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An efficient multi-channel MAC protocol for wireless ad hoc networks

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ABSTRACT

IEEE 802.11 MAC is designed for single channel and based on Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA). The throughput of network is limited by the bandwidth of the single channel and the CSMA-based MAC protocol with omnidirectional antennas can cause the serious unfairness or flow starvation. By exploiting the multiple channels and using the directional antennas, nodes located in each other's vicinity may communicate simultaneously. This helps to increase the spatial reuse of the wireless channel and thus increase the network performance. In this paper, we propose a Multi-channel MAC protocol with Directional Antennas (MMAC-DA) that adopts IEEE 802.11 Power Saving Mechanism (PSM) and exploits multiple channel resources and directional antennas. Nodes have to exchange control packets during the Announcement Traffic Indication Message (ATIM) window to select data channels and determine the beam directions which are used to exchange data packets during the data window. The simulation results show that MMAC-DA can improve the network performance in terms of aggregate throughput, packet delivery ratio, energy efficiency and fairness index.

1. Introduction

In a dense network, nodes may suffer from intensive contention from their neighbor nodes. As a result, some flows may be starved and refrained from their transmissions for a long time. There are three well-known sources of starvation [1,2] such as hidden node starvation, asymmetric sense starvation and carrier sense starvation. IEEE 802.11 [3] provides multiple channels at Physical layer (three non-overlapping channels in IEEE 802.11b and g, and twelve non-overlapping channels in IEEE 802.11a) but the MAC layer is designed for single channel. By exploiting multiple channel resources, applying appropriate power control mechanisms or using directional antennas, more concurrent transmissions are supported and the starvation can be mitigated.

The multi-channel MAC protocols can be classified into 4 categories: Dedicated Control Channel [4], Split Phase [5–7], Common Hopping and Parallel Rendezvous. Each node has two transceivers in Dynamic Channel Assignment (DCA) [4]. One transceiver is tuned to control channel for exchanging control packets while another can switch to any data channel for data transmissions. This scheme does not require synchronization, however, it may suffer the bottle-neck on the control channel. Both Multi-channel MAC (MMAC) [5] and Hybrid Multi-channel MAC (H-MMAC) [6,7] protocols adopt IEEE 802.11 PSM in which

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the ATIM window is used for exchanging control packets for channel negotiation. They require time synchronization. MMAC does not allow nodes to exchange data packets during the ATIM window while H-MMAC allows nodes to use the ATIM window for data transmissions to utilize the channel resources more efficiently.

In Power Control MAC (PCM) [8], nodes increase the transmission power periodically during the data transmission in order to warn nodes in the carrier sensing range. PCM helps mobile nodes to save energy, it does not improve the spatial reuse of wireless channel through the power control algorithm. The SINR-based transmission power control (STPC-MAC) [9] guarantees the SINR at the receiver. Nodes exchange the transmission power information during the ATIM window. Based on overheard transmission power information, neighbor nodes estimate the transmission power which they can use to transmit simultaneously. STPC-MAC does not only improve the spatial reuse of wireless channel, but also save the energy of wireless nodes. The power control algorithm can be combined with multi-channel MAC protocols to mitigate the starvation in wireless ad hoc network in [2,10].

In addition to two above approaches, using directional antennas can improve the spatial reuse. Dai et al. [11] present an overview of using directional antennas in wireless network. The Directional Virtual Carrier Sensing (DVCS) [12] employs a steerable antenna system which can point to any specified direction. Each node maintains a list of neighbor nodes and their directions based on Angle of Arrival (AoA) of the overheard signals. The Directional Network Allocation Vector (DNAV) is used instead of the traditional Network Allocation Vector (NAV) for channel reservation to increase the network capacity 3 to 4 times. Circular Directional RTS (CDR-MAC) [13] uses the circular directional RTS in which the RTS is transmitted directional consecutively in circular way. This helps the intended receiver to identify the location of the sender. The receiver replies with the directional CTS at the direction of the sender. CDR-MAC cannot avoid the deafness problem as the receiver only transmits the directional CTS and it suffers from the overhead of the circular directional RTS when the number of beams increases. All RTS/CTS packets are transmitted in directional mode in Multi-hop Directional RTS MAC (MMAC) [14]. The sender uses the multi-hop RTSs to establish link to the intended receiver, then they transmit CTS, DATA and ACK in directional mode over single hop. An additional busy tone is used in Dual Sensing Directional MAC (DSDMAC) [15] with two patterns: continuous and ON/OFF patterns. MMAC-DA [16] employs the directional antenna to multi-channel MAC MMAC protocol [5] to exploit multiple channels as well as improve spatial reuse of wireless channel. However, it does not utilize channel resources during the ATIM window.

In this paper, we propose a multi-channel MAC protocol with directional antennas (MMAC-DA). Similar to MMAC [5] and H-MMAC [7], MMAC-DA uses the ATIM window to exchange control packets to select data channels. Moreover, nodes use data structures to maintain the status of the neighbor nodes and the channel availability. Compared to the previous MMAC-DA [16], the current proposal allows nodes to exchange data packets during the ATIM window in order to utilize the channel resource more efficiently.

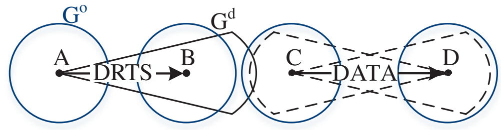

Fig. 1. Hidden terminal due to the asymmetric antenna gains.

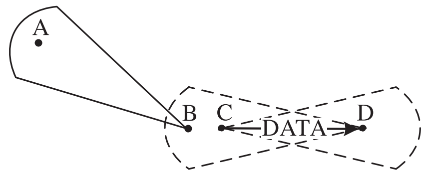

Fig. 2. Hidden terminal due to the unheard RTS/CTS.

The rest of this paper is organized as follows. In Section 2, we discuss some MAC issues related to multi-channel environment and directional antennas. We describe briefly the operation of IEEE 802.11 PSM in Section 3. The antenna model is presented in Section 4. Section 5 explains the proposed MMAC-DA protocol in details. The performance evaluation is given in Section 7. Finally, we conclude our paper in Section 8.

2. MAC issues with multi-channel and directional antennas

2.1. Neighbor discovery

Neighbor discovery is one of critical issues in wireless network with directional antennas. A node needs to determine the intended receiver in order to beamform to it. It is very difficult when two nodes do not beamform to each other in directional mode. A node can obtain the location information of other neighbor nodes through the overheard RTS/CTS. Based on the overheard control packets RTS and CTS, a node knows the Angle of Arrival (AoA) as well as the power of the received signals, it can estimate the direction and the distance to its neighbors.

2.2. Hidden terminal problem

A hidden node is not aware of another on-going transmission and its transmitted packets may cause the collision with the on-going transmission. The hidden terminal problem can be caused by the asymmetric antenna gains (Fig. 1) or the unheard RTS/CTS (Figs. 2 and 3). The hidden terminal problem in multi-channel environment is also known as multi-channel hidden terminal problem (Fig. 3). In Fig. 1, since node A is listening in omnidirectional mode with gain G^o, it may not overhear the directional CTS (DCTS) from node D. While node C is transmitting data packets to node D in directional mode with gain G^d, node A has data packets to node B. Node A senses channel in direction toward node B, and channel is idle because node D is in the receiving state. Node A starts transmitting the

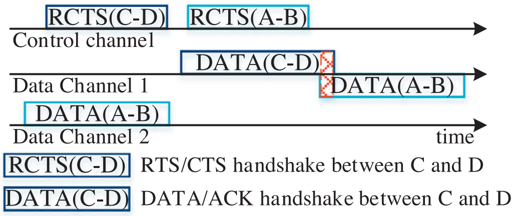

Fig. 3. Multi-channel hidden terminal problem.

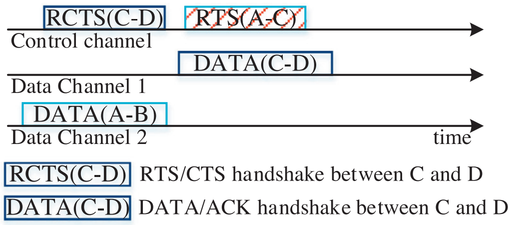

Fig. 4. Missing receiver due to multi-channel environment.

directional RTS (DRTS) to node B. The DRTS of node A may interfere with the data packets of node C at node D.

In Fig. 2, while nodes A and B are exchanging data packets, nodes C and D perform the directional RTS/CTS (DRTS/DCTS) handshake. Node B cannot overhear the DCTS from node D. After finishing the transmission with node A, node B has data packets for node C. The DRTS of node B collides with the data packet of node C at node D.

The multi-channel hidden terminal problem is illustrated in Fig. 3. While nodes A and B are exchanging data packets on data channel 2, nodes C and D perform the RTS/CTS handshake to select data channel 1. After finishing the transmission, both nodes A and B switch back to control channel and they perform the RTS/CTS handshake for another data transmission. Since nodes A and B do not overhear the RTS/CTS from nodes C and D, they may choose the same data channel 1. When nodes A and B switch to data channel 1 to exchange data packets. These data packets collide with the data packets of transmission between nodes C and D.

2.3. Missing receiver problem—Deafness problem

The missing receiver problem in multi-channel environment and deafness problem when using direction antennas are caused when a sender fails to communicate with its intended receiver. In Fig. 4, nodes A and B cannot overhear the RTS/CTS of nodes C and D because they are on data channel 2. After finishing the data transmission with node B, node A has data packets for node C. Node A starts sending the RTS to node C. However, node C is on data channel 1, it cannot receive the RTS and reply with the CTS to node A. Node A doubles its contention window (CW) and retransmits the RTS until the retry limit is reached.

The directional antennas can cause the deafness problem as shown in Fig. 5. Node A which does not overhear the DRTS/DCTS of nodes B and C transmits the DRTS to

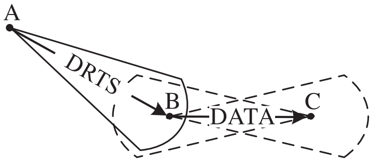

Fig. 5. Deafness due to directional antennas.

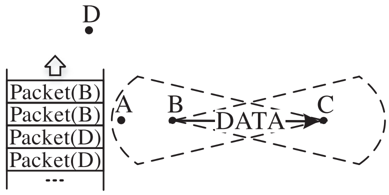

Fig. 6. Head of Line blocking problem.

node B. Since node B is beamforming to node C, it cannot receive the DRTS from node A and reply with the DCTS to node A. Node A does not receive the DCTS before time-out, it increases its CW and retransmits the DRTS until the retry limit is reached.

2.4. Head of line blocking problem

The First In First Out (FIFO) manner of the buffer in wireless network causes the head of line blocking problem. When the first data packet is blocked because of directional NAV (DNAV) or missing receiver—deafness problem, the other packets are also blocked. However, in some cases other data packets should not be blocked because their transmission directions or receivers are available. As in Fig. 6, node A has some packets for nodes B and D. Since node B is sending data packets directionally to node C, node A cannot send data packets to node B. However, the direction to node D is not blocked and node A should not block data packets destined to node D.

3. IEEE 802.11 power saving mechanism

In IEEE 802.11 PSM, ATIM message is used for power management. Fig. 7 illustrates the operations of IEEE 802.11 PSM. All nodes are synchronized by periodic beacon transmissions. Time is divided into beacon intervals, and there is a short ATIM window at the start of the beacon interval. All nodes have to be awake during the ATIM window. In the ATIM window, source node S and destination node D perform a handshake by exchanging ATIM-Request/ATIM-Acknowledgment. After the ATIM window, both nodes S and D exchange DATA/ACK packets. Other nodes which do not have packets to send or receive go to doze mode to save energy and they wake up at the start of the next beacon. In doze mode, a node consumes much less energy compared to idle mode, but it cannot send or receive packets. The proposed MMAC-DA adopts IEEE 802.11 PSM to take the advantage of power conservation.

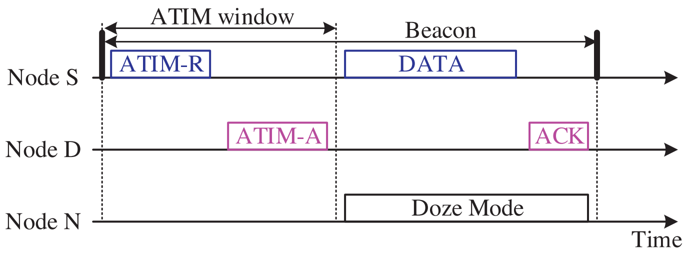

Fig. 7. The operation of IEEE 802.11 PSM.

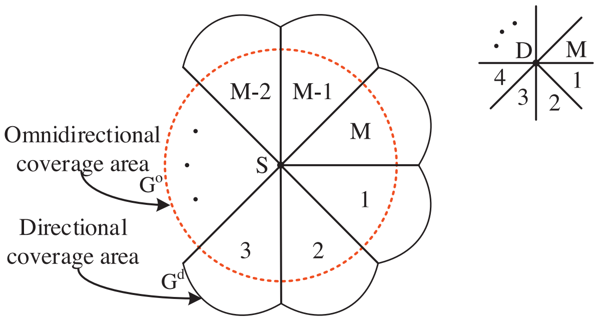

Fig. 8. Antenna model.

4. Antenna model

The antenna can operate in either *Omnidirectional* mode or *Directional* mode. In directional mode, the antenna can beamform to one of M ($M = 2^n, n \geq 0$) fixed directions. The antenna gain in omnidirectional and directional modes are G^o and G^d (typically, $G^d \geq G^o$), respectively. In MMAC-DA, the omnidirectional mode is used when nodes exchange control packets (ATIM/A-ACK/A-RES) on the control channel while the directional mode is used for data transmissions. Moreover, directional mode is also used to warn the directional hidden nodes.

5. The proposed MMAC-DA protocol

We assume that there are N non-overlapping channels in the system. Each node has a single half-duplex transceiver which can either transmit or listen but cannot do both simultaneously. All nodes are time synchronized. The clock synchronization can be achieved by using GPS (Global Positioning System) or the IEEE 802.11 TFS (Timing Synchronization Mechanism) [3]. In addition, several clock synchronization protocols have been proposed in [17,18]. The synchronization overhead is small and the maximum clock offset can be achieved as 15 µs [18]. We adopt the time structure of IEEE 802.11 PSM where time is divided into beacon intervals. Each beacon is further divided into ATIM window and data window. One channel is defined as a Control CHannel (CCH) and the others are Data CHannels (DCHs). During the ATIM window, all nodes have to be on the CCH to exchange control packets for the handshake. Nodes can select one of N channels for data transmissions in data window. That means the CCH also is used for data transmissions only during the data window.

In our previous proposal [16], all nodes have to be on the control channel during the ATIM window while the other data channels are free. That means the channel resource of data channels is wasted during the ATIM window. So, we allows nodes to utilize the data channels during the ATIM window. When the network load is high, some nodes are on the control channel to exchange ATIM messages while the others are exchanging data packets on selected data channels. In other words, the data transmission can be extended to the next ATIM window. There are two transmission modes in our proposed MMAC-DA: Normal transmission (N-Tx) and Extended transmission (E-Tx), as shown in Fig. 9. Based on the network load, nodes decide the transmission mode. Note that, since the ATIM window is used for exchanging ATIM messages on the control channel, the Extended transmission is not available on the control channel.

5.1. Main idea

Fig. 10 shows the idea of the proposed MMAC-DA protocol. During the ATIM window, nodes perform 3-way ATIM (ATIM/A-ACK/A-RES) handshake in omnidirectional mode to select the data channel and transmit DRES messages in directional mode to warn the hidden neighbor nodes. Source node S transmits the ATIM message which

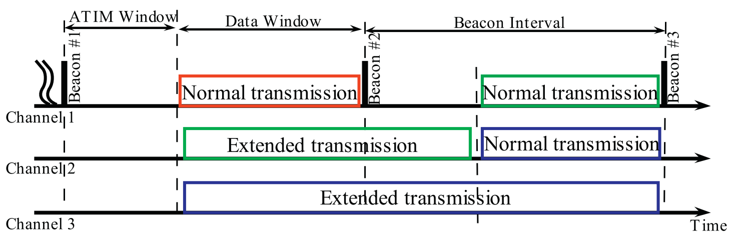

Fig. 9. An example of transmission modes.

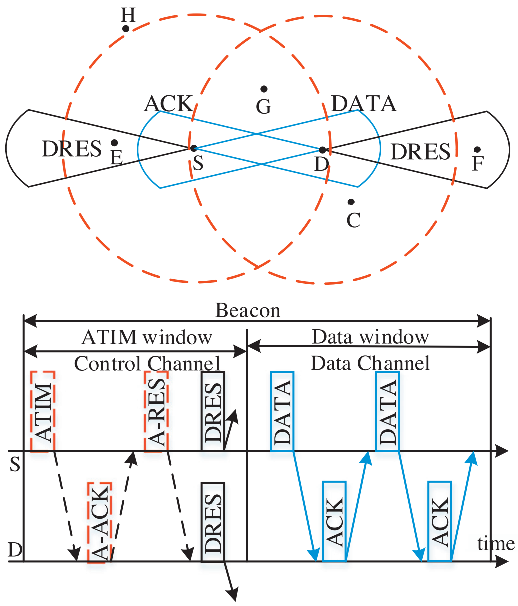

Fig. 10. The idea of MMAC-DA.

contains the information about the available channels in its point of view. After receiving the ATIM message, destination node D determines the beam direction toward source node S and selects the data channel based on the determined beam direction, its available channel list and the source node S's available channel list. Destination node D replies the A-ACK (ATIM Acknowledgment) to source node S. The A-ACK includes the selected data channel information and the beam's direction (beam index). Upon receiving the A-ACK message, source node S confirms with the A-RES (ATIM Reservation). The A-RES has the same information with the A-ACK. After that, both source and destination nodes S and D transmit the DRES (Directional Reservation) to the opposite direction of destination node and source node, respectively. The neighbor nodes which overhear the A-ACK, A-RES and D-RES messages update their data structures accordingly.

Before any data transmission, nodes have to perform ATIM handshake to select a data channel as well as determine the beam direction. To keep track of the status of neighbor nodes and the availability of data channel, each node maintains its data structures, which are called Neighbor Information List (NIL) and Channel Usage List (CUL). The NIL shows the information of neighbor nodes while the CUL shows the channel availability.

Now, we show that how the proposed MMAC-DA protocol solves the MAC issues which are raised in Section 2. Most of MAC issues are addressed through the ATIM handshake during the ATIM window. A node gets the neighbor status by overhearing the ATIM/A-ACK/A-RES/DRES messages and maintaining the NIL. The NIL also helps to solve missing receiver. To avoid the hidden terminal problem and deafness problem, the ATIM messages are transmitted in omnidirectional mode and DRES message is transmitted in directional mode during the ATIM window before any data transmission. However, MMAC-DA does not address the head of line blocking problem.

Table 1
Node S's NIL.

Node	Next_ATIM
D	2
E	1
G	0
–	–

MMAC-DA exploits the multiple channels efficiently, improves the spatial reuse of wireless channel and provides collision-free transmissions on data channels at the price of the overhead of control packets and ATIM window size. MMAC-DA requires 3-way ATIM handshake and DRES transmission for channel negotiation and neighbor notification during the ATIM window. The ATIM window size which limits the number of successful ATIM handshake affects the network performance. Not all nodes can exchange ATIM messages to negotiate data channels during the short ATIM window. On the other hand, the channel will be left idle for much of the time after all nodes exchange the ATIM messages in the long ATIM window. However, similar to H-MMAC [7], the ATIM window should not be too short.

The details of MMAC-DA is described in the following sections.

5.2. Neighbor information list

The Neighbor Information List (NIL) is used to store the status of the neighbor nodes via Next_ATIM value. Table 1 shows an example of node S's NIL. Next_ATIM = 0 means that the corresponding neighbor node is available on the CCH during the current ATIM window. Otherwise, the neighbor node is exchanging data packets on data channel (E-Tx mode) or already performs the ATIM handshake with another node. A node cannot perform the ATIM handshake with its neighbor node whose Next_ATIM is not zero.

By overhearing the A-ACK/A-RES/DRES from a neighbor node, the transmission mode (Tx) is determined. Node updates its NIL by Algorithm 1. The N-Tx mode means that neighbor node is on the CCH in next ATIM window (one ATIM window), Next_ATIM = 1, accordingly. A neighbor node is on the CCH in next two ATIM windows for the E-Tx mode and Next_ATIM = 2. If a node is on the data channel in the ATIM window, it misses all control messages. So, it assumes that all nodes that are on the CCH (nodes which have Next_ATIM = 0) will use the E-Tx mode (Next_ATIM is updated by 2).

5.3. Channel usage list

Each node also has to maintain another data structure which stores the information about the available channels. The Channel Usage List (CUL) stores the available beam's direction of each channel. And the CUL is updated according to the overheard A-ACK, A-RES and DRES messages. Table 2 shows an example of CUL of nodes S and D. In the point of view of node S, there are two available directions 2 and M on the CCH. In some cases, node S does not know

Algorithm 1 Update node A's NIL in each ATIM window.

```
/*At the beginning of ATIM window*/
Next_ATIM ← Next_ATIM - 1 for all neighbors in NIL
if Node A is on the data channel then
  for All neighbor node i do
    if Next_ATIM[i] == 0 then
      Next_ATIM[i] ← 2 /*E-Tx assumption*/
    end if
  end for
else
  repeat
    if Receives A-ACK/A-RES/DRES from node i then
      /*Determines the Tx mode and updates NIL*/
      if N-Tx mode then
        Next_ATIM[i] ← 1
      else
        Next_ATIM[i] ← 2
      end if
      Updates CUL for the corresponding DCH
    end if
  until ATIM window ends
end if
```

Table 2
Channel Usage List—CUL.

(a) Node S		(b) Node D	
Channel	Beam's direction	Channel	Beam's direction
CCH	2, M	CCH	2, 4
DCH_1	1, 4, M	DCH_1	1, 3, M-1
DCH_2	2, M-1	DCH_2	2, M

about the location of node D, so it has to include the CUL in the ATIM message which is sent to node D.

Now, we explain how node D chooses the data channel with an example given in Fig. 8. When node D receives node S's CUL, it has to perform the following steps:

1. Node D determines which direction it has to beamform to node S, i.e. $beam_{DS}$ based on the received signal of the ATIM message. For example, node D has to use beam #4 to communicate with node S, $beam_{DS} = 4$.
2. Node D also determines $beam_{SD}$ in which node S beamforms to node D $beam_{SD} = M$.
3. Node D chooses a common beam of a common data channel based on determined beams $beam_{DS}$, $beam_{SD}$, node S's CUL and its CUL (Table 2) through Algorithm 2. The CCH is selected with $beam_{DS} = 4$ (while $beam_{SD} = M$).
4. Node D sends the A-ACK including the selected channel and beam's direction $beam_{DS} = 4$.

In our proposed MMAC-DA protocol, we do not get benefit of directional antennas in terms of transmission range. The source and destination nodes are in the transmission range of the omnidirectional antennas. However, we get the benefit of directional antennas in terms of data rate (higher received signal) and spatial reuse.

Algorithm 2 Algorithm to select DCH and beam index.

```
if Receives ATIM(CUL) from node S then
  Determines beam_DS and beam_SD
  for Data channel i do
    if beam_DS and beam_SD of DCH[i] exist in CUL of
    nodes D and S, respectively then
      Select_DCH = i
      Select_beam = beam_DS
      Break for loop
    end if
  end for
  Sends A-ACK including Select_DCH and Select_beam
end if
```

5.4. The operation of MMAC-DA protocol

The operation of MMAC-DA is illustrated in Fig. 10. We assume that node S has data packets for node D. The procedure of MMAC-DA is described as follows:

1. During the ATIM window, node S checks the status of node D in its NIL. If node D is available, it starts contending the control channel to send an ATIM. The ATIM message including the CUL and transmission mode Tx is transmitted to node D in omnidirectional mode. Otherwise, node S has to wait for the next beacon.
2. Upon receiving the ATIM message, node D determines the beam direction to node S and selects the data channel based on the determined beam direction, the sender S's CUL and its CUL. Then, node D replies with the A-ACK message including the selected data channel and beam direction in omnidirectional mode to node S.
3. Node S confirms the selected data channel and beam direction by sending the A-RES message including the selected data channel. Note that the beam directions of source node and destination node are different since they are in opposite directions.
4. Both nodes S and D transmit the DRES messages in directional mode in the opposite directions of the destination and source, respectively.
5. Neighbor nodes which overhear the A-ACK/A-RES/DRES messages update their CULs.
6. During the data window, nodes S and D switch to selected data channel to exchange data packets without any contention. The other nodes that do not exchange the ATIM messages successfully go to doze mode to save energy.

According to the operation of MMAC-DA, there is an overhead of using the ATIM window only on the control channel. All data channels are fully utilized. Moreover, when nodes exchange the ATIM message in the ATIM window successfully, they can transmit multiple data packets without any contention. It means that there is no contention overhead and control packet overhead for each data packet.

Fig. 11 shows an example of the operation of MMAC-DA. During the ATIM window, nodes C and D access the control channel and exchange ATIM messages successfully

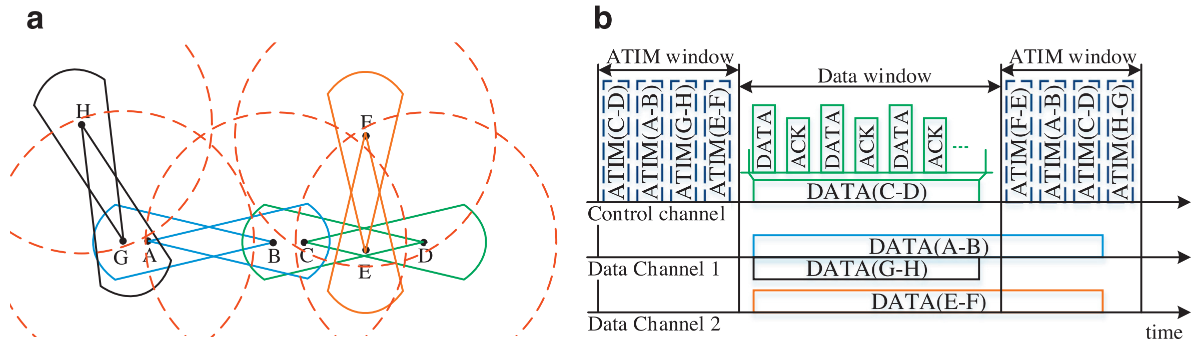

Fig. 11. An example of MMAC-DA.

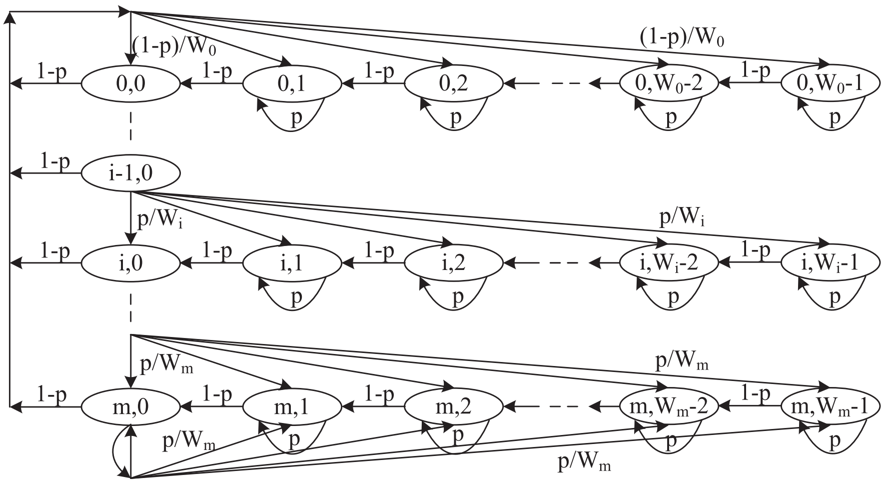

Fig. 12. Markov Chain model.

to select control channel for data transmissions during the data window. Node B overhears the A-RES and DRES messages from node C and updates its CUL in which the direction to node A on the control channel is not available. When nodes A and B exchange the ATIM messages, they cannot choose the control channel. So, they choose the data channel 1. However, nodes G and H may choose the same data channel 1 with nodes A and B since their transmissions are in different directions. And so on, nodes E and F select the data channel 2 for data transmissions. During the data window, nodes C and D still stay on the control channel, nodes A, B, G and H switch to data channel 1 and nodes E and F switch to data channel 2 for data transmissions.

6. Performance analysis

In this analysis, we assume there are N_{ch} available channels and N nodes. Since we analyze the saturation throughput, each node always has data packets to transmit.

We adopt the Markov chain model [19]. Let $b(t)$ and $s(t)$ be the stochastic process representing the back-off counter and back-off stage at slot time t, respectively. Let $W_i = 2^i \cdot W_0$ be the contention window of ith back-off stage, where $i \in [0, m]$, m is the maximum back-off stage. We assume the conditional collision probability p is constant and independent. So, we can model the bi-dimensional process $s(t)$, $b(t)$ with the discrete-time Markov chain, as shown in Fig. 12. The only non-null one-step transition probabilities are

$$\begin{cases} P\{0,k|i,0\} = (1-p)/W_0, & 0 \le k \le W_0 - 1, \quad 0 \le i \le m, \\ P\{i,k|i-1,0\} = p/W_i, & 0 \le k \le W_i - 1, \quad 1 \le i \le m, \\ P\{i,k|i,k+1\} = 1-p, & 0 \le k \le W_i - 2, \quad 0 \le i \le m, \\ P\{i,k|i,k\} = p, & 1 \le k \le W_i - 1, \quad 0 \le i \le m, \\ P\{m,k|m,0\} = p/W_m, & 0 \le k \le W_m - 1. \end{cases} \tag{1}$$

Let $b_{i,k} = \lim_{t\to\infty} P\{s(t) = i, b(t) = k\}, 0 \le i \le m, 0 \le k \le W_i - 1$ be the stationary distribution of the Markov chain. From the Markov chain, we can obtain

$$b_{0,0} = \frac{2(1-p)^2(1-2p)}{(1-2p)(1+W_0) + pW_0(1-(2p)^m)} \tag{2}$$

As a packet is transmitted when the back-off counter is zero, regardless of the back-off stage, the probability τ that node transmits in a time slot is

$$\tau = \sum_{i=0}^{m} b_{i,0} = \frac{b_{0,0}}{1-p} = \frac{2(1-p)(1-2p)}{(1-2p)(1+W_0) + pW_0(1-(2p)^m)} \tag{3}$$

The conditional collision probability p is the probability that more than one node transmits in a time slot and can be expressed as

$$p = 1 - (1-\tau)^{N-1} \tag{4}$$

The probability p_{ilde}, p_{busy}, p_{suc} and p_{col} in each time slot during the ATIM window are given as

$$\begin{cases} p_{idle} = (1-\tau)^N \\ p_{busy} = 1 - p_{idle} = 1 - (1-\tau)^N \\ p_{suc} = N\tau(1-\tau)^{N-1} \\ p_{col} = p_{busy} - p_{suc} = 1 - (1-\tau)^N - N\tau(1-\tau)^{N-1} \end{cases} \tag{5}$$

The duration for a collision transmission T_{col} and for a successful transmission T_{suc} are

$$\begin{cases} T_{col} = T_{atim} + T_{difs} \\ T_{suc} = T_{atim} + T_{atim\_ack} + T_{atim\_res} + T_{dres} + 3 \cdot T_{sifs} + T_{difs} \end{cases} \tag{6}$$

The expected time for a successful ATIM handshake E_{suc}

$$E_{suc} = \frac{p_{idle}}{p_{suc}}\sigma + \frac{p_{col}}{p_{suc}}T_{col} + T_{suc} \tag{7}$$

Once source and destination nodes perform ATIM handshake successfully, they do not contend the default channel any more. So, there are $N-2$ nodes continue contending the default channel. The number of contending nodes is decreased after every successful ATIM handshake until all nodes finish their handshakes or the ATIM window ends. Accordingly, we get the number of successful ATIM handshake N_a during the ATIM window T_{atim_window}. Let N_{con} be the possible concurrent transmissions on each channel. N_{con} depends on the number of beams M and node density. For N_{ch} channels, there are $N_{con}.N_{ch}$ possible concurrent transmissions in the network. Each source node can choose either Normal transmission mode or Extended transmission mode. However, there is only Normal transmission mode on default channel. The average number of data packets transmitted in Normal and Extended transmission mode in each beacon are D_n and D_e, respectively. With the average length of data packet is L, the average aggregate throughput can be calculated as

$$S = \frac{0.5\frac{\min(N_a, N_{con}.N_{ch})}{N_{ch}}[(N_{ch}+1)D_n + (N_{ch}-1)D_e]L}{T_{beacon}} \tag{8}$$

Since the ATIM window size affects the number of successful ATIM handshakes, the optimal ATIM window size $T^*_{atim\_window}$ needs to be estimated in order to maximize the number of concurrent transmissions N_{tx}, where

$$N_{tx} = \min\left(\frac{T^*_{atim\_window}}{E_{suc}}, N_{con}.N_{ch}\right) \tag{9}$$

Table 3
Simulation's Parameters.

Parameters	Value
Number of channels	3 channels
Number of beams	4 beams
Beacon interval/ATIM window	100 ms/20 ms
SIFS/DIFS/Slot time	16 µs/34 µs/9 µs
ATIM	28 bytes
A-ACK	16 bytes
A-RES	16 bytes
DRES	16 bytes
Basic rate	1 Mbps
Data rate	2 Mbps
Data packet size	512 bytes
Retry limit	4
Transmission range	250 m
Transmit/Receive power consumption	1.65 W/1.4 W
Idle/Doze power consumption	1.15 W/0.045 W

Now, we validate our analytical model through extensive simulations. All nodes are in the transmission range of each other. The simulation parameters are given in Table 3. *nCmB* denotes n channels and m beams.

Fig. 13 shows the saturated throughput of MMAC-DA with different number of channels and antenna beams. More channels and/or more beams helps MMAC-DA to provide more concurrent transmissions. Nodes have more chance to transmit data packets, aggregate throughput increases. With the same number of channels, when the number of antenna beams increases, the concurrent transmissions increases and the aggregate throughput increases. Also, with the same number of beams, the aggregate throughput increases when the number of channels increases. However, the ATIM window also affects the number of concurrent transmissions.

Since the ATIM window limits the number of successful ATIM handshake, it impacts the network performance, as shown in Fig. 14. There is no data packet transmitted during the ATIM window on the control channel. The longer ATIM window, the smaller data window. The ATIM window limits the number of ATIM handshakes while the data window limits the number of data packets transmitted on control channel. When the ATIM window size is short, only few nodes perform the ATIM handshakes successful to reserve a data channel with a certain beam. So, the aggregate throughput increases as the ATIM window size increases until the optimal value. The optimal value means that the ATIM window is lone enough for nodes to exchange ATIM messages. If the ATIM window increases after the optimal value, the aggregate throughput decreases slowly since the data window decreases. So, the ATIM window should be adjusted adaptively to achieve high performance according to the observed network conditions.

7. Performance evaluation

In this section, we have evaluated IEEE 802.11 [3], MMAC [5], H-MMAC [7] and our proposed MMAC-DA protocol by our developed event-driven simulation in Matlab. The time resolution of the simulation program is exactly

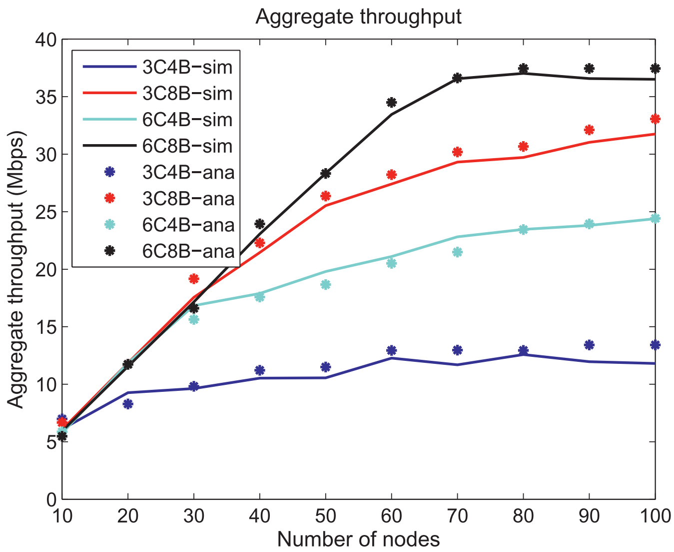

Fig. 13. Saturated throughput of MMAC-DA.

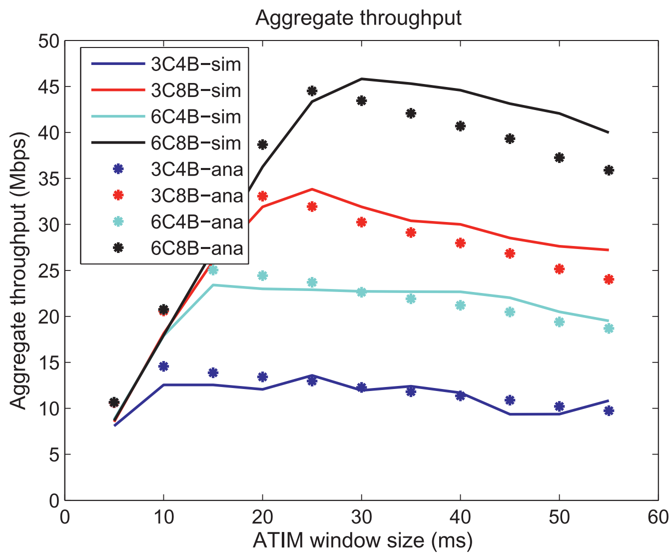

Fig. 14. Impact of ATIM window size.

the minimum time unit (1 μs) specified in IEEE 802.11 standard.

7.1. Simulation model

The simulations are conducted with 100 nodes which are placed in a 500 m × 500 m area. Each node selects the neighbor node within its transmission range to form a sender–receiver pair. A node generates and transmits a constant-bit-rate traffic to its receiver. An antenna in each node can operate in either directional mode or omnidirectional mode. The other simulation parameters are given in Table 3. Each simulation is conducted in 10 s and the simulation results are the average of 100 runs of different topologies.

In the simulation, Jain's fairness index is used as one of performance metrics. We use the following metrics to evaluate the TCP performance of different protocols.

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

$$\text{Packet\_Delivery\_Ratio} = \frac{\text{Packet\_Received\_by\_Receiver}}{\text{Packet\_Generated\_by\_Sender}}$$

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

$$\text{Fairness\_Index} = \frac{(\sum \text{Throughput}_i)^2}{\text{Number\_Node} * \sum \text{Throughput}_i^2}$$

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

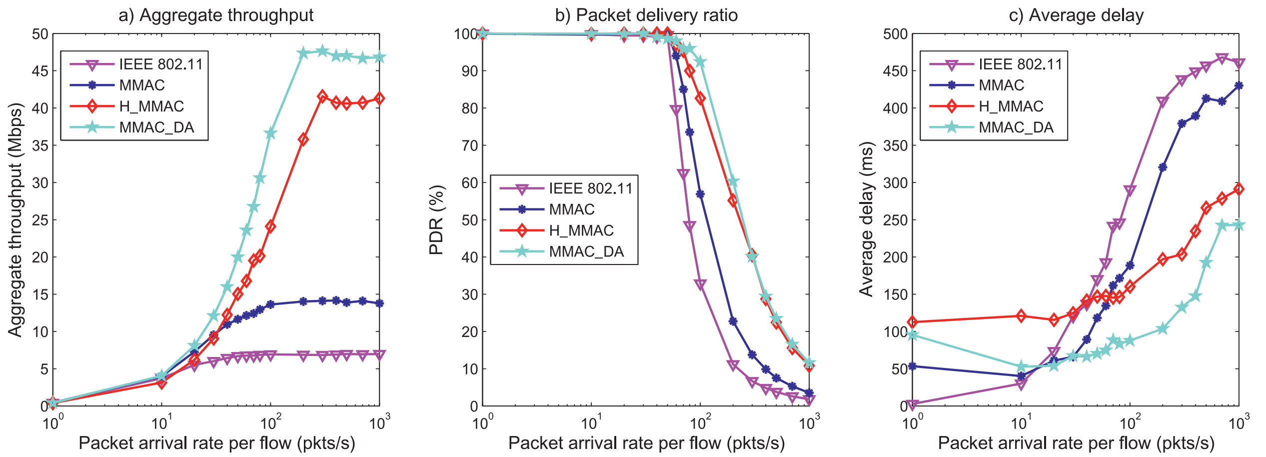

Fig. 15. Performance comparison of different protocols.

7.2. Simulation results

Fig. 15 shows the performance comparison of different protocols in terms of aggregate throughput, packet delivery ratio and average delay. The network load increases as the packet arrival rate increases. As shown in Fig. 15(a), the aggregate throughput of different protocols are similar when the packet arrival rate is low. However, when the network goes near saturation, MMAC-DA provides higher aggregate throughput than the others. Since MMAC, H-MMAC and MMAC-DA exploit multiple channel resources, they provides more concurrent transmissions than IEEE 802.11 which supports single channel. H-MMAC can utilize the multiple channels efficiently, but it does not have high spatial reuse as well as support collision-free transmissions on data channel. By using the directional antennas as well as exploiting multiple channel resources in data transmissions, MMAC-DA allows more nodes to transmit data packets simultaneously. Moreover, after nodes perform the ATIM handshake successfully to select data channel with determined beam direction, nodes can transmit multiple data packets without any collision during the data window. In other words, MMAC-DA reduces the overhead of control packets in data transmissions on the data channels during the data window. That is why MMAC-DA has higher aggregate throughput than the multi-channel MAC MMAC and H-MMAC protocols and the single channel MAC IEEE 802.11 protocol.

The packet delivery ratio (PDR) of different protocols is shown in Fig. 15(b). Obviously, when the packet arrival rate increases, more nodes contend the channel to transmit the data packets or to reserve the data channel. Collision probability increases and causes packet loss. Moreover, data packets are dropped due to limited queue size. Therefore, the PDR decreases as the packet arrival rate increases. The multi-channel MAC protocols MMAC, H-MMAC and MMAC-DA reduce the contention level by distributing nodes over different channels and provides more concurrent data transmissions on different channels. MMAC, H-MMAC and MMAC-DA thus achieve the higher PDR than IEEE 802.11. Using the directional antenna to improve the spatial reuse of wireless channel, MMAC-DA supports more concurrent data transmissions on each channel. For that reason, MMAC-DA has higher PDR than MMAC.

Fig. 15 (c) shows the average delay of different protocols. When the packet arrival rate is too low, IEEE 802.11 has low delay than MMAC, H-MMAC and MMAC-DA. In IEEE 802.11, when a node has a data packet to transmit, it contends the channel to transmit the data packet. In MMAC and H-MMAC, if a node which is in doze mode has a data packet, it has to wait for the next ATIM window to select a data channel. Then, it contends the selected data channel during the data window to send the data packets. That is why, MMAC and H-MMAC have longer delay than IEEE 802.11 when the network load is very low. Similarly, a node only can transmit a data packet after it performs the ATIM handshake successfully in the ATIM window. Nodes share the data channel, contend the data channel to transmit data packet while nodes do not share the data channel after they reserve the data channel successfully in the ATIM window. When the network load is high, the multi-channel MAC protocols support more concurrent data transmissions than single channel MAC. It results in the low delay in multi-channel MAC protocols. The more concurrent data transmissions, the lower delay.

Power consumption is one of important issues in wireless ad hoc network since nodes are usually powered by battery with limited capacity. By adopting IEEE 802.11 PSM, MMAC, H-MMAC and MMAC-DA gain the efficiency of energy consumption, as shown in Fig. 16(a). In these protocols, nodes do not have data packets to exchange go to doze mode in the data window to save energy. But node stays awake (idle state) even though it does not have any data packet to exchange in IEEE 802.11. Node consumes 0.045 W in doze mode which is smaller than 1.15 W in idle mode. Consuming less power and transmitting more data packets, MMAC-DA consumes less energy per data packet (512 bytes).

The last performance metric is Jain's fairness index, as shown in Fig. 16(b). In the CSMA-based IEEE 802.11 MAC protocol, if nodes always exchange data packets, other nodes may not have chance to access the channel due to the starvation problems [1]. That is why IEEE 802.11 has lower Jain's fairness index. In the multi-channel MAC

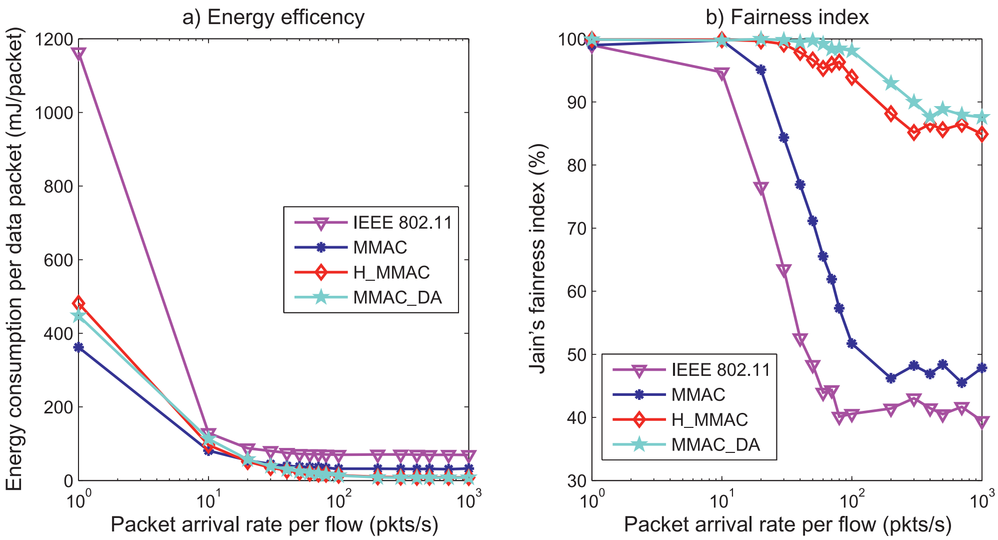

Fig. 16. Performance comparison of different protocols.

protocols, multiple channels are exploited, and nodes have more chance to transmit their data packets. Especially, MMAC-DA has a high spatial reuse to give more chance to nodes to transmit data packets. In MMAC, H-MMAC and MMAC-DA, even though nodes have many data packets to transmit, they have only to reserve the data channel once during the ATIM window. After nodes exchanged ATIM messages successfully, other nodes have chances to exchange their ATIM messages. Therefore, MMAC, H-MMAC and MMAC-DA have high Jain's fairness index.

8. Conclusions

In this paper, we propose a new MAC protocol, named MMAC-DA, by combining the multi-channel MAC with directional antennas. MMAC-DA can exploit the multiple channel resources and increase the spatial reuse of wireless channel. The trade-off is the time synchronization and the overhead of the ATIM window. The simulation results show that MMAC-DA can improve network performance in terms of aggregate throughput and packet delivery ratio and energy efficiency.

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