Multi-channel MAC protocol with Directional Antennas in Wireless Ad hoc Networks

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***Abstract*—IEEE 802.11 Distributed Coordination Function (DCF) is based on Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA). However, the CSMA-based access 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 and energy efficiency.**

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

I. 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] such as hidden node starvation, asymmetric sense starvation and carrier sense starvation. IEEE 802.11 [2] provides multiple channels at Physical layer 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 [3], Split Phase [4], [5], Common Hopping and Parallel Rendezvous. Each node has two transceivers in Dynamic Channel Assignment (DCA) [3]. One transceiver is tuned to control channel for exchanging control packets while another can switch to any data channel for data transmissions. Both Multi-channel MAC (MMAC) [4] and Hybrid Multi-channel MAC (H-MMAC) [5] adopt IEEE 802.11 PSM in which the ATIM is used for exchanging control packets. H-MMAC allows nodes to use the ATIM window for data transmissions to utilize the channel resources efficiently.

In Power Control MAC (PCM) [6], nodes increase the transmission power periodically during the data transmission in order to warn nodes in the carrier sensing range. The SINR-based transmission power control (STPC-MAC) [7] 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. The power control algorithm is combined with multi-channel MAC protocols to mitigate the starvation in wireless ad hoc network in [1], [8].

In addition to two above approaches, using directional antennas can improve the spatial reuse. Dai *et al.* [9] present an overview of using directional antennas in wireless network. The Directional Virtual Carrier Sensing (DVCS) [10] 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. The proposal in [11] 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. All RTS/CTS packets are transmitted in directional mode in Multi-hop Directional RTS MAC (MMAC) [12]. 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) [13] with two patterns: continuous and ON/OFF patterns.

In this paper, we propose a multi-channel MAC protocol with directional antennas (MMAC-DA). Similar to MMAC [4] and H-MMAC [5], 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 channels.

The rest of this paper is organized as follows. In Section II, 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 III. The antenna model is presented in Section IV. Section V describes the detailed MMAC-DA protocol. The performance evaluation is given in Section VI. Finally, we conclude our paper in Section VII.

II. MAC issues with multi-channel and directional antennas

A. *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.

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

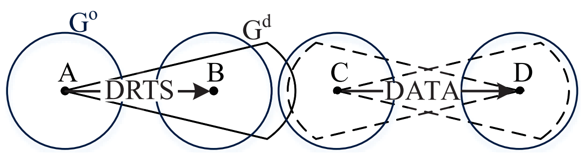

Fig. 1: Hidden terminal due to the asymmetric antenna gains.

In Fig. 2, while nodes A and B are exchanging data packets, nodes C and D perform the 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.

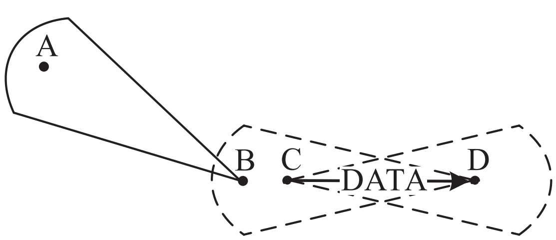

Fig. 2: Hidden terminal due to the unheard RTS/CTS.

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 RTS/CTS handshake to select data channel 1. After finishing the transmission, both

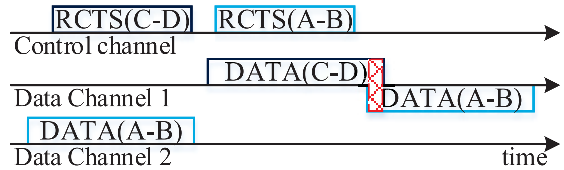

Fig. 3: Multi-channel hidden terminal problem.

nodes A and B switch back to control channel and they have data packets to exchange. 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.

C. *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.

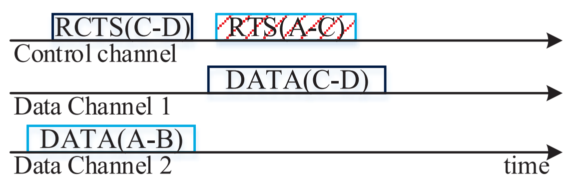

Fig. 4: Missing receiver due to multi-channel environment.

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 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.

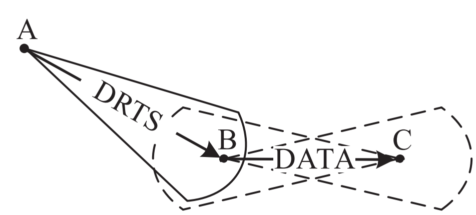

Fig. 5: Deafness due to directional antennas.

D. *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 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.

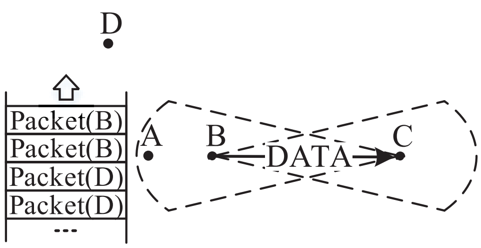

Fig. 6: Head of Line blocking problem.

III. IEEE 802.11 Power Saving Mechanism

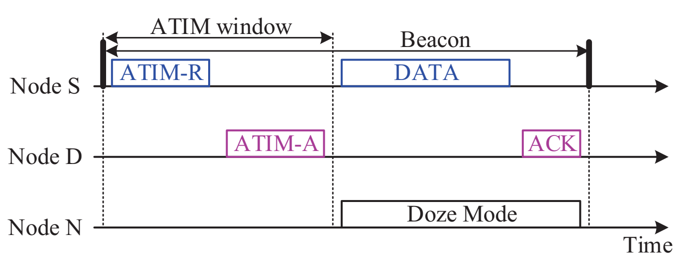

Fig. 7: The operation of IEEE 802.11 PSM.

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 while other nodes which do not have packets to send or receive go to doze mode to save energy. In doze mode, a node consumes much less energy compared to idle mode, but it cannot send or receive packets.

IV. 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.

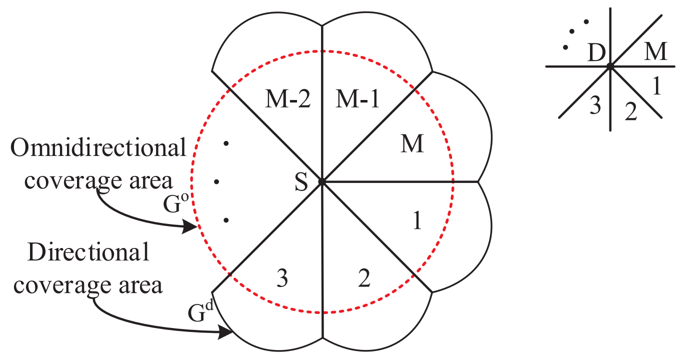

Fig. 8: Antenna model.

V. The proposed MMAC-DA protocol

We assume that there are N non-overlapping channels in the system and all nodes are time synchronized. 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. That means the CCH also is used for data transmissions during the data window.

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 contains the information about the available channels in its point of view. After receiving the ATIM message, destination node R 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 R 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 R 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.

A. Neighbor Information List

The Neighbor Information List (NIL) is used to store the status of the neighbor nodes: Busy (1) or Available (0). By overhearing from the A-ACK/A-RES/DRES that a neighbor node is going to exchange data packets during the data window, node marks Busy in its NIL for that neighbor. Table I shows an example of node S's NIL.

TABLE I: Node S's NIL

Node	Status
D	0
E	1
G	0
...	...

B. 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 II 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 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. 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 based on the received signal of the ATIM message. For example, node D has to use beam #4 to communicate with node S.
2) Node D converts node S's CUL into its point of view. For each beam i in node S's CUL, new converted beam $j = (i + M/2) \bmod M$.
3) Based on determined beam (step 1), converted node S's CUL (step 2) and its CUL, node D lists the common beams for each channel.
4) Node D chooses a common beam and sends the A-ACK including the selected channel and beam's direction.

TABLE II: Channel Usage List - CUL

(a) Node S

Channel	Beam's direction
CCH	2, M
DCH_1	1, 4, M
DCH_2	2, M-1

(b) Node D

Channel	Beam's direction
CCH	2, 4
DCH_1	1, 3, M-1
DCH_2	2, M

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.

C. The operation of MMAC-DA protocol

The operation of MMAC-DA is illustrated in Fig. 9. We assume that node S has data packets for node D. The procedure of MMAC-DA is described as follows:

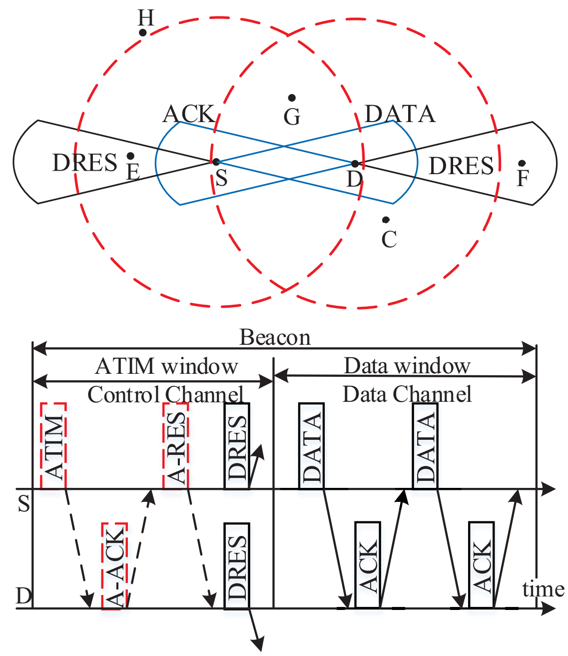

Fig. 9: The idea of MMAC-DA.

1) During the ATIM window, node S checks the status of node D in its NIL. If node D is available, it sends an ATIM including its CUL to node D in omnidirectional mode. Otherwise, node S has to wait for the next beacon.
2) Upon receiving the ATIM message, node D selects the data channel based on the sender S's CUL and its CUL. Then, node D replies with the A-ACK including the selected data channel and beam's direction in omnidirectional mode to node S.
3) Node S confirms the selected data channel and beam's direction by sending the A-RES including the selected data channel. Note that the beam's directions of source node and destination node are different since they are in opposite directions.
4) Both nodes S and D transmit the DRES 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 CUL.
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. During the ATIM window, only control packets are transmitted. The longer ATIM window, the more overhead. However, 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.

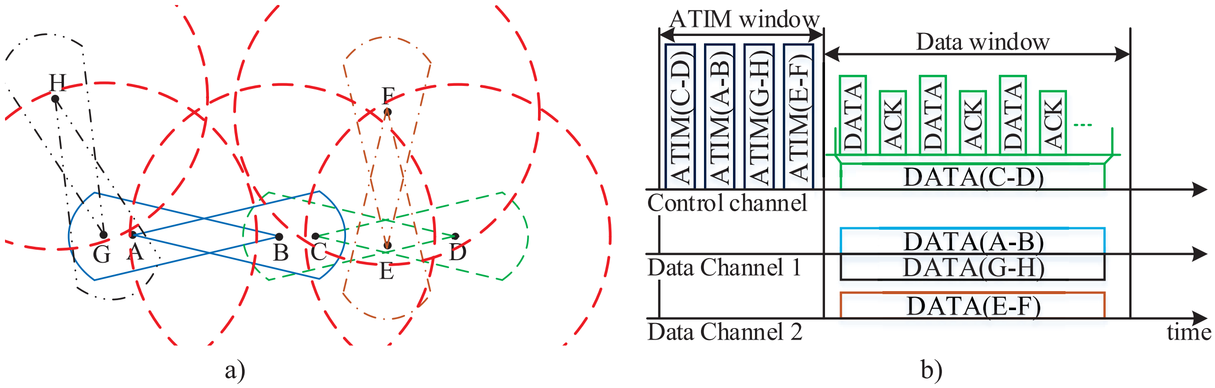

Fig. 10: An example of MMAC-DA.

Fig. 10 shows an example of the operation of MMAC-DA. During the ATIM window, nodes C and D access the control and exchange ATIM messages successfully to select control channel for data transmissions during the data window. Node B overhears the A-RES and DRES 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.

VI. Performance Evaluation

In this section, we have evaluated IEEE 802.11 [2], MMAC [4] and our proposed MMAC-DA protocol by our developed event-driven simulation in Matlab.

TABLE III: 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 / A-RES	16 bytes / 16 bytes
DRES	16 bytes
Basic rate / Data rate	1 Mbps / 2 Mbps
Data packet size	512 bytes
Retry limit	4
Transmit / Receive power consumption	1.65 W / 1.4 W
Idle / Doze power consumption	1.15 W / 0.045 W

A. Simulation model

The simulations are conducted with 50 nodes which are placed in a 500 m x 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 III. Each simulation is conducted in 10 seconds and the simulation results are the average of 100 runs of different topologies.

We use the following metrics to evaluate the performances of different protocols:

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

$$Packet\_Delivery\_Ratio = \frac{No\_Successful\_Packets}{Total\_Transmitted\_Packets}$$

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

B. Simulation results

Fig. 11 shows the performance comparison of different protocols in terms of aggregate throughput, packet delivery ratio and energy efficiency. As shown in Fig. 11(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 exploits multiple channel resources, it has more concurrent transmissions than IEEE 802.11 which supports single channel. By using the directional antennas in data transmissions as well as exploiting multiple channel resources, MMAC-DA allows more nodes to transmit data packets simultaneously. Moreover, after nodes perform the ATIM messages 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 the single channel MAC IEEE 802.11.

The packet delivery ratio (PDR) of different protocols is shown in Fig. 11(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

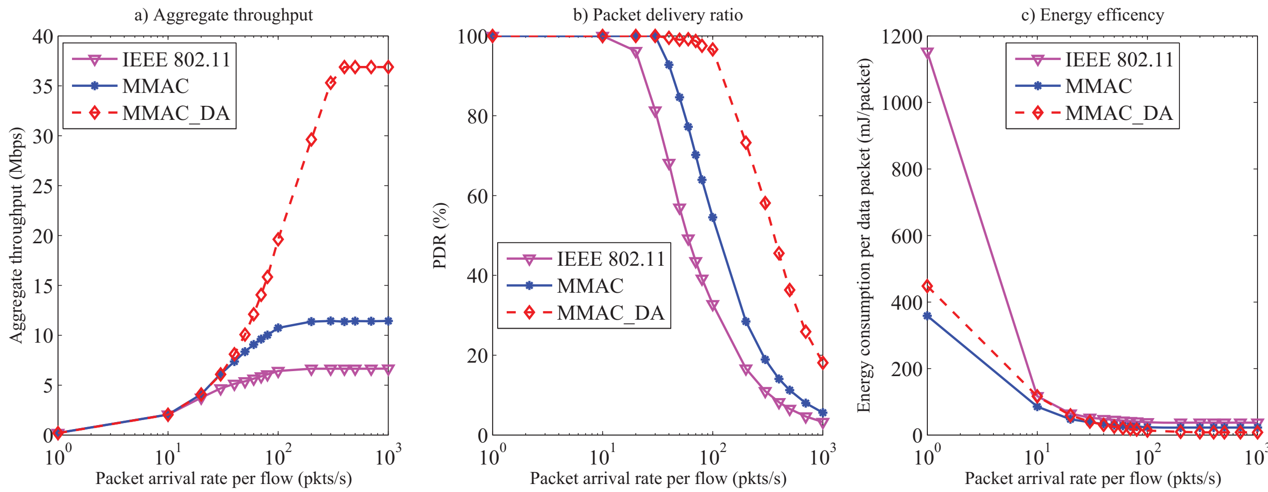

Fig. 11: Performance comparison of different protocols.

PDR decreases as the packet arrival rate increases. The multi-channel MAC protocols MMAC and MMAC-DA reduces the contention level by distributing nodes over different channels and provides more concurrent data transmissions on different channels. MMAC and MMAC-DA thus give 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.

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, both MMAC and MMAC-DA gain the efficiency of energy consumption. In MMAC and MMAC-DA, nodes do not data packets to exchange go to doze mode to save energy. In IEEE 802.11, node stays awake (idle state) even though it does not have any data packet to exchange. Node consumes 0.045 W in doze mode which is smaller than 1.15 W in idle mode. Fig. 11(c) shows the energy efficiency. MMAC-DA consumes less energy in order to transmit a data packet (512 bytes) successfully.

VII. 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 simulation results show that MMAC-DA can improve network performance in terms of aggregate throughput and packet delivery ratio and energy efficiency.

Acknowledgment

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