superframe of data channel is composed of four separate intervals: Home channel beacon (HCB), Home channel information beacon (HCI), data transfer and quiet period. A home channel beacon has a time-slotted architecture and the size of HCB depends upon the number of nodes on home channel. The number of time-slot equals the number of nodes on home channel + 1. The extra slot is used for the purpose of migration of a foreign node onto the home channel. During HCB, all home nodes exchange beacons including RN of that channel. In this period the RN distributes the information gained from CCB, and therefore all nodes on a home channel know about the information about the home channels of all other nodes in the network including the distribution of quiet period and channel conditions. Thus after HCB, all nodes in the network have information about all other nodes in the network including distribution of quiet periods and channel characteristics. A HCI is used to elect an RN from the set of all home nodes. The usage of RN allows rest of the nodes to perform parallel communication on data channel while beacon exchange is taking place on the control channel. All home nodes use a metric to indicate their busyness in the network. The node which has the least amount of load is elected as a RN. The metric used to indicate the load varies with the application of the CRN. For our purpose we assume the load metric to be weighted average of packets...
sent/received in last 5 frames. The weighted average gives higher priority to transmission that happened recently. The load can be calculated as:

\[
Load = \frac{\sum_{i=0}^{5}(5-i) \cdot N_i}{\sum_{i=0}^{5}(5-i)}
\]

Here \(N_i\) represents the number of packets sent/received in last \(i\)th frame.

Therefore at the end of HCI, whichever home node has the least load, will act as RN for that channel. In case of tie, the last node with the least load in the HCI is elected as RN. A reservation based channel (RBC) divides the data transfer period further into ATIM (ad-hoc transfer indication message) and reservation data period. The reserved data period of RBC comprises of small segments of time-slots during which the data transfer between two communicating nodes take place; similar to the method proposed in [21]. Communicating node exchanges three way handshake ATIM messages for reserving time-slots in reservation data period. The three way handshake mitigates the multi-channel hidden terminal problem. The reservation of a channel before actual data transmission allows higher priority service to maintain a minimum grade of QoS. Stream based data services (voice and video) requires contiguous data slots, for which RBC is apt. In contrast, the CBC utilizes a mechanism similar to the optional RTS/CTS mechanism of 802.11 with four way handshake to avoid multi-channel hidden terminal problem.

A. Network Initialization

The cognitive radio network starts with the selection of a common control channel which can be done similar to the selection of a rendezvous channel in C-MAC [17]. Once the control channel is established, all other CR nodes join through CCB. Initially, nodes on control channel perform out-of-band sensing to gather information about data channels. The node joins a data channel based on its preferences like application priorities, bandwidth requirement, channel availability etc. If no node exists on a data channel, then a new node migrates from control channel to the data channel and starts its own beacon (HCB) so that other nodes can migrate to this channel. If a node already exist on a channel, the migrating node joins the channel through the help of extra slot in HCB. The formation of reservation based channel and contention based channel are done on the basis of channel availability. The channel which have higher availability are assigned as reservation based channels while channels which have low availability are assigned as contention based channels. A channel type indicator bit is used in HCB to indicate the type of data channel (RBC or CBC). For our purpose we assume that all nodes in the network are uniformly randomly initialized, therefore on average there are \(N/C\) CR users per channel during initialization.

B. QCR-MAC Working

A node which has real time packet (preferably stream based data like voice or video) to transfer would prefer to be on reservation based channel (RBC). All other types of packet transfer are done on contention based channels. The system implements QoS provisioning through the help of different interframe spaces. An interframe space is a random duration defined in [0,interval], which a system has to wait before performing any transmission. A counter is initialized with the value of interframe space and is decremented whenever the channel is sensed to be free. When the counter reaches zero, the node performs its transmission. Four different interframe spaces are defined and is shown in Table II. A node waits for short interframe space (SIFS), medium interframe space (MIFS), intermediate interframe space (IIFS) and large interframe space (LIFS) before sending request to send (RTS) packets for voice, video, best effort and background data respectively. The node also wait for SIFS duration before sending clear to send (CTS), DATA or ACK packet.

\[
\text{Load} = \frac{\sum_{i=0}^{5}(5-i) \cdot N_i}{\sum_{i=0}^{5}(5-i)}
\]

Here \(N_i\) represents the number of packets sent/received in last \(i\)th frame.

Since communication over different channels will require different etiquette (contention or reservation), the etiquette of the channel is followed onto which the communication takes place. Depending upon the home channels of transmitter and receiver, the communication may take place on either of the home channels of participating node. If the specified channel characteristics are not available then the communication may take over a foreign channel having the desired characteristics for communication. A node has all information about all channels in the network which it gained directly through HCB and in-directly through CCB.

1) Data Transfer on Reservation based channels: If both transmitter and receiver are on the same channel, then the nodes contend during the ATIM period using three way handshake RTS/CTS/ACK to reserve time-slots in the reservation data period. The sender node waits for the appropriate inter-frame space and then sends a request to send (RTS) packet to destined node which contains channel occupancy list (COL). A COL is an array consisting of either 0 or 1 which indicates the availability of channel for corresponding time-slot as shown in Figure 3. An entry of 0 indicates that the time-slot for that index is free while an entry of 1 indicates that the time-slot has been reserved by some other communicating nodes. Therefore each entry in COL corresponds to the time-slots in data period of reservation based channels. The receiver matches the received COL with its own COL, if agrees replies with agreed time slot (ATS) in clear to send (CTS) packet. An example of ATS is shown in Figure 4, where time-slots 11−14 is reserved by the receiver. The sender again confirms the communication time-slots in acknowledgement (ACK) packet. All neighbors which are on the same channel over hears this agreed time-
slot for communication and update their own COL by marking
those time-slots with 1. If all slots in COL are filled up, a node
may ask other node to move to a CBC foreign channel and then
perform the communication on the foreign channel. Once the
reserved data period starts the communicating node start using
the reserved time periods of the channel. All nodes which are
not involved in the communication go into doze mode during
the reserved data period.

The usage of NAV allows other nodes on the channel to
go into doze mode for power saving operation similar to the
power saving mode (PSM) in Wi-Fi [28].

3) Data Transfer on a Foreign channel: If the destination
node lies on a channel other than that of the home channel of
sender, the sender moves to the home channel of the destina-
tion node after HCB and perform communication according to
the channel etiquette of the receiver. Both sender and receiver
stays on the home channel of the receiving node and perform
the communication. Once the communication is finished or
HCI of the home channel of the sender starts, the sender moves
back to its own home channel.

If the home channels of either participating node is not ca-
pable to support the communication, then the communication
takes place over a channel which has the desired characteristics
to support the communication. A sender first moves to the
home channel of the destination node and sends a MOV
packet during the ATIM period of RBC or contention period

2) Data Transfer on Contention based channels: If both
transmitter and receiver are on the same channel, then
communication takes place using RTS/CTS/DATA/ACK
mechanism. The sender node waits for appropriate interframe
space and sends the RTS packet containing network
allocation vector (NAV) to the destination. NAV provides

![Diagram](image-url)

**Fig. 2. Superframe structures for channels in QCR-MAC**

![Diagram](image-url)

**Fig. 3. Channel occupancy list (COL)**

![Diagram](image-url)

**Fig. 4. Agreed time slots COL**
of CBC. The MOV packet contains the destination ID along with the channel to which destination node should move on. If the receiver agrees, it replies with an acknowledgement. Immediately after acknowledgement, both sender and receiver move to the specified channel. Both sender and receiver follow the etiquette of the specified channel i.e. if the communicating channel is RBC then they exchange ATIM packets during ATIM period for reserving the time-slots. Similarly, etiquettes of CBC are applied for communication over a CBC. The MOV packet follows the etiquette of RTS packet for determining the size of its own interframe space.

IV. PERFORMANCE EVALUATION

To evaluate the performance of our proposed MAC scheme, we have written a discrete event simulator in Matlab. Our proposed scheme is compared against C-MAC scheme [17]. The performance is evaluated in terms of throughput obtained in the system and the connection failed for real-time connections. Real-time connection failed is evaluated using real-time connection fail ratio which is defined as the ratio of total number of real-time connections failed to the total number of real-time connections originated in the system. The simulation environment utilizes RTS, CTS and ACK of size 30 bytes each. The size of DATA used is 1000 bytes. To simplify the simulation analysis we use 3 channels in the system, each having bandwidth of 3 Mbps. One channel is used as control channel, one as RBC and one as CBC. The control channel act as CBC during communication period. The size of superframe and quiet period used is 100 ms and 1 ms respectively. The size of CCB, HCB and HCI used is 1.5 ms, 1.2 ms and 0.8 ms respectively. The size of ATIM period used in CBC is 10 ms while the number of time-slots used in reserved data period is 32. A total of 9 nodes are used, with uniform distribution over channels. The total simulation time is 100 seconds while each data point on the graph is an average run of 10 tests. All nodes are assumed to be in communication range of each other and for a fair comparison with C-MAC protocol, we assume that all communication between nodes takes place on the same channel. Therefore transmitter and receiver are selected randomly among nodes of the same channel. The size of interframe spaces is taken from Table II. The traffic consist of voice, video, best effort and background data in equal ratio. The data arrival is modelled as poisson distribution with varying arrival rate. The availability of a channel is modelled as two-state markov chain as discussed in Section II-C.

Figure 5 shows the aggregate throughput of the system along with the packet arrival rate. The packet arrival rate is varied from 7 packets/second/node to 30 packets/second/node in the system. The channel availability parameter ($P_i$) for all channels is set to 0.9. From graph it is clear that QCR-MAC has higher throughput than C-MAC and as the packet arrival rate increases, our proposed mac scheme outperforms C-MAC scheme. The higher aggregate throughput of QCR-MAC is attributed to the small size of beacons on RBC and CBC, which allows more communication opportunities for nodes in the network in a single superframe. As the packet arrival rate increases the difference also increases, implying that our proposed technique performs better under heavy load condition.

Figure 6 shows the real time connection fail ratio with packet arrival rate. The packet arrival rate is varied from 7 packets/second/node to 30 packets/second/node in the system. The channel availability parameter ($P_i$) for all channels is set to 0.9. The graph shows that, as the packet arrival rate increases the real time connection fail ratio also increases due to more traffic collisions in the network. As the packet arrival rate increases the difference between QCR-MAC and C-MAC also increases indicating that our proposed scheme performs better under high packet arrival rate. The increase in difference is attributed to the small interframe size used for real-time packets in QCR-MAC. Since the size of interframe is small, less real-time packets are prone to lose the contention.
Figure 7 shows the aggregate throughput of the system with channel availability probability for QCR-MAC and C-MAC. The probability that a channel is available is uniformly increased from 0.1 to 1. The arrival rate used is 10 packets/second/node. As the channel available probability is increased, the throughput of both scheme increases. The increase in throughput is attributed to the availability of more transmission opportunities by having available channels. The graph shows that the QCR-MAC has higher aggregate throughput than C-MAC, and the difference increases with increase in channel available probability. The QCR-MAC scheme has higher throughput due to small beacon size and large data transfer window which aggregates to show an increase in difference in comparison to C-MAC scheme.

Figure 8 shows a comparison of QCR-MAC and C-MAC in terms of real time connection fail ratio with varying channel availability. The arrival rate used is 10 packets/second/node while the channel available probability is varied from 0.1 to 1. As the channel available probability increases, both scheme shows a decrease in real-time connection fail ratio; which is attributed to the increase in more transmission opportunities by having available channels. It can also be clearly articulated that the proposed QCR-MAC provides higher priority services to real time data in comparison to C-MAC scheme by providing less connection fail ratio. The real time data gets higher privilege and thus suffers from less blocking/failure.

V. CONCLUSION

In this paper we have proposed an energy efficient QoS provisioning MAC scheme for distributed ad-hoc cognitive radio network which supports four types of packet priority. The proposed MAC scheme utilizes a beacon based structure for information interchange which allows nodes to gather information about the network. Nodes perform contention on separate channels while utilizing temporal synchronization with 3/4 way handshake mechanism to mitigate multi-channel hidden terminal problem. The scheme utilizes power saving operation to go into doze mode to conserve energy. Two different spectrum access etiquettes are used according to the type of channel and data type. One spectrum etiquette favours stream based real-time data transfer while another favours bursty traffic. Different interframe spaces allows implementation of prioritized service in the network. Non-overlapping quiet periods are used on all channel for the purpose of sensing; which mitigates the throughput loss of out-of-band sensing time. Performance analysis is done against a similar scheme with the help of simulation. The results shows that the proposed scheme outperforms in terms of real-time connection fail ratio as well as the aggregate throughput of the system.

REFERENCES


