

# A Distributed Medium Access Control Protocol for Cognitive Radio Ad Hoc Networks

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## Abstract

We propose a distributed medium access control protocol for cognitive radio networks to opportunistically utilize multiple channels. Under the proposed protocol, cognitive radio nodes forecast and rank channel availability observing primary users' activities on the channels for a period of time by time series analyzing using smoothing models for seasonal data by Winters' method. The proposed approach protects primary users, mitigates channel access delay, and increases network performance. We analyze the optimal time to sense channels to avoid conflict with the primary users. We simulate and compare the proposed protocol with the existing protocol. The results show that the proposed approach utilizes channels more efficiently.

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**Keywords:** Opportunistic spectrum access, cognitive radio networks, medium access control, MAC protocol

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## 1. Introduction

The electromagnetic spectrum is a key resource to enlarge the radio and broadcasting industry that helps develop other industries. Demand for spectrum is increasing daily due to the innovations of new technologies and businesses. Cognitive radio networks (CRNs) came up with an idea to use unutilized spectrum in the licensed bands. Cognitive radio (CR) may play a vital role in mitigating spectrum deficit issues.

Because CRNs use channels opportunistically, the medium access control (MAC) protocol is a key factor in making the CR approach successful. In addition to other responsibilities, the MAC protocol for CRNs has one more responsibility—it has to protect incumbent license users, also called primary users (PUs).

This paper proposes a MAC protocol for cognitive radio networks that ranks channels based on the behavioral history of incumbent licensed users. One of the main problems in CRNs is how to rendezvous and then start communications without suffering from the multi-channel hidden node problem. The proposed protocol is a common control channel-based MAC protocol that does not suffer from the multi-channel hidden node problem but requires a dedicated common control channel (CCC).

This paper proposes a novel channel selection algorithm based on prediction of PUs' behavior on the channels. In most of existing MAC protocols for CRNs in the literature, the CR nodes do not send data packets while channel negotiation goes on. The proposed protocol does not wait until the end of the channel negotiation and it allows sending data packets just after successful channel negotiation. With this approach, the average additional maximum achievement in each beacon interval is the product of the channel access probability, half of the time allocated for the channel access and total number of data channels available.

This protocol carries out many strategies to protect the rights of the PUs. SUs share the sensing information and maintain knowledge of the channels' status in the entire networks (called cooperative sensing), so that collision with PUs can be avoided. SUs sense channels twice in a single beacon interval to protect the PUs with tolerable or no damage, only with the small cost of delay. This paper also analyzes the optimum time to start fast sensing.

The remainder of this paper is organized as follows. Section 2 reviews some of the related works. Section 3 describes the proposed distributed medium access control protocol for cognitive radio ad hoc networks. Section 4 analyzes optimum time for the fast sensing. Section 5 discusses simulation results and performance evaluations. Section 6 gives conclusions.

## 2. Related Work

A number of protocols have been proposed in the literature to opportunistically access spectrum using cognitive radio [1-3]. The IEEE 802.22 working group [4] already standardized a MAC layer based on CR to reuse spectrum allocated to TV broadcast services. IEEE 802.22 specifies that the network should operate point-to-multipoint. The architecture of the 802.22 MAC layer is centralized and relies on the base station. Many locations where licensed spectrum bands are underutilized lack infrastructure. Therefore, a decentralized approach can be the solution to utilize those spectrum holes, because ad-hoc networks do not require a central infrastructure.

The distributed coordinated spectrum sharing (DCSS) MAC protocol for cognitive radio [5] is a dynamic channel allocation (DCA)-based protocol. Similar to DCA [6], in DCSS, request to send (RTS) and clear to send (CTS) are exchanged before communications. RTS/CTS messages include the available data channel list. The time slot mechanism in DCSS is used to detect incumbents. However, DCA negotiates for a data channel per packet. It fully relies on a CCC, which may incur control channel starvation. In DCA-based protocols, the CCC can be a bottleneck when too much control information is sent over this channel. All nodes need to contend for access to the control channel, and the data channels remain underutilized [7]. The maximum number of channels that can be fully utilized using DCA-based protocols is around  $L_d/3L_c$ , where  $L_d$  is the data packet size and  $L_c$  is the control packet size.

A group-based DCA protocol was proposed by Zhang et al. [8]. This protocol divides the channels into several groups. Each group has one CCC and several data channels. Unlike traditional DCA, they exchange control information over several channels simultaneously, so it mitigates the early CCC starvation problem.

A multichannel MAC protocol for cognitive radio (MMAC-CR) was proposed by Timmers et al. [9]. This is a single transceiver-based protocol. As in the 802.11 power-saving mode (PSM) standard [10], under the MMAC-CR protocol, time is divided into the ad hoc traffic indication message (ATIM) window and the data window (DW). In ATIM windows, control packets for channel negotiation and channel reservation are transferred, and in data windows, data packets are transferred. Similar to MMAC-CR, an energy-efficient cognitive radio MAC protocol for quality of service (QoS) provisioning [11] was proposed. This is also a single transceiver-based protocol. All these protocols waste channel bandwidth during channel negotiation time (i.e. the ATIM window). Nodes neither send nor receive data packets during this time. Hence, it wastes all data channels' bandwidth.

These protocols have to switch channels multiple times. There is no mechanism to detect the primary user's arrival in the channel after the channel negotiation period. These protocols can also suffer from the multi-channel hidden node problem.

We extended MMAC-CR with PU-behavior estimation and ranking of channels. Furthermore, the proposed protocol also utilizes the ATIM window for data communication opportunities that otherwise go to waste under MMAC-CR.

### 3. Proposed Protocol

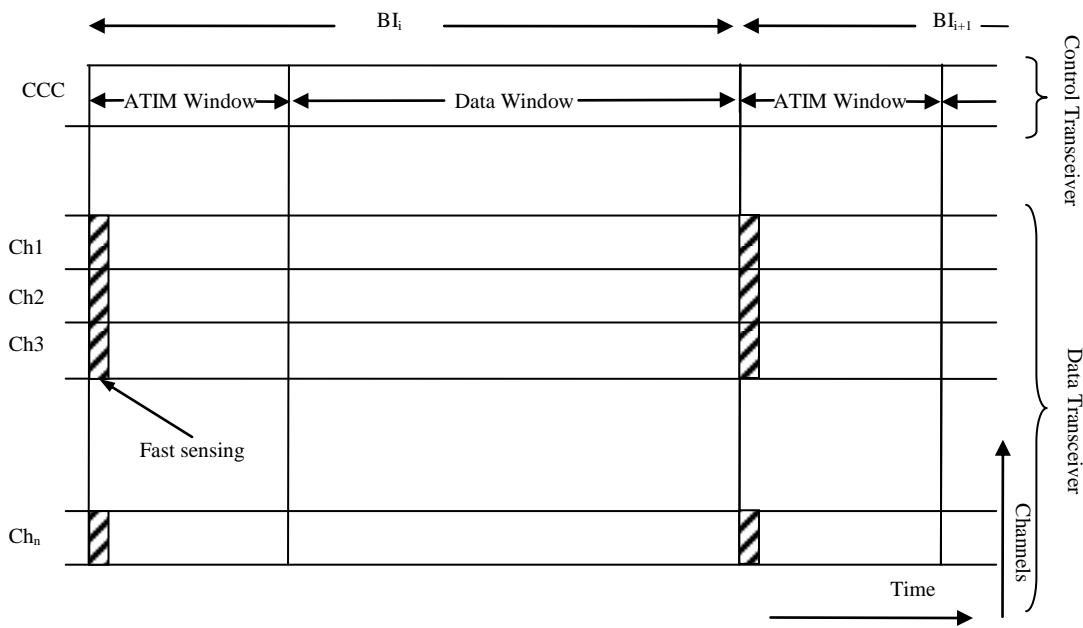
We assume that each CR device is equipped with two transceivers. One is for the control channel and another for data channels. There are  $\{Ch|Chi, i=1,2,\dots, N\}$  non-overlapping licensed channels. These channels are conditionally and opportunistically accessible by secondary users (SU) and are called data channels.

We further assume that a common control channel is available with all the required qualities for reliable communications at all times. The CCC is free from interference by the incumbents and is mainly used for control packet exchange. This channel is common to all SU nodes in the network.

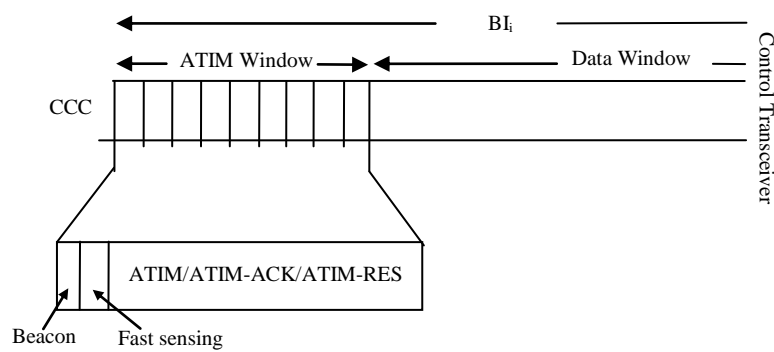
The SUs in the network synchronize and share channel sensing information with other SUs. Synchronization is similar to the 802.11 time synchronization function (TSF) [10]. Time is divided into beacon intervals, and each beacon interval (BI) is further divided into a channel negotiation window (or ATIM window) and a data communications window. Each SU maintains a table to record the status of the channels by sensing each channel and overhearing channel negotiation messages from the neighbors. There are two kinds of sensing: fast sensing

and fine sensing. Fast sensing is done at the beginning of each ATIM window and in the middle of the BI, as shown in Fig. 1 (a).

Fast sensing takes a very short time and gives one of three results: (a) the channel is busy, (b) the channel is idle and (c) the status is uncertain. If there are no data to send or receive, the data transceiver starts fine sensing. This takes a long time and gives one of two results: (a) the channel is busy, (b) the channel is idle.



(a)



(b)

**Fig. 1.** Structure of the proposed protocol. (a) BIs, ATIM windows, the data window and sensing periods. (b) ATIM window model.

In the channel negotiation window, nodes negotiate for the channels by sending over the CCC a list of the idle data channels available for communications, as shown in Fig. 1(b).

Channel selection is carried out based on the history of incumbents' behavior on the channel over a period of time. Using the data recorded in the channel status table, SUs estimate the channels' status based on the multiplicative seasonal model for the next time slot. In the real world, availability of the channel is seasonal. For example, if we consider mobile phone bands as primary licensed spectrum, most of the channels are busy during business hours, particularly between 8:00 am to 10:00 am and 4:00 pm to 6:00 pm. Therefore, we used Winters' method [12, 13] to estimate the status of the channels. SUs start estimation only after a period of  $m$  seasons. This is because Winters' method requires initial values of the parameters  $\hat{a}_1(0)$ ,  $\hat{b}_2(0)$  and  $\hat{s}_1(0)$  for  $t=1, 2, 3, \dots, L$ . where,  $L$  is the length of the total season, that is,  $L = \sum_1^L s_i$ ,  $\hat{a}_1(t)$  is a permanent component,  $\hat{b}_2(t)$  is a trend component, and  $\hat{s}_1(t)$  is a multiplicative seasonal factor.

Let  $\bar{x}_j, j=1,2,3,\dots,m$  be the average of the observations during the  $j^{th}$  session. The forecast for channel  $i$  at time  $t_i$  for a desired season  $\hat{c}_i(t_i)$  can be obtained with

$$\hat{c}_i(t_i) = \left[ \hat{a}_1(t_i) + \hat{b}_2(t_i) \right] \hat{s}_1(t_i) \quad (1)$$

Here,  $t_i = 0$  at the start of the first period. Permanent component  $\hat{a}_1(t_i)$ , and trend component  $\hat{b}_2(t_i)$  can be estimated as

$$\hat{b}_2(t_i) = \frac{\bar{x}_m - \bar{x}_1}{(m-1)L} \quad (2)$$

$$\hat{a}_1(t_i) = \bar{x}_1 - \frac{L}{2} \hat{b}_2(0) \quad (3)$$

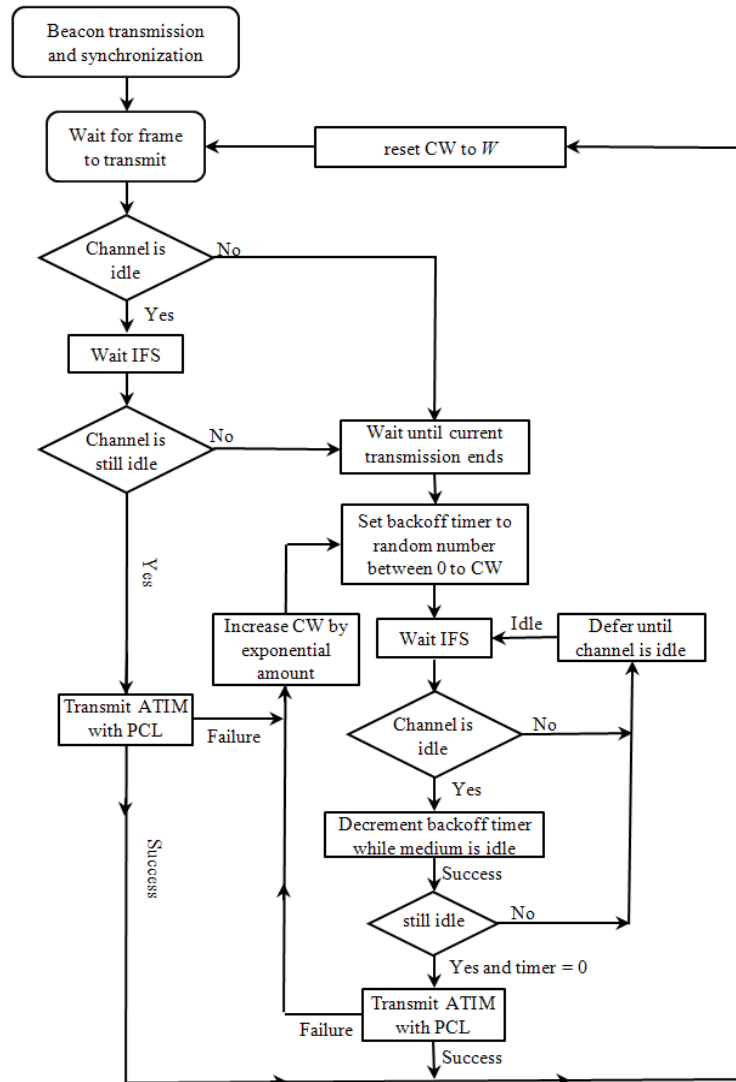
$\hat{s}_1(\dots)$  are computed for each time period  $t=1, 2, \dots, mL$ , as the ratio of the actual observation to the average seasonally adjusted value for that season, further adjusted by the trend; that is,

$$\hat{s}_1(t) = \frac{x_t}{\bar{x}_i - \left[ (L+1)/2 - j \right] \hat{b}_2(0)}, \quad t = 1, 2, 3, \dots, mL \quad (4)$$

Eq. (4) produces  $m$  estimates of the seasonal factor for each period.

Based on these forecasts, SUs rank channels as - larger the forecasted idle period; the higher the ranking of the channel in the season. These channel rankings are used to prepare a preferred channel list (PCL).

When an SU receives a channel negotiation message along with a PCL, the SU sends back acknowledgement (ATIM-ACK) with a common data channel.



**Fig. 2.** Flowchart of the ATIM packets with the PCL sending procedure.

This common data channel is the highest ranked channel between sender and receiver nodes. Finally, the sender SU node sends a channel reservation message (ATIM-RES) to inform the receiver, including neighbors. A flowchart of the sending procedure of the ATIM packets with the PCL is shown in **Fig. 2**.

After successful channel negotiation, SUs exchange RTS/CTS before sending actual data packets to avoid the hidden terminal and exposed terminal problem. The SUs send data packets, as in the 802.11 distributed coordination function (DCF) [10].

In the middle of the BI, SUs pause their transmission and fast-sense the channel; if they sense the incumbent user’s activity on the channel currently used by SUs, the SUs stop sending packets immediately and send an emergency control message in the CCC and handoff spectrum. The optimal time for the fast sensing is analyzed once at the beginning of the session.

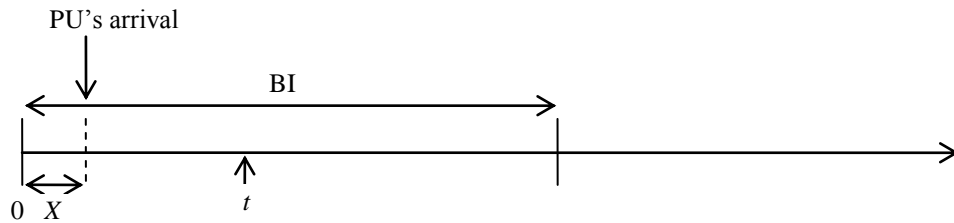
The control transceiver wakes up just before the fast sensing ends in the middle of data

window to send the emergency control message and renegotiate for data channels. It enters the sleep state after the channel negotiation window. The data transceiver is turned off if the SU has no data to send or receive and no fine sensing to do.

#### 4. Analysis of Optimum Time for Fast Sensing

In this work, SUs evaluate optimum time for the sensing. We assume that PU arrival time is exponentially distributed with an average value of  $\frac{1}{\lambda}$  second. If  $X$  is a random variable denoting the PU's arrival time from the start of the current BI, the density function of  $X$  can be expressed as

$$f_x(X) = \lambda e^{-\lambda x}, \quad x \geq 0.$$



**Fig. 3.** Arrival of PUs and optimal time for fast sensing.

In this work, we assume that once a PU arrives in a given BI, the PU stays in the channel until the end of the BI. The fast sensing duration is assumed to be negligibly small compared to the BI duration in the below analysis.

Let us assume that SUs sense the channel at time  $t$  during the BI to detect the presence of a PU. If a PU and SU access a specific channel at the same time, then there will be a collision between them (refer **Fig. 3**).

Let  $Y$  denote a collision period between them. Then,  $Y$  can be expressed as

$$Y = \begin{cases} (t - X), & \text{if } X \leq t. \\ (I - X), & \text{if } t < X \leq I. \text{ (I is the length of BI)} \\ 0, & \text{if } X \geq I. \end{cases} \quad (5)$$

Then, we have

$$\begin{aligned} E[Y] &= \int_0^{\infty} E[Y | X = x] f_x(x) dx \\ &= \int_0^{\infty} E[Y | X = x] \lambda e^{-\lambda x} dx \\ &= \int_0^t E[Y | X = x] \lambda e^{-\lambda x} dx + \int_t^I E[Y | X = x] \lambda e^{-\lambda x} dx + \int_I^{\infty} E[Y | X = x] \lambda e^{-\lambda x} dx \end{aligned}$$

$$\begin{aligned}
&= \int_0^t E[t - X | X = x] \lambda e^{-\lambda x} dx + \int_t^I E[I - X | X = x] \lambda e^{-\lambda x} dx \\
&= \int_0^t (t - x) \lambda e^{-\lambda x} dx + \int_t^I (I - x) \lambda e^{-\lambda x} dx \\
&= t + (I - t) e^{-\lambda t} + \frac{1}{\lambda} (e^{-\lambda I} - 1) \tag{6}
\end{aligned}$$

We find that  $E[Y]$  is dependent on the value of  $t$ . Thus, we put  $g(t) = E[Y]$ . We want to find the value of  $t$ , which minimizes  $E[Y]$ . It is possible to obtain

$$\begin{aligned}
g(0) &= I + \frac{1}{\lambda} (e^{-\lambda I} - 1), \quad g(I) = I + \frac{1}{\lambda} (e^{-\lambda I} - 1), \\
g'(t) &= 1 + (-1)e^{-\lambda t} + (I - t)(-\lambda)e^{-\lambda t} \\
&= 1 - (1 + \lambda I - \lambda t)e^{-\lambda t} \tag{7}
\end{aligned}$$

We can find  $g'(0) < 0$  and  $g'(I) > 0$  from Eq. (7). Thus,  $g(t)$  has the minimum value at  $t$ , where  $g'(t) = 0$ , if  $0 \leq t \leq I$ .

We want to find the value of  $t$  which satisfies  $g'(t) = 0$ . Such  $t$  satisfied the below equation

$$e^{\lambda t} = 1 + \lambda I - \lambda t \tag{8}$$

If  $t^*$  denotes the unique solution of Eq. (8), then the value of  $t^*$  can be obtained numerically, and  $t^*$  is the value of  $t$  which minimizes  $E[Y]$ . Fig. 4 shows the solution of Eq. (8) can be uniquely determined from the intersection of two graphs,  $y = 1 + \lambda I - \lambda t$  and  $y = e^{\lambda t}$ .

Especially, if  $\lambda t \ll 1$ , which might be valid when the primary user arrival rate is very low, the following approximation is valid.

$$e^{\lambda t} \cong 1 + \lambda t \tag{9}$$

Combining (8) and (9) yields

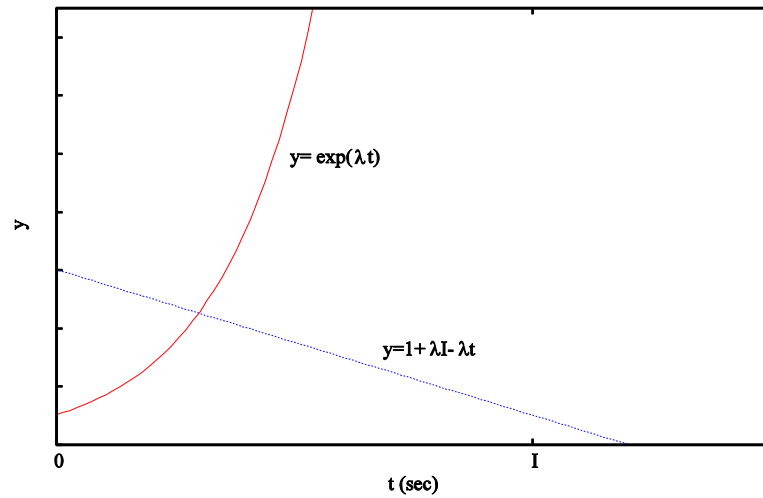
$$t \cong \frac{I}{2} \tag{10}$$

More detailed value of  $t$  can be obtained by solving Eq. (8) numerically.

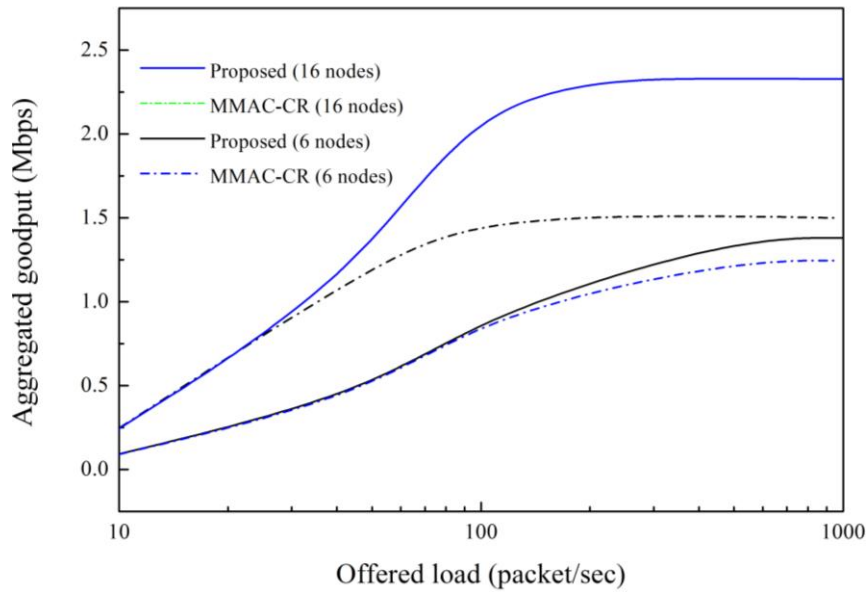
## 5. Performance Evaluation

We simulated the proposed protocol using ns-2 [14] with a common control channel and six data channels of 2 Mbps. The transmission range of the nodes was approximately 250 m. The constant bit rate (CBR) traffic with the offered load varied from 10 packets per second to 1000 packets per second. The channel switching delay was 224 s. We considered the ON/OFF channel usage model. The BI was set to 100 ms and the ATIM window size was 1/4 of the data window size. We compared the aggregated goodput and average packet delay of the proposed protocol against MMAC-CR with various node densities and offered loads.





**Fig. 4.** Graphical explanation on how to evaluate the solution of Eq. (8).



**Fig. 5.** Aggregated goodput at different offered loads with different node densities.

**Fig. 5** shows the comparison of aggregated goodput of the proposed protocol with the offered loads varying from 10 packets per second to 1000 packets per second. We compared 6-node and 16-node scenarios. The system reached a saturation point at similar offered load rates when there are only six nodes. However, MMAC-CR becomes saturated earlier, and goodput is much lower than our proposed protocol when there are 16 nodes. Although MMAC-CR and the proposed protocol perform similar in lower offered load scenario, the proposed protocol outperforms MMAC-CR in both node densities (i.e. 6-node and 16-node) in higher offered load scenario. This is because MMAC-CR is a single transceiver-based MAC protocol that wastes channel negotiation (ATIM window) time engaging only on exchanging control packets, as described in Section 2. On the other hand, the proposed protocol sends data just after channel negotiation and utilizes data channels even during the ATIM window.

The proposed protocol selects a channel according to the behavior of PUs on the channel using time series analysis by Winters’ method. It selects a channel that is less prone to claim by the PUs. Therefore, it incurs less interference from the PUs, which helps to mitigate collision of SUs with the PUs and increasing goodput. Further, the proposed protocol senses the channel in the middle of the beacon interval and reconnects broken links if it is possible. However, SUs wait for the next beacon interval after any link is broken in MMAC-CR.

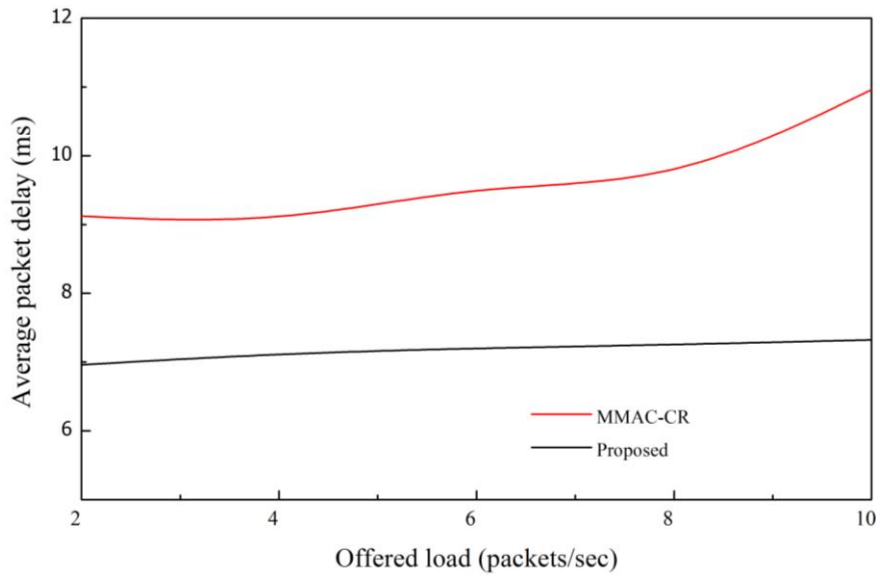


Fig. 6. Average packet delay in the six-node scenario.

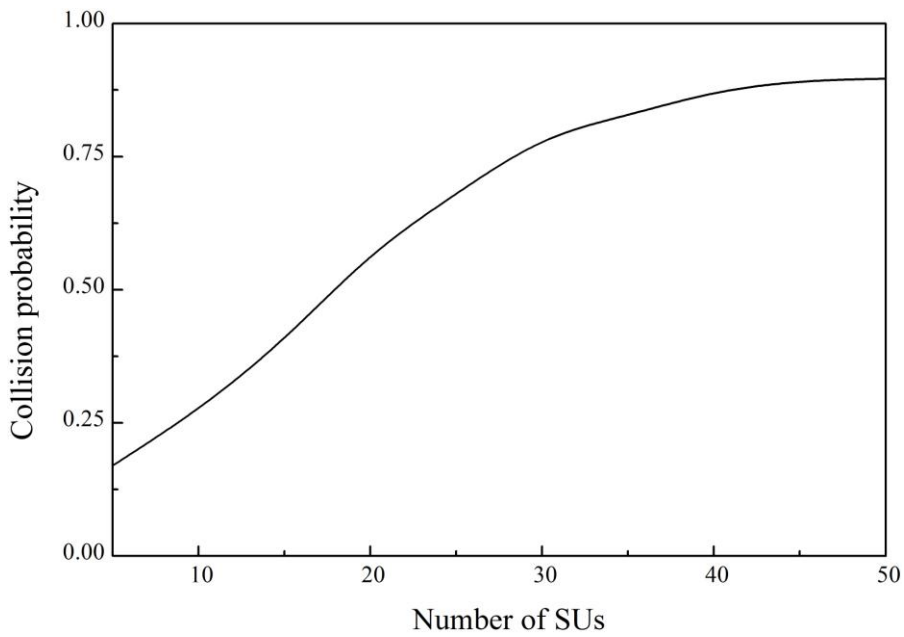


Fig. 7. Collision probability in various SU nodes density.

**Fig. 6** shows the average packet delay in the three-channel and six-node scenario. The proposed protocol has a shorter delay than MMAC-CR due to its strategy of not waiting to finish the ATIM window before transmitting data. The transceiver under MMAC-CR has to stay in the CCC for the entire ATIM period, even if there is no packet to send or receive. It also has to stay in the CCC for the entire ATIM period after negotiation for the channel.

The proposed protocol starts data transmission just after successful channel negotiation. Also, channel ranking and selection strategies play a vital role in decreasing average packet delay. The strategies of channel sensing in the middle of the beacon interval and repairing the broken link due to the presence of PU also help to reduce average packet delay. In case of MMAC-CR, SUs have to wait until the end of the beacon interval and ATIM window time to start sending data packet. Whereas SUs try to reconnect in the same beacon interval without waiting for the next channel negotiation in ATIM window in the proposed protocol.

**Fig. 7** shows the collision probability of PUs with SUs at ATIM windows when the number of PUs is fixed to 15 nodes and number of SUs is varied from 5 nodes to 50 nodes. These results are from simulation based on the above parameters.

## 6. Conclusions

In this paper, we present a distributed multi-channel MAC protocol for cognitive radio ad hoc networks. This paper addresses efficient spectrum utilization and well-known channel allocation problems, and protects licensed users with minimum tolerable damage (or none at all). We compare the performance of the multi-channel MAC protocol with the existing protocol under various offered loads and node densities. MMAC-CR cannot utilize data channels during the ATIM window. It is difficult to observe emergency control messages and renegotiate for a data channel after the incumbent user claims the channel under MMAC-CR. In the proposed protocol, SUs can send and receive data packets even during ATIM windows and can reconnect broken links. Therefore, the proposed protocol efficiently utilizes white space. We also analyzed the optimum channel sensing time. The simulation results show that the proposed protocol achieves better aggregated goodput and lower delay.

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