Multi-Channel Directional Medium Access Control for Ad Hoc Networks: A Cooperative Approach

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***Abstract*—Directional Medium Access Control protocols (DMACs) have been studied for decades. Since most existing DMACs assume an ideal antenna model which does not consider the minor-lobe interference, their performance cannot be guaranteed in practice. Other approaches assuming non-ideal antenna require either extra equipment or clock synchronization, making the system more complicated. It is also observed that directional transmission is rarely discussed in multi-channel scenarios. In this paper, a Cooperative Multi-channel Directional Medium Access Control protocol (CMDMAC) is proposed, incorporating directional transmission and multi-channel transmission to enhance system performance. Without making the terminals more complex or requiring clock synchronization, CMDMAC uses cooperative methods to solve the hidden terminal and deafness problems, taking into account minor-lobe interference effects of the directional antennas. Protocol performance is studied via simulation in NS2, showing that CMDMAC has good performance in terms of throughput and data packet transmission ratio.**

I. Introduction

Directional transmission and multi-channel transmission have been introduced to increase the spatial sharing and enhance the overall capacity of the networks. To benefit from these techniques, efficient Medium Access Control (**MAC**) protocols are needed. The authors of [1]–[4] proposed using global synchronization or dedicated control message radio to solve the deafness and hidden terminal problems. The authors of [5], [7], [10] provided efficient directional MACs, while ignoring the minor-lobe effect of the directional antenna which is shown as non-negligible in [6], [9]. Within these works, researchers either used additional hardware dedicated for control message exchanges or network synchronization which schedules all terminals competing in the contention window to overcome the MAC design challenges. While the extra hardware makes the terminal complex, the global synchronization is difficult to achieve in a multi-hop ad hoc networking scenario. Moreover, we have found that methods to combine directional transmission and multi-channel transmission are rarely explored.

Cooperation was first proposed to solve the multi-channel collision problem in [12] demonstrating good performance.

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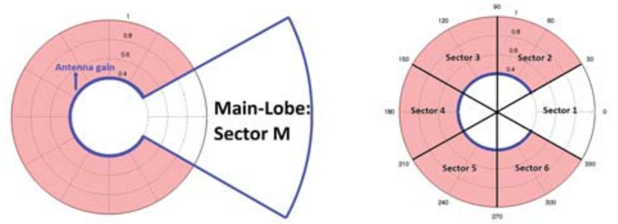

(a) Antenna gains model. (b) Antenna sector model.

Fig. 1. Antenna model with minor-lobe effect.

In this paper, we propose Cooperative Multi-channel Directional Medium Access Control protocol (**CMDMAC**) with the objective of improving the aggregate throughput of networks using multiple channels and directional transmissions jointly. The idea used to overcome the deafness and hidden terminal problems is that the decision becomes more accurate, if the terminals are provided with additional information from its cooperators. CMDMAC operates with one Control Channel (**CC**) and multiple Data Channels (**DC**s). As in [12], we assume that the radio can be tuned among different channels. Moreover, as in [6], [9], we assume that the antenna can work in both omni-directional and directional modes. All control messages are exchanged omni-directionally in the CC, and data packets are transmitted in directional mode in the DCs.

The main contributions of this work are as below:

1) Propose CMDMAC for multi-channel directional ad hoc networks, not requiring extra hardware or clock synchronization.
2) Solve deafness and hidden terminal problems for multi-channel directional ad hoc networks with cooperative methods.
3) Evaluate CMDMAC in terms of aggregate throughput and data packets transmission ratio.
4) Validate CMDMAC by comparison to other related MAC protocols.

The rest of this paper is organized as follows. In Section II, the system model is introduced. In Section III, we discuss directional and multi-channel MAC design. In Section IV, we present the details of the proposed CMDMAC. In Section V, we evaluate the performance of CMDMAC and compare it to

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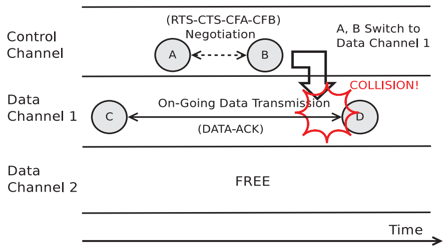


Fig. 2. System model illustration and the multi-channel hidden terminal problem.

other MAC protocols via simulations. Conclusions are drawn in Section VI.

II. System Model

In this section, we introduce the antenna model and system model employed in this paper.

A. Antenna Model

The most widely used directional antenna model is employed [14] . As shown in Fig. 1(a), the main-lobe and minor-lobe gains of the antenna are assumed to be non-zero identical values. The antenna consists of M non-overlapping sectors. For example, M equals 6 in Fig. 1(b). Direction of Arrival (DoA) and Received Signal Strength Indication (RSSI) techniques are assumed to be used. Further, the antenna is assumed to be capable of switching among different sectors and omni-/directional mode without delay [7], [8].

B. System Model

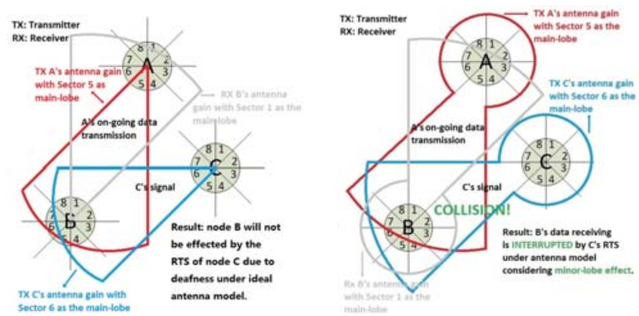
An asynchronous ad hoc network which works in unlicensed band is considered. Multiple independent channels are available in the system, while one of them is selected for control message exchanges and others are used for the data packet transmissions as shown in Fig. 2. Link establishment negotiations are done in the omni-directional mode in the CC, while the data packets are transmitted and received directionally in the DCs. Each terminal is equipped with a single half-duplex transceiver which can be tuned among all the channels.

III. Problems in Multi-Channel Directional MAC

In this section, we introduce the challenges in multi-channel directional MAC design when taking the minor-lobe interference effect into consideration.

A. Vulnerability of the Receivers

The vulnerability of receivers means interference from all directions can interrupt the on-going data reception. The case when ideal antenna model is used is shown in Fig. 3(a), B is receiving from A. As C is in receiver B's minor-lobe Sector 2 and the antenna gain for Sector 2 is 0, there will be no interference from C to B thus no packet collision. For the case when the minor-lobe effect is considered, as in Fig. 3(b), B is receiving from A. The interference from C to B is non-zero, which may result in potential packet collisions.



(a) Interference-free receiver with ideal antenna model.

(b) Vulnerability of receiver with considering minor-lobes.

Fig. 3. Minor-lobe interference to receivers.

B. Multi-Channel Directional Hidden Terminal Problem

First, an example is used to explain the directional hidden terminal problem with single DC. In Fig. 4, A, B, C and D are engaged in data transmission while node E, F establish their link. After transmissions on Link 1 and Link 2 are completed, B wants to transmit to C. Without knowing the existence of Link 3, the new directional link may bring collision to E. Second, we discuss the multi-channel hidden terminal problem with omni-directional transmission. In Fig. 2, node A, B are carrying out the negotiation in the CC without knowing that C, D are communicating in the DC 1. Meanwhile, DC 2 is free. If A, B switch to DC 1 for data transmission, it is obvious that they may bring collision to the current link of C, D. The situation in this work is a combination of the above two cases. In Fig. 4, let's assume there are two DCs. If the new Link 4 is in DC 2 while Link 3 is in DC 1, there will be no collision. For the case in Fig. 2, let's assume A, B, C, D are located as two parallel link, like Link 4 and Link 5 in Fig. 4. Even if the link of C, D is in DC 1, the two links can co-exist.

C. Deafness Problem

In the multi-channel directional networking environment, deafness is caused by missing the negotiation information of the intended receiver. The transmitter may keep sending requests, which wastes the CC resources and reduces the system performance.

D. Collision due to Different Gains

For the reason that transmission and interference ranges in directional and omni-directional mode are different, a node may interfere with another node much farther than its omni-directional transmission range. This is due to the coexistence of omni-directional and directional mode [7].

IV. CMDMAC Protocol Design

The details about CMDMAC are described in this section. To protect the data reception from the control message frames, separated control and DCs are used. To reduce the collision due to different gains, power adaption is used to guarantee the transmission ranges in CC and DCs to be the same value.

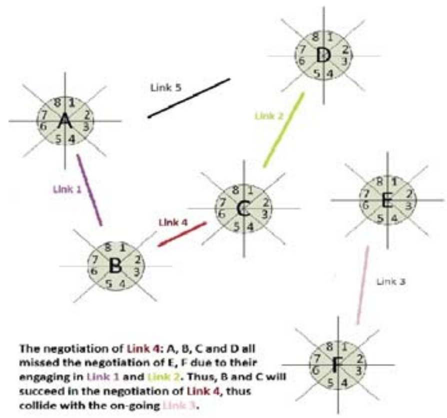


Fig. 4. The directional hidden terminal problem.

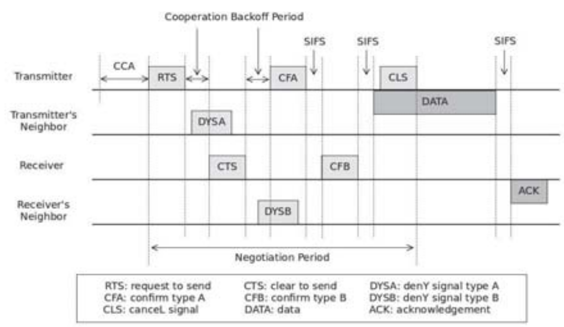


Fig. 5. Negotiation procedures and data channel handshake of CMDMAC.

A. Negotiation Procedure for Link Establishment

We show the four-way CC handshake and define the frame abbreviations, e.g. RTS, CFA and etc, in Fig. 5. A transceiver (**TX**) initializes a negotiation by sending an RTS. Upon correctly receiving the RTS, the receiver (**RX**) checks its Directional Network Allocation Vector (DNAV) [5] to see whether this request should be accepted. If the RX identifies that there are active nodes in the expected sector, it prepares a DYSA; otherwise, it prepares a CTS. At the same time, the TX's other neighbors, who overhear the RTS, also check their DNAVs and the Neighbor Information Table (**NIT**). (See Subsection C for the NIT.) If a neighbor recognizes that the current negotiation will build a link which may collide with certain on-going data transmission, it prepares a DYSA; otherwise, it keeps silent. Then, the TX's cooperators with DYSAs enter the Cooperation Backoff Period (**CBP**) and execute a CSMA-based contention mechanism. They randomly back off and the one with shortest backoff period sends out its DYSA. If the medium is busy after the CBP, the RX cancels its CTS.

If the CTS is not correctly received by the TX, the negotiation ends; otherwise, the TX prepares the CFA to announce the establishment of the new link. Meanwhile, the RX's neighbors who overhear the CTS also check their DNAVs to see whether they should veto to block the expected link. If certain neighbor identifies that this expected link may collide an on-going data transmission, it prepares a DYSB. After the CTS, the RX's cooperators with DYSBs enter the second CBP. If there is no DYSB and CFA is correctly received by the RX, the RX sends the CFB to confirm the link establishment. In a few cases that TX sends the CFA but receives no CFB, it needs to send the CLS to invalidate previous CFA. Correct receptions of both RTS and CFA (or both CTS and CFB) with no CLS means successful link establishment. The nodes which overhear the new link establishment update their DNAVs. With successful negotiation, certain pairs of nodes switch to the DC and start to transmit after a Short Inter-Frame Space (SIFS). As in the original 802.11, if the data packet is correctly received, the RX replies with an acknowledgement frame (**ACK**).

A negotiation which consists of potential hidden terminals will be stopped by the DYSA/DYSB. That is, the multi-channel directional hidden terminal problem is solved. Moreover, with receiving the DYSA/DYSB, the TX knows the reason why it cannot start this link and can make further decision. That is, the deafness problem is solved.

B. Neighbor Information Table

Node Index	1-Hop Information: Neighbor Index (Sector, Too-Close)
G	E(2, 0), F(4, 0), B(7, 0), C(8, 1)
E	F(5, 0), G(6, 0), C(6, 0), D(8, 0)
F	E(1, 0), G(8, 0), C(8, 0)
B	C(2, 0), E(2, 0), G(3, 0), A(8, 0)
C	D(1, 0), E(2, 0), G(4, 1), F(4, 0), B(6, 0), A(7, 0)

TABLE I
NEIGHBOR INFORMATION TABLE

A Neighbor Information Table (**NIT**) which contains two-hop neighbors' relative location information is kept by each of the terminals. We show an example in Table I according to node G in Fig. 6. Take C(8, 1) in Node Index G's row as an instance: 8 means that C is G's Sector 8, and 1 means C is G's too-close neighbor. We define a concept called *too-close*, which means two neighboring nodes can interfere with each other through their minor-lobes. For example, let's assume C is transmitting in the DC with sector 6 and G is receiving in the DC with sector 4 in Fig. 6. That is, they do not use their main-lobes to point towards each other. As they are too-close nodes, the minor-lobe interference of C can still collide with G's current reception. (See Section V for calculating too-close range.) A node can build its one-hop NIT by receiving frames from neighboring nodes with DoA and RSSI, and broadcast this information within the management frames. Thus, all the nodes can build the two-hop NIT. For the static topology in this paper, it is assumed that two-hop neighbor information is provided by the management frames of an upper layer protocol.

C. Node Cooperation

We show an example to illustrate how CMDMAC works in Fig. 6. Link 3 was established in the DC 1 during the transmissions of Link 1 and 2. After the end of transmissions for Link 1 and 2, B wants to initialize a new transmission to

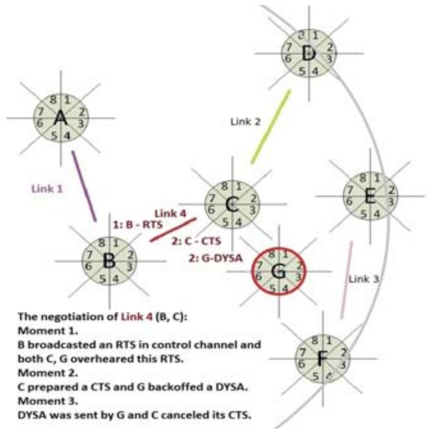


Fig. 6. An example to further illustrate the feature of cooperation.

RTS/CTS

FC	TX_ADDR	RX_ADDR	CH_NO	SEC_NO	SEQ_NO	FCS
(2 bytes)	(6 bytes)	(6 bytes)	(1 bytes)	(1 bytes)	(1 bytes)	(2 bytes)

DYSA/DYSB

FC	TX_ADDR	RS_ADDR	RS_CHSEC	TIME	UP_ADDR	UP_SEC	FCS
(2 bytes)	(6 bytes)	(6 bytes)	(2 bytes)	(2 bytes)	(6 bytes)	(1 bytes)	(2 bytes)

CFA/CFB

FC	UP_ADDR	UP_SEC	TIME	SEQ_NO	FCS
(2 bytes)	(6 bytes)	(1 bytes)	(2 bytes)	(1 bytes)	(2 bytes)

ACK/CLS

FC	SEQ_NO	FCS
(2 bytes)	(1 bytes)	(2 bytes)

Abbreviation List:

FC: frame control	TX_ADDR: transmitter address	RX_ADDR: receiver address
CH_NO: channel number	SEC_NO: sector number	SEQ_NO: sequence number
FCS: frame check sequence	RS_ADDR: reason node address	RS_CHSEC: active sector and channel
LF_TIME: left time	UP_ADDR: updated node address	UP_SEC: updated node sector

Fig. 7. Frame structures of CMDMAC.

C. Thus, B broadcasts an RTS in the CC and expects to start the transmission in the DC 2. Upon overhearing this RTS, C checks its DNAV and accepts this request by preparing a CTS. At the same time, neighbor G checks its DNAV and NIT, finding that E is active in B's expected sector of the expected DC. Thus, G backs off and replies with a DYSA. Upon receiving the DYSA, B and C know the information that E is working with RS_CHSEC (defined in Fig. 7) and may still work for TIME as recorded in the cooperation frame. Then, B can make its further decision based on current channel usage situation. As illustrated, neighboring nodes actively cooperate in the process of negotiation to identify the potential hidden terminals and deaf nodes. This helps to solve the hidden terminal and deafness problems asynchronously without extra devices.

D. Frame Structure

We show the formats of all the frames in Fig. 7. In the RTS/CTS, the expected DC and sector are included in the CH_NO and SEC_NO, respectively. The neighbors who overhear the RTS/CTS may know which DC and sector the negotiating pairs expect to use. Moreover, they also update the NITs based on the received information. In the CFA/CFB, the duration of the link is included in TIME. The neighbors who overhear these frames can update their DNAV according their local clocks. Further, UP_ADDR and UP_SEC are used to update the NITs. In the DYSA/DYSB, RS_ADDR identifies the active node who leads to this "veto" frame and TIME shows its remaining active time. ACK is the same as in IEEE 802.11 protocol. The structure of CLS is the same as ACK.

V. Performance Evaluation

We evaluate the performance of CMDMAC using NS2. For comparison, we define a non-cooperative version of CMDMAC called Non-Cooperative Directional MAC (NCDMAC). The only difference between CMDMAC and NCDMAC is whether or not the neighboring nodes cooperate in solving the directional hidden terminal and deafness problems. Specifically, the neighboring nodes do not send DYSA/DYSB to cooperate in NCDMAC.

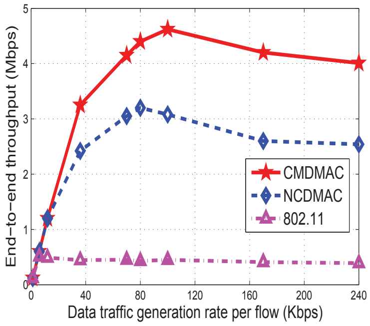
A. Simulation Configuration

The simulation parameters are shown in Table II. We use G_m and G_s to represent the antenna gains of the main-lobe and minor-lobe. The transmission and interference range are determined by the value of $\frac{G_m}{G_s}$ for the two-ray propagation model. Through the adaption of the TX powers for CC and DC, transmission ranges in both CC and DC are made 250m. K nodes are randomly located in the area and K non-disjoint flows (each node is the source and destination of one flow) are generated as data source. The capture effect is implemented based on the comparison of the received power in NS2. Each performance measurement reported below is averaged over 10 executions with randomly generated scenarios.

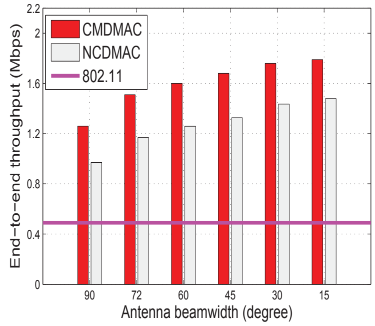
Simulator	NS2
TX power (CC/DC)	24.5 dBm/ 4.5 dBm
RX threshold	-64.375 dBm
Capture threshold	10 dB
Transmission rate	1 Mbps
Cooperation backoff period	40 μs
G_m/G_s	10 dB
Propagation model	two-ray model
Topology dimensions	500 m * 500 m
Simulation time	120 s

TABLE II
Simulation Parameters

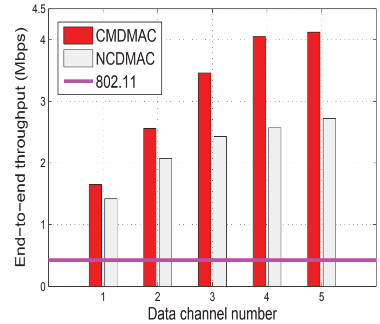
Two performance metrics are examined between CMDMAC and NCDMAC: i) end-to-end (aggregate) throughput, ii) data packet transmission ratio, defined as the ratio of correctly received packets towards sent packets in MAC layer. We take the average aggregate throughput as it is a popular metrics, and it can reflect the average end-to-end delay for the unsaturated networking cases. We take data packet transmission ratio, as it is a one-hop metric and can reflect how much our cooperation reduces the data packet collision. We also talk about saturation break point: all the data demands can be satisfied before this point; queues may be accumulated at some nodes after this point.



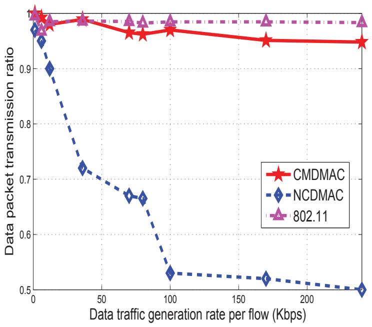
(a) Throughput results with different traffic loads. data channel number: 4; beam-width: 30°; nodes number: 100; packet payload size: 1500 bytes.



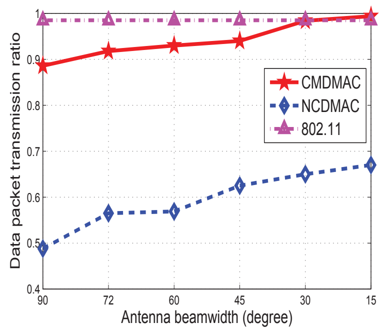
(b) Throughput results with different beam-widths. flow-rate: 240 Kbps; packet-size: 1500 bytes; data channel number: 1; node number: 50.



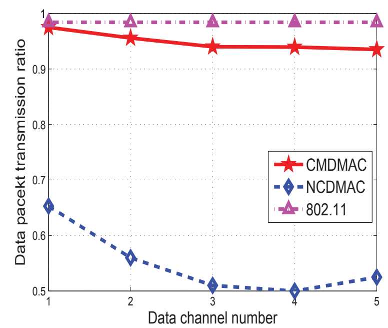
(c) Throughput results with different data channel numbers. beam-width: 30°; packet payload size: 1500; traffic loads: 240 Kbps.



(d) Data packet transmission ratio results with different traffic loads. data channel number: 4; beam-width: 30°; nodes number: 100; packet payload size: 1500 bytes.



(e) Data packet transmission ratio results with different beam-widths. flow-rate: 240 Kbps; packet-size: 1500 bytes; data channel number: 1; node number: 50.



(f) Data packet transmission ratio results with different data channel numbers. beam-width: 30°; packet payload size: 1500; traffic loads: 240 Kbps.

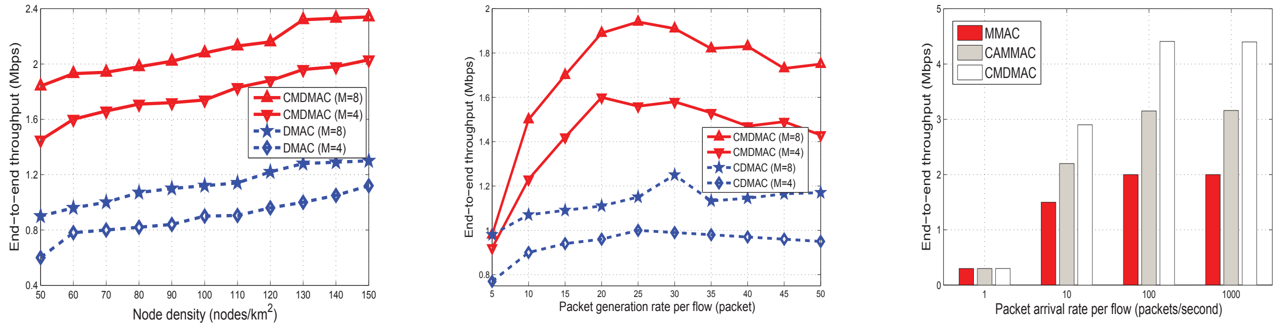
Fig. 8. Simulation with different traffic loads, beam-widths, and data channel numbers.

B. Simulation Results

In Fig. 8(a), it is clear that when the traffic load is light, the throughput is nearly the same for CMDMAC and NCDMAC. Then, we can see that the 802.11 quickly saturates at around 0.5 Mbps while CMDMAC and NCDMAC keeps going up. With the increase of the traffic load, the differences between CMDMAC and NCDMAC in the throughput become larger. CMDMAC outperforms NCDMAC by 42% at the saturation break point and 56% at heavy traffic load of 240 Kbps per flow. In Fig. 8(d), we see that CMDMAC outperforms NCDMAC for all the cases and NCDMAC's ratio keeps reducing as the traffic load becomes higher. Further, it is also noticed that 802.11 is better than both CMDMAC and NCDMAC in terms of data packet transmission ratio. This is because 802.11 is so conservative that a node keeps silent as long as there is another active node inside its carrier sensing range.

In Fig. 8(b) , it is shown that the throughput with wider beam-widths is smaller than that with narrower beam-widths. This can be easily understood that narrower beam-widths provide larger possibilities for different links to co-exist in the network, while more co-existing links support larger throughput. It is also shown that both CMDMAC and NCDMAC have better system throughput as compared to that of omni-directional 802.11 (0.49Mbps). In Fig. 8(e), it is shown that successful ratio keeps increasing while the sector beams become narrower. This change is caused by the nodes pointing their main-lobes to the terminals outside 1-hop range and become the hidden terminals. CMDMAC only has the channel usage information within 1-hop range, thus cannot help prevent this kind of packet collisions.

In Fig. 8(c), the aggregate throughput increases with the number of data channels, but the increment is not linear. The aggregate throughput is an end-to-end issue and can be affected by the topology, the routing protocol and a lot of other factors, while MAC is only one of them. In Fig. 8(f), we show the data packet transmission ratio for CMDMAC, NCDMAC and 802.11. While 802.11 provides nearly 100% packet transmission ratio, that of CMDMAC is around 95%. For NCDMAC, the data packet transmission ratio decreases with more data channels at first. For the case with 5 data channels, the collision rate starts to decrease slightly. An example is provided as follows to give some hints. Assume there are infinite number of data channels, the probability that two links co-exist in one channel becomes 0. Thus, the links conflict possibility is zero. We see that larger number of data channels leads to fewer links in each channel, which results in lower link conflicts possibility.



(a) Comparison with DMAC. channel capacity: 2 Mbps; packet size: 1000 byte; traffic load per flow: 25 packet/second; G_m/G_s: 30 dB; node number: 25; flow number: 25; data channel 1.

(b) Comparison with CDMAC. channel capacity: 2 Mbps; packet size: 1000 byte; topology dimensions: 645m * 645m; G_m/G_s: 30 dB; node number: 25; flow number: 25; data channel: 1.

(c) Comparison with MMAC and CAMMAC. capacity: 2 Mbps; packet size: 1024 byte; channel number: 4; dimensions: 500m*500m; node number: 100; flow number: 40; G_m/G_s: 10dB; beam: 30°.

Fig. 9. Simulation results of comparison towards bench marks.

C. Comparisons with DMAC, CDMAC, MMAC and CAMMAC

In Fig. 9(a), M represents for the sector number. CMDMAC outperforms DMAC [5] in terms of throughput with both 45° and 90° beamwidths with all the node densities. As a benchmark in directional MAC design, DMAC partially solved deafness and hidden terminal problems. Only one channel is needed to perform DMAC. As there are multiple channels available in the unlicensed band, it is no problem if one of them is dedicated as the CC. Moreover, our CMDMAC can work in a multi-channel scenario and benefit from multiple DCs, while DMAC cannot do that.

In Fig. 9(b), it is shown that CDMAC [8] quickly saturates with higher packets generation rate, while CMDMAC can provide about 56% and 60% larger throughput performance than CDMAC (M=8) and CDMAC (M=4), respectively. In CDMAC, the network is divided into a master-slave structure. While the deafness and hidden terminal problems are solved within a local group hosted by a master, there will be packet collisions at the borders of different groups. Again, we want to point out that CMDMAC outperforms CDMAC and DMAC at the cost of an extra control channel.

We compare our CMDMAC to two multi-channel MACs, MMAC [13] and CAMMAC [12]. For MMAC, it needs clock synchronization. In Fig. 9(c), we see that these three MACs have the same throughput for light-load networking scenarios. For the heavy-load cases, CMDMAC achieves about 2.23 times the throughput of MMAC. While CAMMAC can be deemed as an omni-directional version of CMDMAC, CMDMAC with 30° achieves about 1.40 times the throughput of CAMMAC. This is due to the spatial sharing gain provided by directional transmission.

VI. Conclusion

We propose CMDMAC which uses cooperation to solve the deafness and hidden terminal problems. In this paper, the idle terminals actively participate in the negotiation procedures of their neighbors to help them overcome the deafness and hidden terminal problems. Simulation results show that CMDMAC reduces the data packet collision effectively and provides good throughput performance. In future work, we plan to conduct performance analysis of CMDMAC in terms of the probability of cooperation as in [15].

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