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Full Length Research Paper

Mitigating the control channel bottleneck problem in dense cognitive radio networks

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We proposed a group-based multi channel media access control protocol for cognitive radio to mitigate the control channel bottleneck issue and to utilize multiple channels efficiently. The existing multichannel media access control (MMAC) based protocols suffer from higher delay to access data channels. This underutilizes data channels and lowers the network goodput in dense cognitive radio networks. Our approach mitigates channel access delay in dense cognitive radio networks by grouping the channels and distributing channel negotiations in multiple channels. We evaluated our protocol by simulations compared to the existing MMAC-based protocol. Our proposed approach utilizes channels more efficiently and reduces channel access delay.

Key words: Cognitive radio networks, multi-channels networks, cognitive radio device.

INTRODUCTION

The spectrum scarcity issue due to the fixed radio spectrum allocation system has become a bottleneck for future wireless communication. On one hand, licensed channels are underutilized. Many studies (DARPA, 2007; FCC 2003) show that licensed channels are idle most of the time. On the other hand, industrial, scientific and medical (ISM) bands are overcrowded. Cognitive radio (CR) (Mitola and Maguire, 1999; Mitola 2000; Haykin, 2005) devised the idea of an open spectrum that allows non-licensed users to utilize these underutilized licensed spectrum bands opportunistically. Many communication scientists and researchers are involved in developing an efficient CR to efficiently utilize these unutilized or underutilized bands (Al-Gumaei and Dimyati, 2010). Many CR media access control (MAC) protocols exist in the literature. Multichannel media access control (MMAC) (Jung and Vaidya, 2002) based protocols (Timmers et al., 2010; Kamruzzaman et al., 2010a, b) seem promising with their high throughput, less energy consumed and superiority in licensed user protection. However, these protocols suffer from the common control channel (CCC) bottleneck issue in the dense network scenario. This issue is well described and addressed in (Brandon, 2011; Shi et al., 2006). In wireless networks, the throughput capacity per node decreases when the node density increases, such that it is $O(\frac{1}{\sqrt{n}})$, where n is the number of nodes (Gupta and Kumar, 2000). This is even worse in MMAC-based CR networks, because they have to negotiate for the data channel in less than 25% of the total time in the control channel. The CR devices with two transceivers can improve some aggregated throughput by sending data packets just after channel negotiation and without waiting until the end of ATIM window. However, it does not solve the control channel bottleneck problem in the dense environment. In this paper, we present a decentralized MAC protocol for cognitive radio networks to mitigate the control channel bottleneck issue in dense CR networks. Our approach divides entire nodes into small groups. Similar to MMAC-based CR-MAC protocols, in the proposed protocol, networks consist of a global CCC to exchange control messages

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Abbreviations: MMAC, Multichannel media access control; **ISM,** industrial, scientific and medical; **CR,** cognitive radio; **MAC,** media access control; **CCC,** common control channel; **GCC,** group control channel; **BIs,** beacon intervals; **ACL,** available channel list; **DCA,** dynamic channel allocation; **RTS,** requests to send; **CTS,** clear to send; **RES,** reservation; **ID,** identification number; **ATIM**, ad hoc traffic indication messages.

and several data channels. However, each group has a group control channel (GCC) for channel negotiation that mitigates the collision problem in dense CR networks. We consider cognitive devices that can communicate in both ISM spectrum and licensed spectrum. We further consider there are two non-cooperative types of network users, primary and secondary users. Primary users are licensed users of a frequency band. Secondary users use free spectrum opportunistically for communication that is not use by the primary users.

MULTICHANNEL MEDIA ACCESS CONTROL (MMAC)-BASED COGNITIVE RADIO (CR) MEDIA ACCESS CONTROL (MAC) PROTOCOLS

MMAC-based protocols borrow the idea of dividing time into beacon intervals (BIs) and the BIs are further divided into ATIM window and data window (Jung and Vaidya, 2002), as in Figure 1a. At the start of each ATIM window, all nodes in the network are synchronized by periodic beacon transmission. After synchronization, all nodes tune their transceiver into CCC for ATIM window duration. Nodes having data to send compete for channel access. The contention winner sends the ATIM message with available channel list (ACL) to the receiver. The receiver node selects a common channel from its own ACL and sends back an acknowledgement (ATIM-ACK), along with the selected channel. After receiving ATIM-ACK, the sender sends a confirmation message for the channel reservation (ATIM-RES) to inform neighbor nodes about channel selection. The channel selection process is shown in Figure 1b. In Figure 1b, contention winner nodes initiate negotiation for the channel in ATIM window. The sender sends the ATIM message and sends ATIM-RES after receiving ATIM-ACK from the intended receiver.

Dynamic channel allocation (DCA) based MAC protocol (Nan et al., 2007) exchanges requests to send (RTS), clear to send (CTS) and reservation (RES) packets before sending every data packet to negotiate the data channel. As MMAC-based CR protocols exchange the control message only once in one BI, these protocols are better than DCA-based protocol in bandwidth utilization. In addition, MMAC-based protocols are less prone to CCC bottleneck problem.

MMAC-based approaches work well in the sparse CR networks. However, the approaches do not perform very well in the dense CR networks. There are some inefficiency problems in this approach. (a) Channel utilization limitation: in general, the ATIM window is around one fourth of the data window. In these approaches, ATIM messages for channel negotiation are sent only in the ATIM window of the CCC. Hence, the ATIM window can be overcrowded and cannot negotiate for the all-available channels, when the number of communicating pairs exceeds the available time slots in the ATIM window. Thus, some data channels may be unutilized. (b) Bandwidth waste at channel negotiation: if the ATIM window size is too large, then bandwidth of all the data channels is wasted. This is because nodes do not send or receive data packets in ATIM window. (c) Long channel access delay: in the existing approach, the contention loser nodes have to wait until the next BI. This worsens the situation in the dense network, because the probability of losing contention is very high, when the number of nodes is high. Therefore, they might have to wait for a long time to access idle channels.

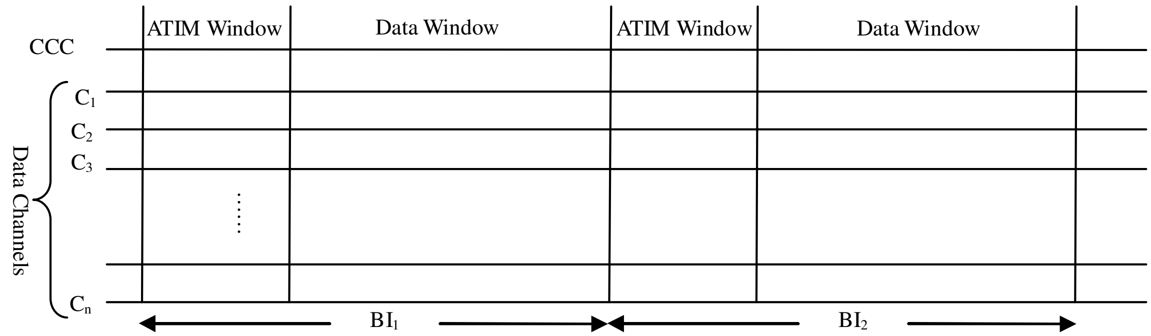
The proposed protocol works similar to the MMAC-based protocols, regardless of offered load in the sparse networks. In the dense networks, the data channels are grouped, and control messages are distributed into the multiple channels. Hence, it mitigates the control channel bottleneck problem and utilizes the multiple channels efficiently.

PROPOSED PROTOCOL

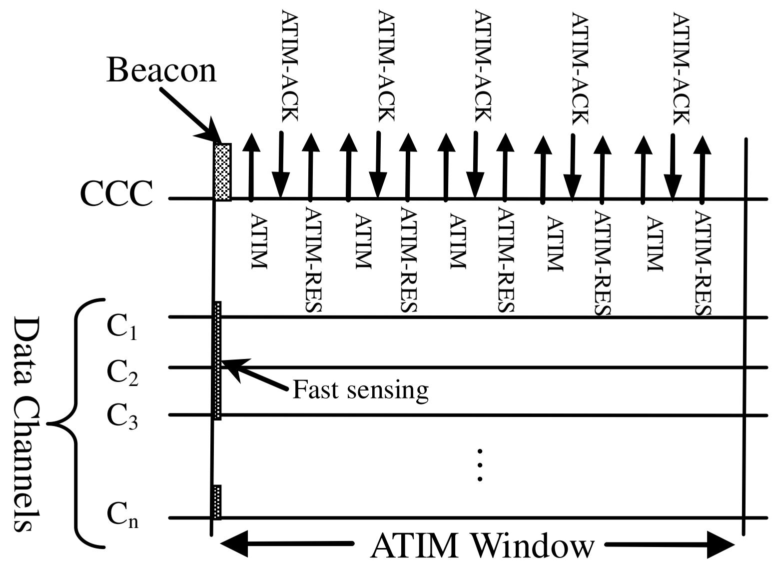
Even though MMAC-based protocols work better than DCA-based protocols, they still cannot perform well in dense CR networks, as mentioned above. We propose a group-based approach, which allows multiple ATIM packet transmissions simultaneously, to solve the inefficiency problem. We assume that each CR radio is equipped with two transceivers, one for control message communication, termed control-transceiver, the other for data communication, termed data-transceiver. Both transceivers are capable of switching multiple types of frequencies dynamically.

Figure 2 shows there are N channels; all channels are divided into k groups. We assume that cognitive radio devices are the intelligent software defined radio devices with the cognition capacity that can observe, orient, plan, learn, decide and act as mentioned in (Mitola and Maguire, 1999; Haykin, 2005). We further assume that CR devices can decide how many k should be there and which channel belongs to which group by monitoring the number of primary channels available to use opportunistically for secondary users. Each CR node has a unique identification number (ID) that is similar to MAC address. The default group of a node is decided by dividing a unique ID by k. Every group has one GCC, but the CCC is the GCC for the first group. The first channel of the group is assigned as the GCC of the group. In Figure 2, GCC_{k-1} is a GCC for group k-1 and CCC is the GCC for Group 0. The GCC of each group is the normal data channel and is use for data communication in the data window. However, CCC is not use for data communication and is reserved to send emergency messages, in case the primary user arrives at the channel.

Similar to the MMAC-based protocols, in the ATIM window, nodes send the ATIM message with ACL to the



a



b

Figure 1. Channel negotiation in MMAC-based CR protocols. a, ATIM window and data window in beacon intervals; b, channel negotiation in MMAC-based CR protocols at ATIM window.

receiver. The receiver node matches the common channel among the available channels and sends ATIM-ACK to the sender. The sender node sends ATIM-RES to the receiver. Other neighboring nodes update their ACL by overhearing the ATIM-RES packets. This ATIM message exchange is performed in CCC for the Group 0 and in GCCs for the remaining groups.

Every sender knows to which group the receiver belongs by its ID. If the receiver is in the same group as the sender, the sender starts sending the data packet in the data window after successfully exchanging ATIM/ATIM-ACK/ATIM-RES packets in the ATIM window. If it is not in the same group as the sender, then the sender tunes its control-transceiver to the GCC of the receiver's group. When it wins contention, the data-transceiver switches to the negotiated channel and sends data in the data window. After completion of the data transmission, it switches back to its default group. If the control-transceiver tune into the receiver is GCC for contention, the data-transceiver starts listening to its own GCC for the ATIM window time to avoid missing packets destined to it.

In the data window, all the nodes tune their control-transceiver into CCC to listen for the emergency control messages from the other nodes. If there is no data to send, the data-transceiver goes into the doze state.

SIMULATION RESULTS

We simulate our protocol using ns-2 (Ns-2, 2011). The results of our protocol are compared to MMAC-based protocol for CR that has a similar approach. The simulated network is composed of different node densities, varying from 18 to 54 nodes. The nodes are deploy to a 500 × 500 m area. The propagation range of each node is 250 m. All the nodes can communicate with each other in the propagation range in one hop. There

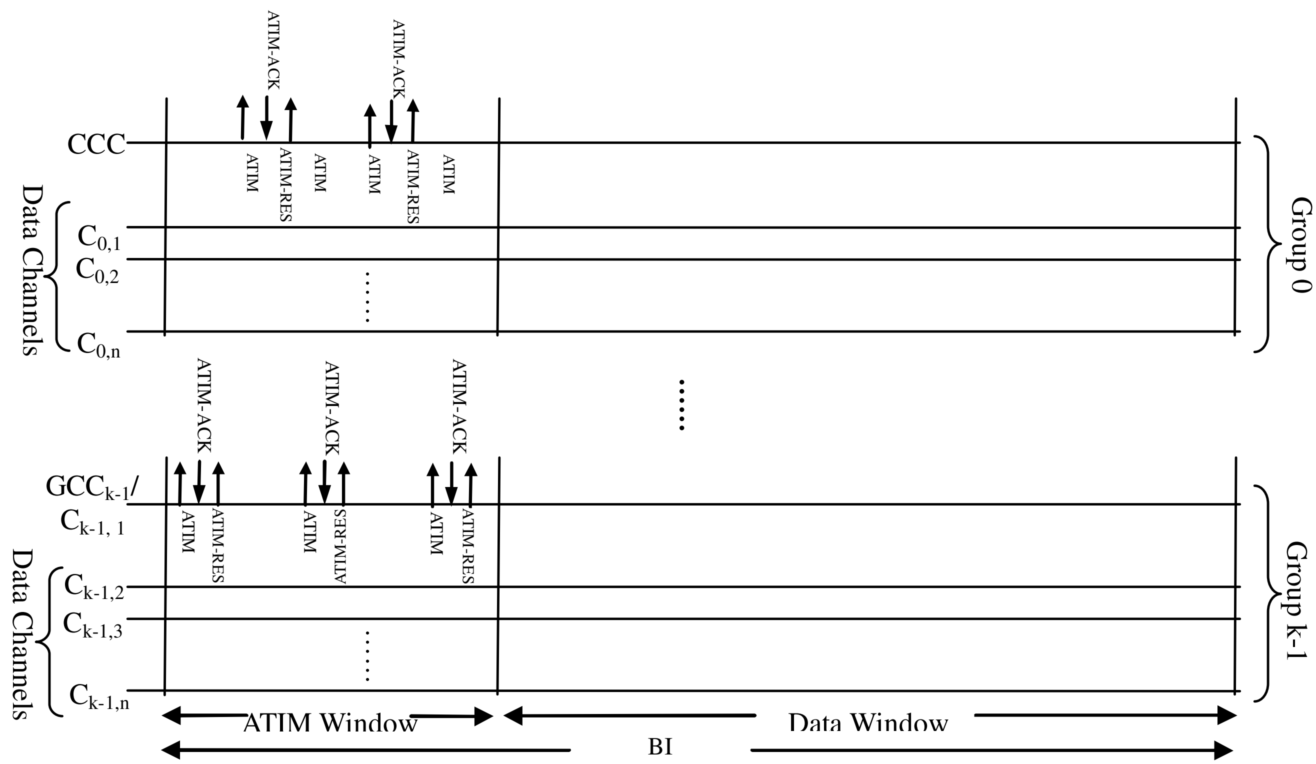


Figure 2. Channel grouping in our approach.

are 12 identical channels with a 2 Mbps data rate. The interface queue size is 50 packets and the offered load is 70 packets per second. One channel is the CCC and the other channels are data channels. The packet size is set to 512 bytes. Each beacon interval is 100 ms and ATIM window size is 20 ms. All simulations are run for around 40 s. The results are averages of 10 simulations. There is always 25% primary traffic and the primary users' arrival probability is 0.5.

In our approach, the data-transceiver has to switch channel only once in one beacon interval after channel negotiation and before sending data. Under the current technology, it is possible for a transceiver to switch from one channel to another channel in 1µs (Garces, 2000; Metricom, 2011). Therefore, we neglect channel-switching delay.

Figure 3 shows the channel access delay for different node densities. In a sparse network topology, the channel access delay is not much different in the proposed method and the MMAC-based protocol. However, there is a big difference in a dense network. In addition, the trend of the channel access delay drastically increases in MMAC-based protocol when the network becomes denser due to the probability of collision increasing and nodes retrying transmission after random backoff, so the delay increases when the number of node increases. If they cannot access a channel in current ATIM window, they wait 80 ms for the next beacon interval. This makes big difference.

Figure 4 gives the ratio of ATIM packets collision. Here, the ratio is the number of dropped packets due to ATIM packet collision divided by the number of packet generated. From the simulation, we observed that a successful negotiation ATIM/ATIM-ACK/ATIM-RES takes 1.27 ms. In the ideal case 15 pairs could exchange ATIM packets in a ATIM window. However, the actual success rate is very low. In the Figure 4, MMAC-based protocol's ATIM packet collision ratio is very high initially due to the MMAC-based approach sharing the CCC among all the nodes in the network. Each node contends for channel access to sends ATIM packets in the ATIM window in the CCC. However, there is less collision in our proposed protocol, because channels are divided into k groups and nodes get k times more channel negotiation period than in the MMAC-based approach. Thus, in our approach the ATIM packets collision ratio is very low compared to the MMAC-based approach, even in dense network topologies. The ratio slightly decreases after 24 nodes in the MMAC-based approach. It is due to our simulation setup, for example, we set the interface queue to 50 packets. Even though the nodes generate more packets, they are discarded for other reasons, rather than collision. Hence, the ratio slightly decreases.

Our grouping mechanism reduces the data channel utilization limitation and data channels' bandwidth waste in the channel negotiation phase, since it has multiple

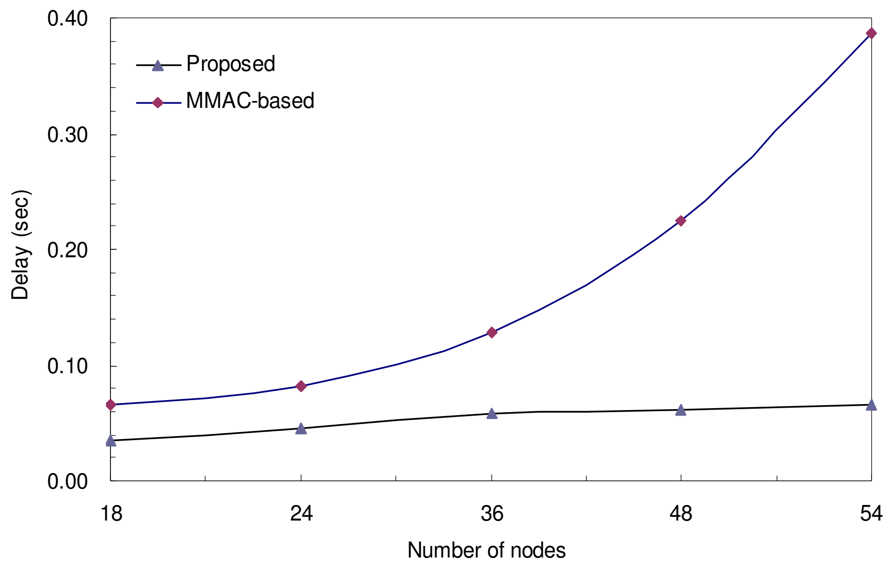


Figure 3. Channel access delay for different node densities.

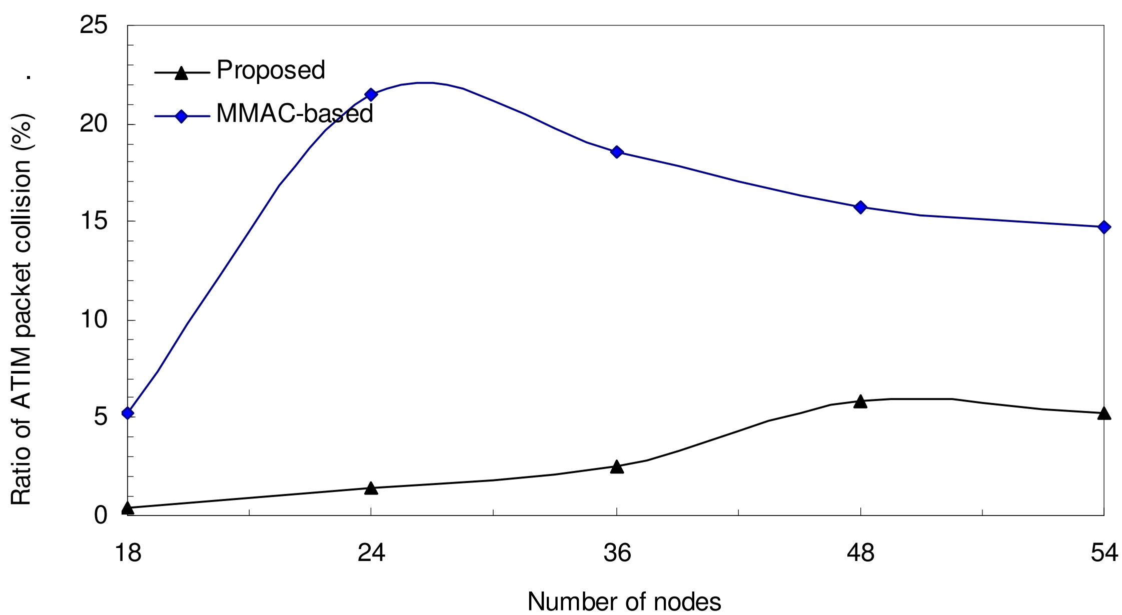


Figure 4. Ratio of ATIM packets collision in various node densities.

GCCs. Figure 5 shows the goodput for different node densities. When the number of nodes is small, our approach and the MMAC-based approach do not differ greatly. However, when the number of nodes increases, network load increases and there is large channel access delay. This creates CCC bottleneck and decreases goodput in the MMAC-based approach. However, in our approach, channel negotiation packets are sent in different GCCs, so CCC is less prone to the bottleneck problem. Higher goodput obviously means higher channel utilization.

CONCLUSION

In this paper, we presented a new MAC protocol to mitigate the bottleneck issue in CR networks. Simulations show our approach mitigates collision significantly, reduces delay and increases goodput. This may help increase network life time in an ad hoc environment, as transceivers turn off when there are no data to send or receive. Nodes can send an emergency message within a tolerable delay time in the case of primary users' arrival, because the CCC is free in the data window. This helps

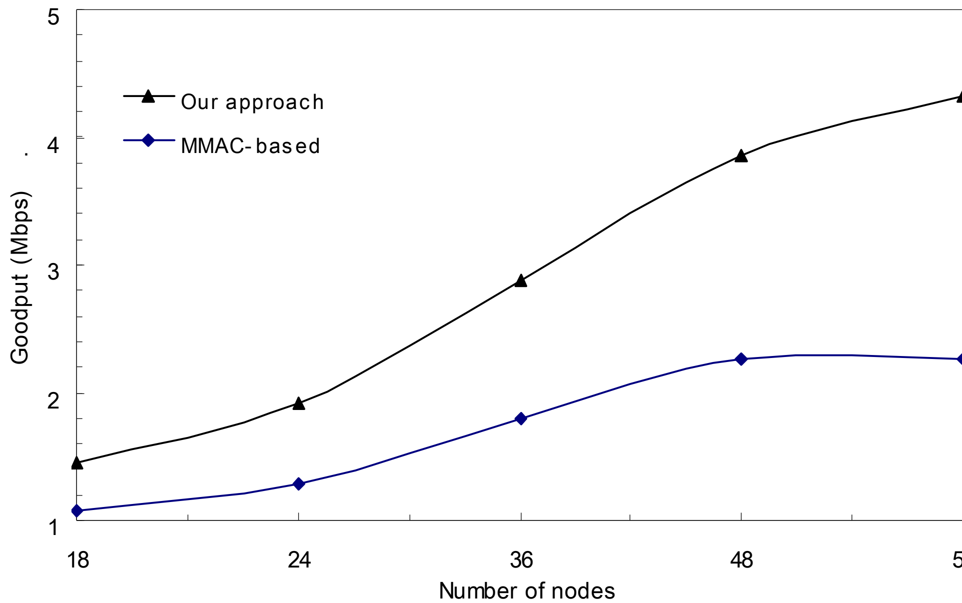


Figure 5. Goodput comparison in different node densities.

protect primary users from further collision.

Some groups may be are overcrowded, while some may be less crowded in the proposed protocol. We will consider how to distribute load to the groups as for our future research work. Furthermore, there is no collision resolution protocol in ATIM packets in MMAC-based protocols; this will be kept for our future research.

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