H-MMAC: A Hybrid Multi-channel MAC Protocol for Wireless Ad hoc Networks

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***Abstract*—In regular wireless ad hoc network, the Medium Access Control (MAC) coordinates channel access among nodes and the throughput of the network is limited by the bandwidth of a single channel. The multi-channel MAC protocols can exploit the multiple channels to achieve a high throughput by enabling more concurrent transmissions in the network. Dynamic Channel Assignment (DCA [5]), Multi-channel MAC (MMAC [2]) and Pipelining Multi-channel MAC (π-Mc [7]) are three multi-channel MAC protocol representatives. In the DCA protocol, the dedicated control channel cannot be fully utilized or causes the bottleneck depending on the number of channels. In the MMAC protocol, the data channel resources are wasted during the ATIM window. The data packet size impacts on the performance of π-Mc protocol. In this paper, we propose a hybrid protocol that utilizes the multi-channel resources more efficiently than MMAC and other protocols. The H-MMAC protocol allows nodes to transmit data packets while other nodes try to negotiate the data channel during the ATIM window. The simulation results show that the proposed H-MMAC can improve the performance of the network: aggregate throughput, average delay and energy efficiency.**

***Index Terms*—Multi-channel, MAC protocol, Ad hoc networks.**

I. Introduction

The IEEE 802.11 standard [1] provides a MAC protocol called Distributed Coordination Function (DCF). The IEEE 802.11 DCF uses CSMA/CA (Carrier Sense Multiple Access with Collision Avoidance) technique for Physical Carrier Sensing and RTS/CTS handshake for Virtual Carrier Sensing. There are 3 non-overlapping channels in the IEEE 802.11b, g and 12 non-overlapping channels in the IEEE 802.11a. Although the IEEE 802.11 provides multiple channels for wireless communications at Physical Layer, the MAC protocol is designed only for a single channel. If multiple channels are exploited, many concurrent transmissions can take place without interfering. We can achieve a higher network throughput than using single channel.

However, it is not easy to design the MAC protocol that can exploit multiple channels with a single half-duplex transceiver. The transceiver can switch channel radio dynamically, but it cannot sense all channels simultaneously. It may lose the channel reservation messages from its neighbors on another channel. This leads to a new type of hidden terminal problem in a multi-channel environment, which we refer to as *multi-channel hidden terminal problem*. There are four approaches for multi-channel MAC protocol as the classification from [4]: Dedicated Control Channel (DCA [5], DCA-PC [9]), Split Phase (MMAC [2], TAMMAC [3]), Common Hopping (CHMA [6], π-Mc [7]) and McMAC [8]. We can apply the power control mechanism to these multi-channel protocols to improve spatial reuse of wireless channel. Nodes have to be on the certain channel at the certain time to exchange the transmitting power information. It is very difficult to apply power control for the common hopping or McMAC approaches. That is why we analyze DCA and MMAC protocol, and propose a new hybrid protocol named H-MMAC protocol.

The rest of the paper is organized as follows. Section II reviews the related work of Multi-channel MAC protocol in ad hoc networks. Our proposed protocol is described in details in section III. We evaluate the proposed protocol through extensive simulations and discuss the results of our simulations in section IV. Finally, we conclude this paper in section V.

II. Motivation

Fig. 1 illustrates the operations of DCA, MMAC and π-Mc protocols. In the DCA protocol, each node is equipped with two transceivers: control transceiver is tuned to the control channel and data transceiver can switch to any other channels for data transmission. Node uses the control transceiver to perform RTS/CTS/RES handshake for data channel negotiation. Then, DATA and ACK are transmitted on agreed data channel by using the data transceiver. While some nodes are exchanging data on data channels, the others can negotiate data channels in order to use them right after they are idle. In Fig. 1a, T_d and T_c are defined as the transmission duration of data packets and control packets, respectively. The maximum number of data channels that can be fully utilized is T_d/T_c. If the number of data channels is less than T_d/T_c, the control channel resource is wasted. On the other hand, if the number of data channels is greater than T_d/T_c, the data channel resources cannot be fully utilized because of the control channel saturation. When the traffic load is high, the throughput of the network suffers from high contention among control packets. We can increase the data packet size to reduce the impact of control channel saturation on the throughput.

Time is divided into beacon intervals in the MMAC protocol (Fig. 1b). Each beacon interval has a small window called the ATIM window followed by data window. One of the multiple

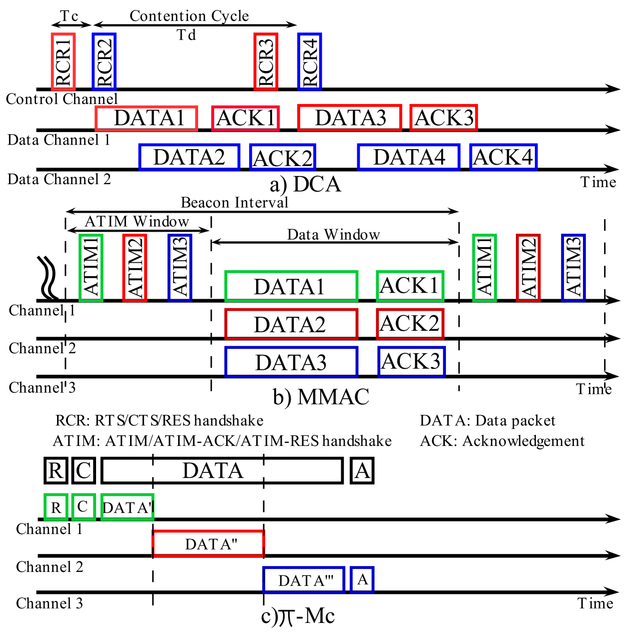

Fig. 1. The operations of DCA and MMAC protocols

channels is predefined as the default channel. All nodes have to switch to the default channel in the ATIM window and all ATIM messages (Ad hoc Traffic Indication Messages) are sent on this channel to negotiate the data channel. After the ATIM window, nodes switch to agreed channel to transmit data packets. The resources of other channels are wasted during the ATIM window. If we reduce the ATIM window size, there will be not enough time for some nodes to exchange ATIM messages to negotiate data channel. On the other hand, if longer ATIM window is used, much of the time the channel will be left as idle, because nodes cannot send data packets in this interval. Traffic Aware Multi-channel MAC (TAMMAC) [3] proposed a mechanism to adjust the ATIM window dynamically according to the traffic of the network but the resources of other channels are still wasted during the ATIM window.

The core idea of the pipelining multi-channel MAC (π-Mc) [7] is similar to a pipeline technique (Fig. 1c). The transmission task is divided into many subtasks. All of the subtasks are transmitted on different channels sequentially. All nodes which have data to transmit should contend to transmit first subtask on the first channel. If the first subtask is transmitted successfully, all the other subtasks also succeed in transmission. Although, π-Mc is modified to adapt to data size, the overhead of backoff procedure on the first channel affects the performance of the network. Moreover, the channel switching time (224 μs [1]) also impacts the performance especially when the number of channels is large.

We propose the Hybrid Multi-channel MAC protocol by combining the advantages of DCA and MMAC protocols. The enhancement of the H-MMAC protocol compared to the MMAC protocol is that the H-MMAC protocol allows some nodes to transmit data packets while other nodes are exchanging ATIM messages during the ATIM window. For N channels, the H-MMAC protocol utilizes (N-1) channels in the ATIM window. The H-MMAC protocol can improve the throughput compared to the MMAC protocol.

$$Improvement = (\frac{N-1}{N})\frac{ATIM\_window\_size}{Data\_window\_size}$$

The detail of the H-MMAC protocol is described in the following section.

III. The Proposed H-MMAC Protocol

First, we summarize our assumptions as follows:

- There are N non-overlapping channels which can be used. The beacon interval is divided into 2 sub-intervals: ATIM window, data window. One channel is defined as a default channel (CH1) just in ATIM window. The default channel is used to transfer data packets like other channels outside the ATIM window.
- Nodes have prior knowledge of how many channels are available.
- Each node has a single half-duplex transceiver which is capable of switching the channel dynamically.
- All nodes are time-synchronized and operate the IEEE 802.11 DCF mechanism.

A. Neighbor Information List and Preferable Channel List

Each node maintains its data structures called the Neighbor Information List (NIL) and Preferable Channel List (PCL). The NIL stores the state, type and transmission mode (Tx mode) of neighbor nodes. The PCL stores the state of every channel and how many node pairs already reserved this channel.

TABLE I
Node A's NIL

Node	State	Type	Tx mode
B	Idle	Limited	N-Tx
C	Idle	Unknown	N-Tx
D	Busy	Normal	E-Tx
E	Idle	Unknown	N-Tx
...	...	...	...

TABLE II
Node A's PCL

Channel	State	Counter
1	Idle	0
2	Busy	1
3	Selected	2

TABLE III
NIL's Update

Node A's	Before update			After update		
Type	State	Type	Tx mode	State	Type	Tx mode
Normal	-	Unknown	N-Tx	Idle	Normal	N-Tx
Normal	-	Unknown	E-Tx	-	Unknown	N-Tx
Normal	Idle	Limited	E-Tx	Idle	Normal	N-Tx
Normal	Busy	Ongoing	E-Tx	Idle	Limited	E-Tx
Any	Busy	Normal	E-Tx	Busy	Ongoing	E-Tx
Ongoing	-	$\overline{\text{Ongoing}}$	-	-	Unknown	E-Tx
Normal	Busy	Normal	N-Tx	Idle	Normal	N-Tx
Any: Normal or Ongoing type			$\overline{\text{Ongoing}}$: node that is not Ongoing type			

There are 2 states of a neighbor node: Idle and Busy. Idle node do not exchange data packets in the current beacon

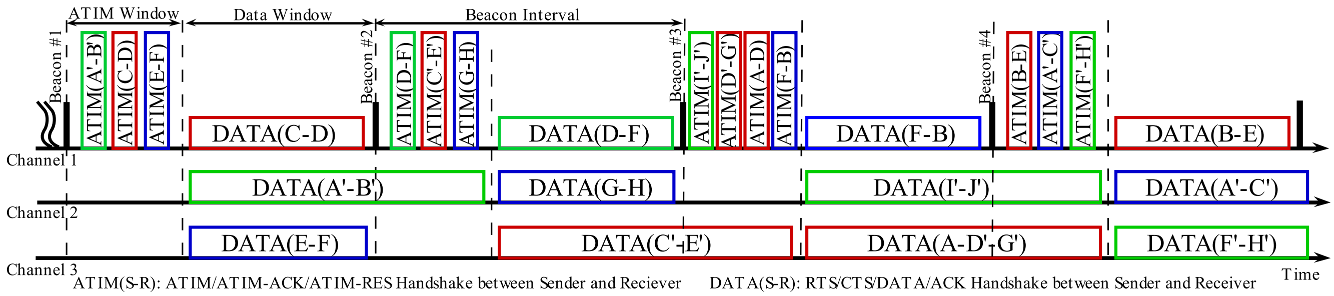

Fig. 2. The operation of H-MMAC protocol

interval. Busy state indicates the node will exchange data packets in the current beacon. Normal transmission (N-Tx) is the transmission performed within data window. By using the next ATIM window for data transmission, Extra transmission (E-Tx) is longer than Normal transmission. Each node can choose either one of the transmission modes according to the number of packets in its buffer (Pkt_Threshold) and the number of nodes allowed to transmit during ATIM window (ExtraTx_Threshold).

The type of neighbor node can be one of 4 types: Normal, Ongoing, Limited and Unknown. Normal nodes are the nodes that do not lose any control messages from their neighbors. Nodes which are exchanging data during the ATIM window are classified as Ongoing nodes. Limited nodes are the nodes which lost information of some neighbors because they were busy with data transmission in the last ATIM window. If a node does not know any information of its neighbor node, the neighbor node is an Unknown node. Let's find the type of node A's neighbor node at the start of the third ATIM window of an example in Fig. 2. Node B is a Limited node because it was Ongoing node in the last ATIM window. Node C is an Unknown node because node A lost node C's ATIM messages in the last ATIM window. But in the node D's point of view, node C is an Ongoing node and node G is a Normal node. If the neighbor node uses E-Tx mode from the beacon 1, its type is changed to Ongoing, Limited and Normal in the ATIM window of beacon 2, 3 and 4 respectively in the NIL.

Node A updates its type itself (Normal or Ongoing) and then updates its NIL before each beacon as the Table III. Whenever node A overhears ATIM messages from node j, the State changes from Idle to Busy and Tx type is updated to corresponding transmission mode of node j.

The PCL is updated when the node overhears ATIM-ACK/ATIM-RES messages or when the node selects a channel to use in data window.

- All the channels are reset to Idle state at the start of each beacon interval.
- If node A selects a channel to exchange data, this channel is changed to Selected state.
- When node A knows that its neighbor will use channel j through ATIM-ACK/ATIM-RES, it changes the state of that channel from Idle to Busy and increases the counter by one.

Table I and II are the NIL and the PCL of node A after node A exchanged ATIM messages with node D at the third beacon (Fig. 2).

B. The operation of H-MMAC protocol

In the ATIM window, there are four types of node: Ongoing, Limited, Normal and Unknown. The node must be Normal or Limited type in order to be a receiver.

1) If a node has data to send, it checks the receiver's type in its NIL. If the receiver's type is Ongoing or Unknown, it has to wait for next beacon to try again.
2) Based on the Pkt_Threshold and ExtraTx_Threshold, the sender decides which transmission mode is used.
3) The sender attaches its PCL and transmission mode into ATIM packet and sends to the receiver.
4) Upon receiving ATIM, the receiver selects the best channel from its PCL and the sender's PCL by using Algorithm 1. Then the receiver sends ATIM-ACK indicating the selected channel to the sender.
5) The sender sends ATIM-RES to confirm the data channel selected by the receiver.
6) After the ATIM window, the sender and receiver switch to agreed channel for exchanging data.

Algorithm 1 Algorithm to select the "best" channel

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if There is a Selected channel in destination's PCL then
    This channel is selected.
else if There is a Selected channel in source's PCL then
    This channel is selected.
else if There is at least one Idle channel in both source's
PCL and destination's PCL then
    One Idle channel is selected arbitrarily.
else if There is at least one Idle channel in one of source's
PCL and destination's PCL then
    One Idle channel is selected arbitrarily.
else if The channels are all Busy then
    The channel which has the least counter value is selected.
else
    Cannot select any channel.
end if
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Fig. 2 shows an example for the operation of H-MMAC protocol. (X'-Y') denotes sender X and receiver Y using E-

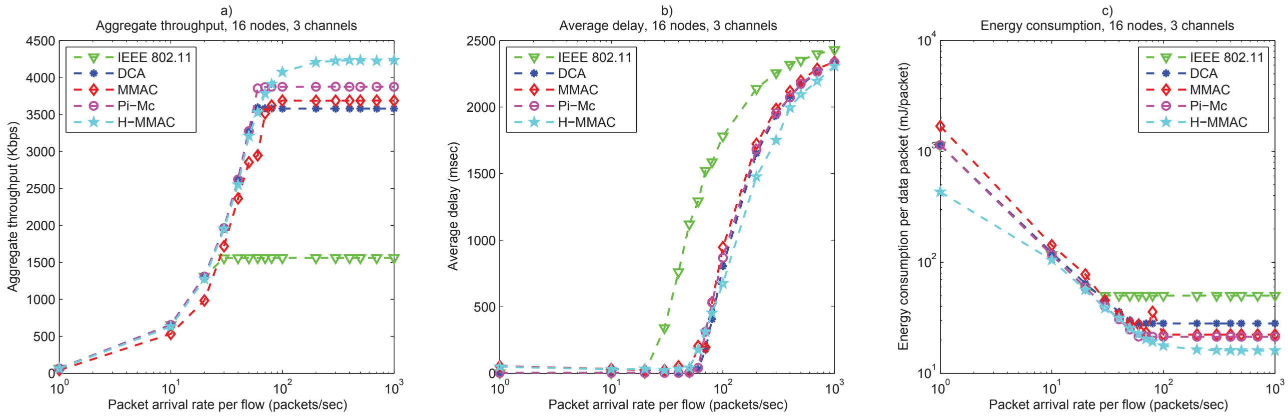

Fig. 3. Performance of different protocols in scenario 1

Tx mode. In the first beacon, nodes A and B use E-Tx mode. In the second ATIM window, nodes A and B are Ongoing nodes, therefore they lose the control messages from their neighbor nodes. In the third ATIM window, nodes A and B become Limited nodes which have limited information about their neighbor nodes. Node D is an Unknown node in node A's NIL. After node A overhears ATIM message from node D, it knows that node D is now on default channel and update node D information in its NIL. If node A has data for node D, it can exchange ATIM messages to node D. Then nodes A, D and G switch to channel 3 to contend for data transmission. But only nodes D and G perform E-Tx as they already negotiated in the ATIM window, node A switches to default channel at the end of beacon 3. Node B lost control messages of other nodes from the second ATIM window, and it does not know about the state of node E during the third ATIM window. In the worst case, if node E is Ongoing node in the third ATIM window, node E will be on default channel in the fourth ATIM window. Therefore, node B can exchange data with node E from the fourth beacon.

IV. Performance Evaluations

In this section, we have simulated IEEE 802.11, DCA, MMAC, π-Mc and our proposed H-MMAC protocol.

TABLE IV
Simulation's Parameters

Parameters	Scenario 1	Scenario 2
Number of channels	3	8
Number of nodes	16	36
Transmission range	250 m	
Data rate	2 Mbps	
Data packet size	512 bytes	
Beacon Interval	100 ms	
ATIM window	20 ms	
SIFS / DIFS /Slot time	16 μs / 34 μs / 9 μs	
Retry limit	4	
Channel switching time	224 μs	
Transmit/Receive power consumption	1.65W / 1.4W	
Idle/Doze power consumption	1.15W / 0.045W	
Pkt_Threshold	20 packets	
ExtraTx_Threshold	1 node	

A. Simulation Model

The network consists of n nodes in a 250m x 250m area. Each node can have random location. Each node can be a source or a destination. The destination of each source node is one of the nodes that are in the source's transmission range. Node can choose one destination in the neighbor nodes in its transmission range. Each node generates and transmits constant-bit-rate (CBR) traffic. The other simulation parameters in our simulations are listed in Table IV. Each simulation was performed for 5 seconds and the simulation results are the average of 30 runs.

In the simulation, we use the following metrics to evaluate the performance.

$$Throughput = \frac{Packet\_Size * No\_Successful\_Packets}{Total\_SimTime}$$

$$Average\_Delay = \frac{Total\_Packet\_Delay}{No\_Successful\_Packets}$$

$$Energy\_Efficiency = \frac{Total\_Energy\_Consumption}{No\_Successful\_Packets}$$

B. Simulation Result

Fig. 3 shows the performance of different protocols with 16 nodes and 3 channels. As we can see from the Fig. 3a, the aggregate throughputs of multi-channel MAC protocols are higher than IEEE 802.11 MAC protocol designed for single channel. Although the throughput of π-Mc protocol is higher than that of DCA and MMAC protocol, it is affected by the channel switching time and the backoff duration. In the proposed H-MMAC protocol, nodes can transmit during the ATIM window while others try to negotiate the channel. The throughput of H-MMAC is higher than that of other protocols. In MMAC and H-MMAC, if nodes have data to transmit, they have to switch the channel from default channel to agreed channel and back to default channel. On the other hand, nodes have to switch channel N times in π-Mc protocol with N channels. By exploiting the multiple channels, the multi-channel MAC protocols have more data packets transferred than IEEE 802.11 MAC protocol. That is why, the average

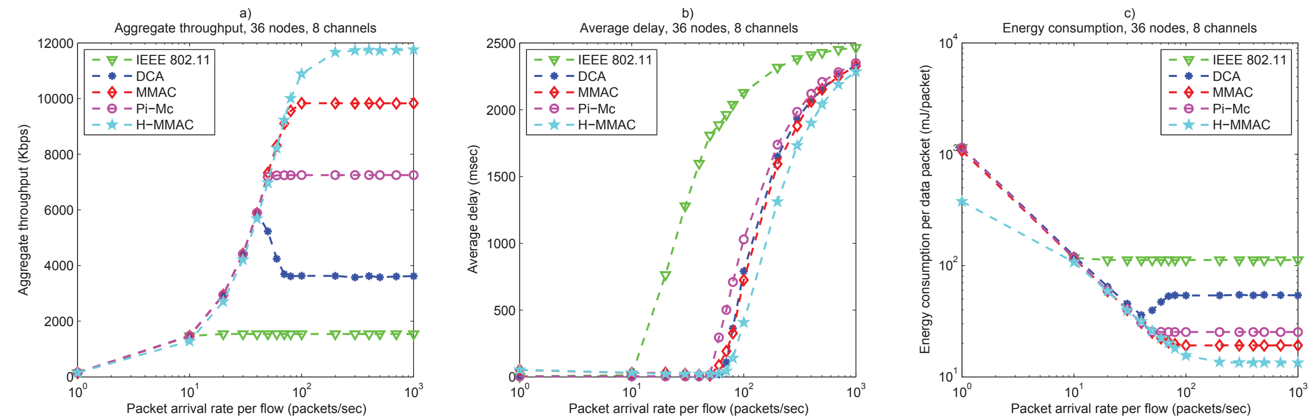

Fig. 4. Performance of different protocols in scenario 2

delays of the multi-channel MAC protocols are lower than that of IEEE 802.11 MAC. Our proposed H-MMAC protocol has the lower delay than DCA, MMAC and π-Mc protocols. Like the MMAC protocol, the H-MMAC also implements power saving mechanism (PSM). All nodes which do not have data to exchange or cannot contend the data channel in the ATIM windows enter the doze mode with small power consumption 0.045 W. In other protocols, all idle nodes have to stay awake and spend idle power of 1.15 W. With the less energy consumption and higher throughput, the energy efficiency of the H-MMAC protocol is better than other protocols as shown on Fig. 3c.

The aggregate throughput, the average delay and the energy efficiency of scenario 2 are shown in Fig. 4a, b and c respectively. The π-Mc protocol does not have a good performance when the number of channels is large because the channel switching time impacts the performance. As we mentioned above, the performance of the DCA protocol is affected by the T_d/T_c ratio. If the number of channels is larger than T_d/T_c, the DCA protocol cannot utilize the multiple channel fully. For the MMAC protocol, the more the number of channels is used, the more channel resources are wasted during the ATIM window. Although the ATIM window impacts the performance of the H-MMAC protocol on default channel, the other channels are fully utilized when the traffic load is high. From Fig. 4a, the throughput of H-MMAC protocol is about 18% higher than that of MMAC protocol. Since more data packets are transmitted, the average delay of H-MMAC protocol is low as shown in Fig. 4b. And the energy consumption per packet of H-MMAC protocol is also lower than other protocols.

V. Conclusions and Future Work

In this paper, we have proposed a hybrid multi-channel MAC protocol, named H-MMAC, that utilizes almost all of the entire channel resources to improve the network performance. By using the PSM and allowing nodes transmit data during the ATIM window, H-MMAC can achieve higher performance than other multi-channel MAC protocols. Simulation results show that the H-MMAC's performance is increased significantly when the number of channels is large.

The nodes of H-MMAC protocol are on the default channel during the ATIM window, so they can exchange their transmitting power information. We can apply power control algorithm for the H-MMAC protocol to improve the spatial reuse of wireless channels. The H-MMAC protocol with power control can improve the network performance significantly. We are going to implement this protocol as the future work.

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