A MAC Protocol with Directional Antennas for Deafness Avoidance in Ad Hoc Networks

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***Abstract*—Directional antennas are expected to provide significant improvements over omni-directional antennas in wireless ad hoc networks. Directional MAC protocols, however, introduce new kinds of problems arising from directivity. One major problem is deafness, caused by a lack of state information from neighbor nodes (i.e., idle or busy). This paper proposes DMAC/DA (Directional MAC with Deafness Avoidance) to overcome the deafness problem. In DMAC/DA, WTS (Wait To Send) frames are transmitted by the transmitter and the receiver after the successful exchange of directional RTS (Request To Send) and CTS (Clear To Send) to notify the on-going communication to potential transmitters that may experience deafness. Furthermore, DMAC/DA is enhanced by the next packet notification to distinguish transmitters from neighbors. We evaluate our protocol through extensive simulation study with different values of parameters such as the number of flows, data size and beamwidth. The experimental results show that DMAC/DA outperforms existing directional MAC protocols, such as DMAC (Directional MAC) and MDA (MAC protocol for Directional Antennas), in terms of throughput, RTS failure ratio, and control overhead.**

I. INTRODUCTION

In previous works on wireless ad hoc networks [1], omni-directional antennas that radiate or receive power equally well in all directions are usually used. Traditional MAC protocols using omni-directional antennas such as IEEE 802.11 DCF (Distributed Coordination Function) [2] cannot achieve high throughput in wireless ad hoc networks because they waste a large portion of the network capacity as discussed in [3]. Directional antennas have great potential to deal with this problem and to improve the network performance, such as high spatial reuse and range extension. Therefore, several MAC protocols using directional antennas for ad hoc networks have been proposed recently.

However, directional MAC protocols inherently introduce new kinds of problems related to directional transmissions as identified in [4], [5]. Communication failure factors in directional MAC protocols are classified as follows [5]:

- Deafness: The receiver node cannot receive RTS (Request To Send) because the receiver is beamformed towards the direction away from the transmitter.
- RTS collision: RTS is not received correctly by the receiver since other nodes are transmitting.
- CTS (Clear To Send) collision: The receiver node sends CTS, however the transmitter cannot receive it because of collision.
- DNAV (Directional Network Allocation Vector) blocking: The receiver node receives RTS correctly, but cannot send CTS because DNAVs are set in the direction of the transmitter.
- Directional hidden-terminal problem: Hidden terminal due to asymmetry in gain or hidden terminal due to unheard RTS/CTS [4].
- Out of range: The addressed receiver node moves out of range of the transmitter's communication range.
- Location information staleness: The gap between the cached location information and actual location of the addressed node becomes larger than the beamwidth.

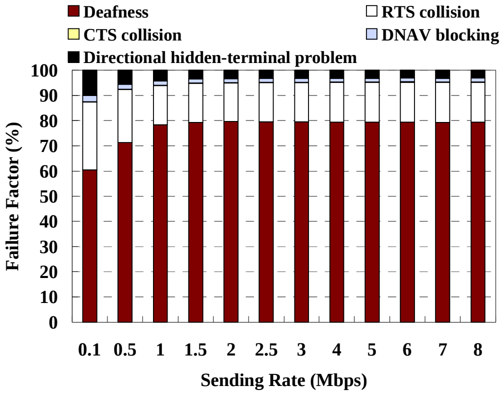

Fig. 1. Communication failure factors of DMAC.

Fig. 1 shows communication failure factors of DMAC (Directional MAC) [4] obtained by simulations with parameters described in Section V. The results show that most communication failures occur due to deafness and the deafness problem is a significant problem in directional MAC protocols. Deafness is caused when a transmitter repeatedly attempts to communicate with its intended receiver, but it fails because the receiver has its beam pointed away from the transmitter. While directional transmissions can increase spatial reuse of the wireless channel by reducing interference between nodes, each node cannot identify the state of neighbor nodes (i.e., idle or busy) because frame transmissions are restricted in the specific area. As discussed in [6], the deafness problem leads to unproductive retransmissions and wastage of the wireless channel.

This paper proposes DMAC/DA (Directional MAC with

Deafness Avoidance) to handle the issue of deafness in directional MAC protocols. In DMAC/DA, WTS (Wait To Send) frames are transmitted by the transmitter and the receiver after the successful exchange of directional RTS and CTS to notify the on-going communication to potential transmitters that may experience deafness. WTS frames are transmitted only through those sectors where potential transmitters are located to reduce the control overhead. In addition, DMAC/DA is enhanced by the next packet notification to distinguish transmitters from neighbor nodes. We evaluate our protocol through extensive simulation study with different values of parameters such as the number of flows, data size and beamwidth. The experimental results show that DMAC/DA outperforms existing directional MAC protocols in terms of throughput, RTS failure ratio, and control overhead in the majority of scenarios investigated.

II. RELATED WORK

Recently, several MAC protocols using directional antennas, typically referred to as directional MAC protocols, have been proposed for wireless ad hoc networks. In [4], Choudhury et al. propose DMAC in which all frames are transmitted and received directionally, and physical and virtual carrier sense functions are also performed directionally. In this paper, we refer to this protocol as DMAC with DPCS (Directional Physical Carrier Sensing). Directional virtual carrier sensing is realized by DNAV, a directional version of NAV. The issues of directional MAC protocols including deafness are discussed but no solution is provided.

Although omni-directional RTS/CTS [7], [8] is one simple solution to avoid deafness by notifying the on-going communication to all neighbors, this reduces the benefits of spatial reuse and range extension.

To solve the deafness problem, several directional MAC protocols use additional control frames to inform neighboring nodes of imminent communication. In Circular RTS MAC [9], multiple directional RTS frames are transmitted consecutively in a circular way to notify the on-going communication to neighbor nodes. While it prevents deafness in the neighborhood of the transmitter, deafness in the neighborhood of the receiving node may appear. To handle deafness at the receiver side, Circular RTS and CTS MAC (CRCM) [10] uses the circular CTS frames transmitted towards unaware neighbor nodes. Although it can notify the on-going communication to all neighbor nodes around the transmitter and the receiver, the circular transmission of RTS/CTS for each transmitted data packet may incur not only the delay and large control overhead but also collisions between control frames. In MDA (MAC protocol for Directional Antennas) [11], multiple directional RTS and CTS frames are transmitted in Diametrically Opposite Directions, called DOD procedure, through the antenna beams with neighbors after the successful exchange of directional RTS and CTS to optimize the circular transmission of control frames. However, it is unnecessary to notify the imminent communication to neighbors, which do not intend to communicate with the transmitter or the receiver. Obviously, there is a fundamental tradeoff between deafness avoidance using control frames and overhead reduction using the optimized control frame transmission mechanism. This paper addresses this tradeoff.

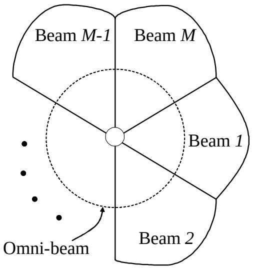

Fig. 2. Antenna model with M beams.

Choudhury and Vaidya [6] propose ToneDMAC, a tone-based mechanism to handle deafness reactively. They first propose the omni-directional physical carrier sensing during backoff periods. In this paper, we refer to this variation of DMAC as DMAC with OPCS (Omni-directional Physical Carrier Sensing). DMAC with OPCS is simple but only prevents deafness during backoff periods. They then propose the tone-based feedback mechanism, called ToneDMAC, to distinguish deafness from collision. However, ToneDNAC needs a dedicated control channel to transmit tones as well as a data channel. Wang et al. [12] propose SYN-DMAC, which alleviates deafness using the timing structure with clock synchronization. The time that deafness lasts is compressed to a short duration. However, this scheme requires that nodes are synchronized to identify the timing structure.

Because this paper focuses on handling deafness, for simplicity of discussion, we assume that each node knows the location of neighboring nodes a priori to point the beam in the appropriate direction. Mechanisms to determine the neighbors' location are proposed in [9], [13], [14].

III. ANTENNA MODEL

We assume that each node is equipped with a switched beam antenna system which is comprised of M fixed beam patterns (Fig. 2). Non-overlapping directional beams are numbered from 1 to M, starting at the three o'clock position and running clockwise. The antenna system possesses two separate modes: Omni and Directional. In Omni mode, a node receives signals from all directions with gain G^o. An idle node waits for signals in Omni mode. After a signal is sensed in Omni mode, the antenna detects the beam (direction) on which the signal power is strongest and goes into the Directional mode. In Directional mode, a node can point its beam towards a specific direction with gain $G^d (> G^o)$. Most existing research assumes the same antenna model [4–14]

IV. DMAC/DA

In this section, we propose DMAC/DA protocol to solve the tradeoff between deafness avoidance and overhead reduction as discussed in Section II. In DMAC/DA, each node maintains

TABLE I
NEIGHBOR TABLE

ID	Beam Number	Deafness Duration	Link Activity
B	1	–	–
D	3	–	D_{RxTime}
C	4	T_C	–
E	6	–	E_{RxTime}

a neighbor table, and WTS frames are transmitted by the transmitter and the receiver after the successful exchange of directional RTS and CTS to notify the on-going communication to potential transmitters. In addition, this section proposes an enhanced version of DMAC/DA, called DMAC/DA with NPN (Next Packet Notification), to reduce the overhead of the control frame transmissions. The details of DMAC/DA are presented next.

A. Neighbor Table

In DMAC/DA, each node maintains a neighbor table with one record for every node that it has heard. Initially, the neighbor table is empty and it is continuously updated upon overhearing any transmission. Table I shows the structure of neighbor table (example of A's neighbor table in Fig. 3). The record of Table I means that A can transmit to or receive from D by beam 3. Beam number field maintains the beam from which the node heard the frame and it is updated whenever each node receives any frame, regardless of whether the frame is sent to the node. Deafness duration field represents the duration that D is deaf (busy). The detail description of this field is mentioned in the next subsection. Link activity field indicates the reception time of the previous transmission between D and A where D was the transmitter and A was the intended receiver. If D delivered packets to A in the near past, it is reasonable to consider that D is intending to deliver the next packet to A. Therefore, this field presents potential transmitters and it is used to select the beam in which the control frame should be transmitted. If the elapsed time from the previous reception exceeds a certain threshold value T_h, it is removed from the table for handling mobility.

B. Procedure of Communicating Nodes

We use Fig. 3 to explain the procedure of DMAC/DA. When node A has a packet to be sent towards node B, firstly, it performs physical carrier sensing in the Omni mode during backoff periods as similar to DMAC with OPCS [6]. If the channel remains idle during backoff periods, node A determines the number of K_A beams, in which potential transmitters exist (out of $M - 1$, where M is the number of beams). It checks its own neighbor table and also DNAV table for each beam to determine whether potential transmitters are located and DNAV is not set in its beam. In the case of Fig. 3, K_A is set to two because nodes D (beam 3) and E (beam 6) are registered as the potential transmitters in the neighbor table of A. K_A is included in its RTS and then node A switches to the Directional mode and sends RTS in the direction of B and waits for the CTS (Fig. 3 (1)). If node B receives RTS, it also determines the number of K_B beams, in which potential transmitters exist. In the case of Fig. 3, K_B is set to one because node G is registered as the potential transmitter of B. Then, node B switches to the Directional mode and sends CTS including K_B (Fig. 3 (2)). It is only after the RTS/CTS handshake is successfully completed, that A and B send WTS frames using the selected K_A or K_B beams in order to inform the potential transmitters of the imminent communication. WTS frames are sequentially transmitted counter-clockwise to avoid collisions between WTS frames. Node A transmits WTS in the direction of E, and, at the same time, node B transmits WTS in the direction of G (Fig. 3 (3)). Node A then transmits WTS in the direction of D, and node B waits for the completion of the WTS transmission of A (Fig. 3 (4)). The frame format of WTS is the same as that of RTS. Duration field of WTS frames can be decremented accurately because node A can obtain K_B from the CTS and node B vice versa. Although handling the mobility of nodes is beyond the scope of this paper, the transmission of WTS frames is also useful to update the location of neighboring nodes. After both of the nodes complete WTS transmissions, node A sends the directional Data frame and node B sends the directional ACK frame (Fig. 3 (5, 6)). Both A and B switch back to the Omni mode after the Data/ACK frame exchange.

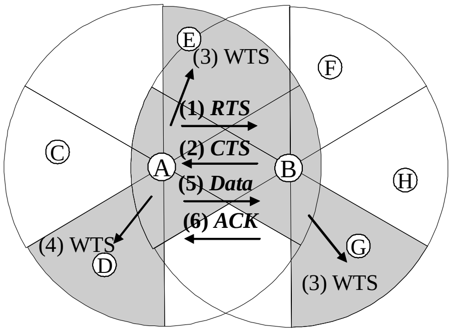

Fig. 3. DMAC/DA.

C. Procedure of Neighboring Nodes

When the neighbor nodes receive the WTS, these nodes set the sender of the WTS as a deaf node in its own neighbor table and defer their own transmissions addressed to it to avoid deafness until the entire data transmission completes. This can prevent packet drops due to unproductive retransmissions caused by the deafness problem.

In addition, if the neighbor node fails to communicate with the sender of WTS and the backoff procedure is invoked before receiving WTS, it discards the frozen backoff counter and reselects a new backoff counter from [0, CW_{min}] for the next attempt. Fig. 4 shows this scenario. This reduces the channel wastage due to unnecessary backoff caused by the deafness problem.

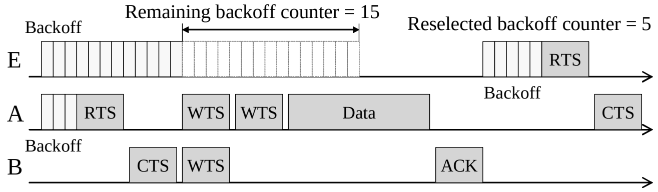

Fig. 4. Handling the wastage of the wireless channel.

D. DMAC/DA with NPN (Next Packet Notification)

Basic DMAC/DA uses the history of the previous communications to select potential transmitters. Therefore, if the potential transmitter does not have more packets addressed to the same receiver, WTS frame transmitted to the node is unnecessary. If each node can acquire the next packet information of neighbor nodes, it can transmit WTS frames more effectively to mitigate deafness and also reduce the control overhead. Therefore, in DMAC/DA with NPN, if there is a packet addressed to the same receiver at the head of its queue (i.e., a next packet), the transmitter sets More Data bit in the frame control header of the Data frame; otherwise the bit is set to zero. When the node receives the Data frame, it checks the More Data bit to determine whether the transmitter has more packets to send for it or not. Link activity field of the neighbor table is updated only when More Data bit is set. Each node can distinguish active transmitters from neighbor nodes by using this method, and WTS frames are transmitted only through the beams with active transmitters. DMAC/DA with NPN reduces the overhead involved in unnecessary transmission of WTS frames caused in basic DMAC/DA. Procedures of DMAC/DA with NPN are the same as that of basic DMAC/DA except for the update policy of the link activity field.

V. PERFORMANCE EVALUATION

To evaluate the performance of DMAC/DA, we developed an event driven simulator. We make the following assumptions. A hundred nodes are arranged at random in a square area with dimensions of 1500 m. Random source-destination pairs of CBR traffic are chosen at random and the routes are statically assigned using the shortest path. The transmission range of the omni-directional antenna is 250 m and that of the directional antenna is 500 m. The data rate is 11 Mbps. We do not consider mobility in our simulations. We change the parameters such as sending rate of each flow, number of flows, data size and number of beams. Other parameters not described in this paper, such as the interframe space and the contention window size, follow the IEEE 802.11 DSSS specifications [2]. The simulation results are the average of 10 runs, and one million application packets are generated for each simulation. In most cases, the 95 percent confidence interval for the measured data is less than 5 percent of the sample mean.

We first evaluate the performance of different MAC protocols when the sending rate of each flow is changed from 100 kbps to 8 Mbps. The number of flows is five, data size is 1024 bytes, and the number of beams M is six. Fig. 5 shows the throughput of eight MAC protocols. As shown in the figure, Circular RTS MAC and CRCM perform lower than IEEE 802.11 because these directional MAC protocols introduce the large control overhead and increase collisions. Throughput of MDA is higher than DMAC with OPCS and DMAC with DPCS. This is because MDA mitigates deafness proactively using the DOD procedure although it has the larger control overhead than DMAC. DMAC/DA outperforms existing MAC protocols because it reduces the number of control messages compared with MDA, and also maintains the ability to handle deafness. Furthermore, DMAC/DA with NPN achieves the highest throughput because it reduces the unnecessary WTS transmission compared with basic DMAC/DA based on the next packet information of neighbor nodes.

To confirm the ability to handle deafness of each directional MAC protocol, we define RTS failure ratio and deafness ratio. RTS failure ratio (RFR) is calculated as follows:

$$RFR = 1 - \frac{N_{CTS}}{N_{RTS}}, \tag{1}$$

where N_{RTS} is the number of transmitted RTS frames towards the intended receiver and N_{CTS} is the number of successful CTS frames. Deafness ratio is defined as the ratio of the communication failure due to deafness over the whole communication failure factors. Figs. 6 and 7 show the RTS failure ratio and deafness ratio, respectively. Because there is no significant difference between basic DMAC/DA and DMAC/DA with NPN in these performance metrics, results of DMAC/DA with NPN are omitted here. The results show that DMAC with DPCS cannot resolve deafness and most of the communication failures occur due to deafness. DMAC with OPCS mitigates unproductive retransmissions of RTS and solves the deafness problem partially. Deafness ratio of Circular RTS MAC is higher than CRCM because deafness appears due to the transmission of single directional CTS. As shown in Fig. 7, it may not be possible to completely eliminate the deafness problem. Even in conservative deafness avoidance schemes, such as CRCM and MDA, deafness accounts for half of the failure factors. RTS failure ratio of DMAC/DA is lower than other directional MAC protocols and the deafness ratio is almost the same as MDA. Note that DMAC/DA cannot decrease the deafness ratio significantly. However, the throughput of DMAC/DA is much higher than that of other protocols because DMAC/DA reduces the control overhead, and balances the tradeoff between deafness avoidance and spatial reuse.

Fig. 8 shows the overhead performance. The overhead is defined as the average number of bits transmitted to deliver 1 bit of payload to the receiver at the MAC layer. Overhead becomes large when a large number of control bits are transmitted and/or frames are retransmitted. Circular RTS MAC and CRCM have large control overheads due to the circular transmission of RTS/CTS and the increase of retransmissions. In DMAC/DA, WTS frames are transmitted only through those sectors where potential transmitters are located to reduce the control overhead, whereas these frames are transmitted to all

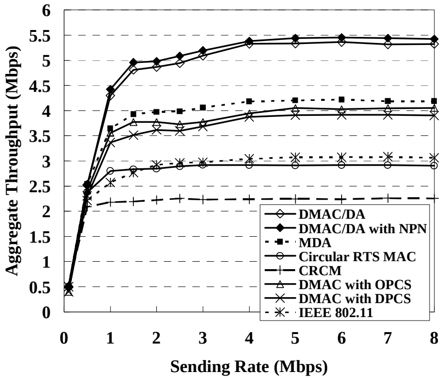

Fig. 5. Aggregate throughput.

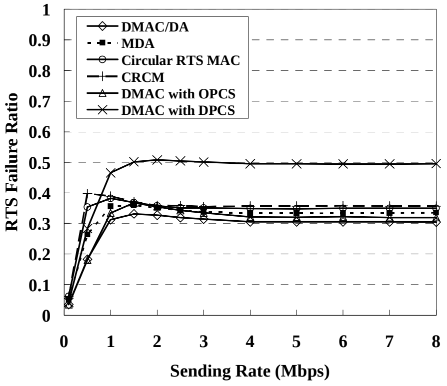

Fig. 6. RTS failure ratio.

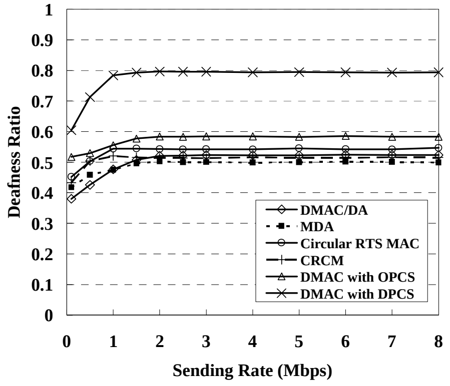

Fig. 7. Deafness ratio.

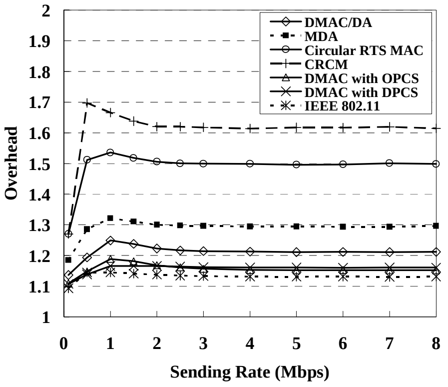

Fig. 8. Overhead.

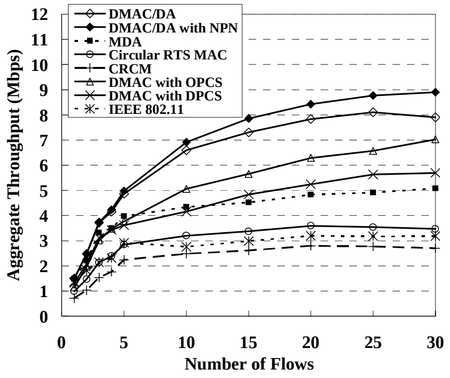

Fig. 9. Effects of the number of flows.

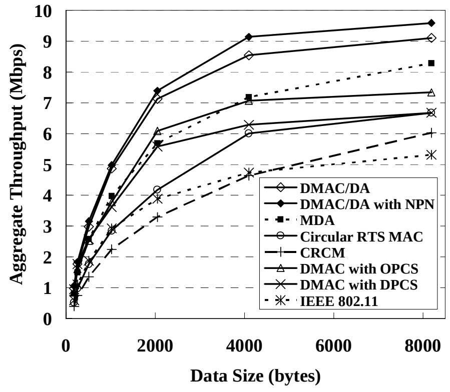

Fig. 10. Effects of the data size.

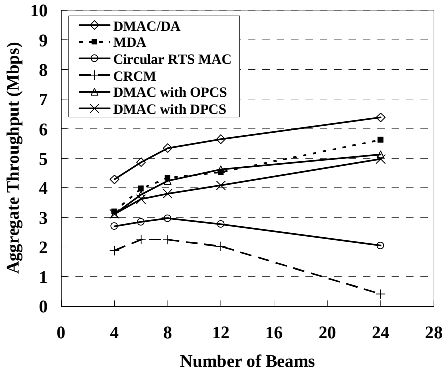

Fig. 11. Effects of the number of beams.

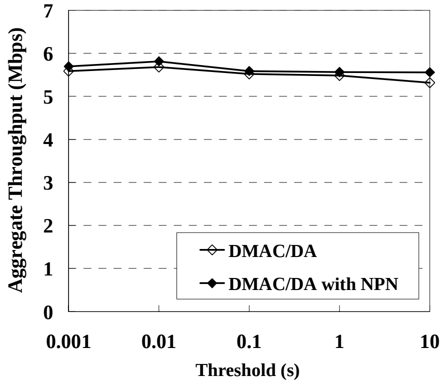

Fig. 12. Effects of the threshold.

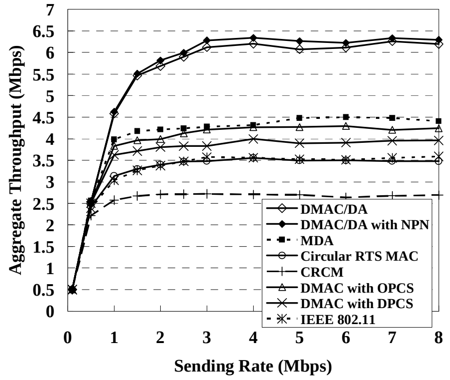

Fig. 13. Throughput in random flow scenario.

neighbors in MDA. Therefore, DMAC/DA has lower overhead than MDA. It can be concluded that DMAC/DA solves deafness effectively and increases throughput performance by reducing the control overhead.

We next evaluate the MAC protocols with different numbers of flows, data size, and number of beams. Fig. 9 shows the aggregate throughput when the number of flows is changed from 1 to 30 (sending rate of each flow is 2 Mbps, data size is 1024 bytes and M = 6). The results show that MDA, Circular RTS MAC and CRCM do not increase throughput performance as the number of flows increases. Especially, in MDA, when the number of active neighbors increases, it should transmit control frames through most of the beams. On the other hand, DMAC/DA increases the throughput performance as the number of flows increases because it reduces the control overhead using the adaptive WTS scheme. In addition, the benefit of NPN is increased as the number of flows increases. This is because when the number of flows is large, each node participates in several flows and it has several packets addressed to different nodes in its queue. In this case, the notification of the next packet is more useful for transmitting WTS frames effectively and also for reducing the control overhead.

In Fig. 10, data size is changed from 128 bytes to 4096 byte (sending rate is 2 Mbps, number of flows is 5 and M = 6). The control overhead relatively becomes small as the data size increases. However, when the data size is large, the duration that experiences deafness is increased as well as the percentage of collisions. DMAC/DA outperforms others irrespective of the data size because it alleviates deafness and reduces collisions at the same time by the elaborate control frame transmission mechanism.

Fig. 11 shows the throughput of directional MAC protocols when the number of beams M is changed from 4 to 24 (sending rate is 2 Mbps, number of flows is 5 and data size is 1024 bytes). The beamwidth becomes narrower as the number of beams increases, and spatial reuse capabilities are enhanced. Circular RTS MAC and CRCM cannot achieve high throughput because these protocols should transmit control frames as the number of beams increases. On the other hand, DMAC/DA and MDA can achieve high throughput due to reducing the number of control messages and enhancing spatial reuse capabilities.

DMAC/DA distinguishes the potential transmitters from the neighboring nodes to solve the deafness problem and also reduce the control overhead. When the transmitters are changed frequently, DMAC/DA relies on the threshold value, T_h, which removes the stale entry of the table. To evaluate the effect of the threshold value, the following condition is used: Source-destination pairs of traffic are randomly switched in one simulation and the duration of one flow is randomly selected from (0, 10.0] (s). In this scenario, the potential transmitters of each node are changed dynamically according to the change of the flows. Fig. 12 shows the throughput of DMAC/DA and DMAC/DA with NPN when each threshold is from 0.001 to 10 (s) (sending rate is 2 Mbps, number of flows is 5, data size is 1024 bytes and M = 6). The results show that our proposed protocols achieve the highest throughput when the threshold is set to 0.01. When the threshold is small (e.g., in the case of 0.001), the entry is deleted frequently although the flow is still active. In this case, WTS frame is not transmitted to the deleted node and it suffers from deafness. On the other hand, when the threshold is large, WTS frame is transmitted to the neighbor node even when the flow is no longer active. Therefore, there is an optimal value of the threshold, which solves the tradeoff between deafness handling and overhead reduction. However, as shown in Fig. 12, the different values of the threshold do not significantly affect the throughput performance. On the other hand, to optimize the threshold, we must consider the mobility of nodes as well as the traffic pattern. This is included in our future work.

The throughput of eight MAC protocols in this scenario is shown in Fig. 13, where the threshold value of 0.01 is used in DMAC/DA and DMAC/DA with NPN. The results show that DMAC/DA has the highest throughput and DMAC/DA has almost the same performance as DMAC/DA with NPN. It can be concluded that our proposed protocol solves the fundamental tradeoff between deafness handling and spatial reuse.

VI. CONCLUSION

This paper addressed the issue of deafness in directional MAC protocols for wireless ad hoc networks and proposed DMAC/DA to handle the deafness problem proactively. In DMAC/DA, the WTS frames are transmitted by the transmitter and the receiver after the successful exchange of directional RTS and CTS to notify the on-going communication to potential transmitters that may experience deafness. In addition, we proposed DMAC/DA with NPN, enhanced DMAC/DA using the next packet notification. The experimental results show that DMAC/DA outperforms existing directional MAC protocols, especially when the numbers of flows and beams are large (e.g., up to 80% improvement compared with MDA).

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