

Performance Evaluation of Directional MAC Protocols for Deafness Problem in Ad Hoc Networks

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Several directional MAC protocols for ad hoc networks using directional antennas have been proposed recently. Although directional antennas have great potential such as high spatial reuse and range extension, directional MAC protocols inherently introduce new problems arising from directivity. Deafness is one of the major problems and reduces the performance, caused by a lack of state information from neighbor nodes. This paper presents two directional MAC protocols, DMAC/DA (Directional MAC with Deafness Avoidance) and RI-DMAC (Receiver-Initiated Directional MAC), which handle the deafness problem, and mainly evaluates these protocols through extensive simulation study. DMAC/DA is a proactive handling method for deafness. In DMAC/DA, WTS (Wait To Send) frames are transmitted to notify the on-going communication to potential transmitters that may experience deafness. In this paper, DMAC/DA is enhanced by the next packet notification, called DMAC/DA with NPN, to distinguish transmitters from neighbors. On the other hand, RI-DMAC handles deafness reactively using a combination of sender-initiated and receiver-initiated operations. In RI-DMAC, each node polls a potential deafness node using RTR (Ready To Receive) after the completion of every dialog. The experimental results show that our proposed protocols outperform existing directional MAC protocols in terms of throughput, control overhead and packet drop ratio.

1. Introduction

Ad hoc networks are the autonomous system of mobile nodes which share wireless channels to communicate with one another. In the previous works on ad hoc networks¹⁾, omnidirectional antennas that radiate or receive power equally well in all directions are usually used at the physical layer. Traditional MAC (Medium Access Control) protocols, such as IEEE 802.11 DCF (Distributed Coordination Function)²⁾, have been intrinsically designed for omnidirectional antennas and these protocols lead to inefficient use of the wireless channel and consequently reduce the throughput in ad hoc networks as discussed in Ref. 3). On the other hand, directional antennas can transmit or receive in a desired direction and have great potential such as high spatial reuse and range extension. Therefore, several MAC protocols using directional antennas for ad hoc networks have been proposed recently.

Directional MAC protocols, however, inherently introduce new kinds of problems related to directional transmissions as identified in

Refs. 4), 5) and these problems result in factors of communication failure. Communication failure factors in directional MAC protocols are classified as follows⁵⁾:

- Deafness: The receiver node cannot receive RTS 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 (i.e., the receiver node is an exposed-terminal, or two or more nodes transmit control frames concurrently).
- CTS 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/CTS⁴⁾.
- 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

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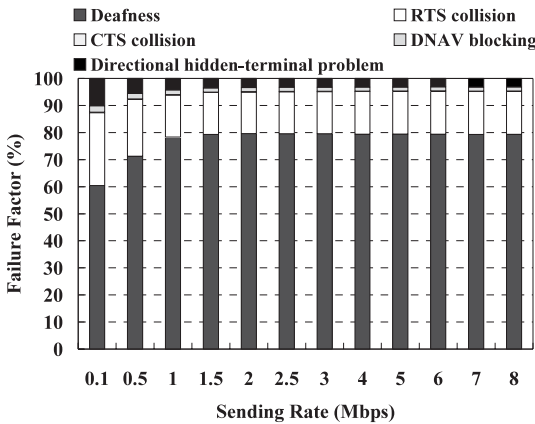


Fig. 1 Communication failure factors of DMAC.

and actual location of the addressed node becomes larger than the beamwidth.

Figure 1 shows communication failure factors of DMAC (Directional MAC)⁴⁾ obtained by simulations with parameters described in Section 6. The results show that most communication failures occur due to deafness and that the deafness problem is a significant problem in directional MAC protocols. 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. Deafness is caused when a transmitter repeatedly attempts to communicate with its intended receiver, but it fails because the receiver is engaged in communication with another node (i.e., either transmitting or receiving) and it has its beam pointed away from the transmitter. In this paper, the transmitter which suffers from deafness is referred to as deafness node. As discussed in Ref. 6), the deafness problem leads to unproductive retransmissions and wastage of the wireless channel.

This paper presents two directional MAC protocols, DMAC/DA (Directional MAC with Deafness Avoidance)⁷⁾ and RI-DMAC (Receiver-Initiated Directional MAC)⁸⁾, which handle the issue of deafness. DMAC/DA is a proactive handling method for deafness. In DMAC/DA, WTS (Wait To Send) frames are simultaneously 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. In this paper, DMAC/DA is

enhanced by the next packet notification, called DMAC/DA with NPN (Next Packet Notification), to distinguish transmitters from neighbor nodes. DMAC/DA with NPN reduces the overhead involved in unnecessary transmission of WTS frames caused in basic DMAC/DA. On the other hand, RI-DMAC handles deafness reactively using a combination of sender-initiated and receiver-initiated operations. In RI-DMAC, each node polls a potential deafness node using the RTR (Ready To Receive) frame after the completion of every dialog. We evaluate our protocols and other conventional protocols through extensive simulation study with different values of parameters such as the number of flows, data size and beamwidth. The experimental results show that our proposed MAC protocols outperform existing directional MAC protocols in terms of throughput, control overhead and packet drop ratio in the majority of scenarios investigated.

2. Antenna Model

We assume that each node is equipped with a switched beam antenna system which is comprised of M fixed beam patterns. 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 on which the signal power is strongest and goes into the Directional mode. In Directional mode, a node points its beam towards a specific direction with gain $G^d (> G^o)$. Most existing research assumes the same antenna model^{4)~18)}.

3. Related Works

In Ref. 4), Choudhury, Yang, Ramanathan and Vaidya 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. They also propose MMAC (Multi-hop RTS MAC) which involves multi-hop RTS to take advantage of the higher antenna gain, and the issues of directional MAC protocols including deafness are discussed but no solution is provided.

In Refs. 9), 10), circular directional transmis-

sion of the periodic hello message is utilized to exploit the increase of the transmission range. Takata, Nagashima and Watanabe¹¹⁾ propose SWAMP (Smart antennas based Wider-range Access MAC Protocol), which provides both spatial reuse and range extension by two types of access mode. The issue of deafness remains unsolved in these protocols because of single directional RTS/CTS.

Although omni-directional RTS/CTS^{12),13)} is one simple solution to avoid deafness by notifying the on-going communication to neighbors, this reduces the benefits of spatial reuse and range extension.

Several recent directional MAC protocols attempt to overcome the issue of deafness. Korakis, Jakllari and Tassiulas¹⁴⁾ propose Circular RTS MAC (CRM), in which multiple directional RTS frames are transmitted consecutively to notify the on-going communication to neighbor nodes. While it prevents deafness in the neighborhood of the transmitter, deafness appears in the neighborhood of the receiving node due to the transmission of single directional CTS. Moreover, if the receiver node does not reply with CTS due to collision or deafness, the neighboring nodes of the transmitter, which receive RTS and set DNAV, also cannot initiate their own transmissions for the reserved entire duration, and it results in serious wastage of the wireless channel.

Jakllari, Broustis, Korakis, Krishnamurthy and Tassiulas¹⁵⁾ propose Circular RTS and CTS MAC (CRCM), in which multiple directional CTS frames are also used as well as RTS frames. 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 frame may incur not only the delay and large control overhead but also collisions between control frames.

In Ref. 16), Gossain, Cordeiro and Agrawal propose MDA (MAC protocol for Directional Antennas). In MDA, multiple directional RTS and CTS frames are transmitted simultaneously in diametrically opposite directions only through the antenna beams with neighbors to reduce overheads of the circular transmission. MDA reduces the overhead involved in the circular transmission of RTS/CTS compared with CRCM, especially when the number of beams is large and nodes are not uniformly distributed. However, it is unnecessary to notify the immi-

nent communication to neighbors, which do not intend to communicate with the transmitter or the receiver.

In Ref. 17), Gossain, Cordeiro, Cavalcanti and Agrawal address the issue of deafness proactively by estimating the state of the intended receiver. As in the case of CRCM, this scheme requires the circular transmission of RTS/CTS for each transmitted data frame to acquire the on-going transmission information of neighborhoods, which may incur large control overhead.

CRM, CRCM and MDA are in-band solutions that use additional control frames to alleviate the deafness problem. The more control frames we use, the more overhead we have. Therefore, there is a fundamental tradeoff between deafness avoidance and overhead reduction. This paper addresses this tradeoff in in-band solutions.

Choudhury and Vaidya⁶⁾ 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, ToneDMAC needs a dedicated control channel to transmit tones as well as a data channel, and it may be relatively complex.

Wang, Fang and Wu¹⁸⁾ propose SYN-DMAC, which alleviates deafness using the timing structure with clock synchronization. Contention and deafness occur during the random access phase in a cycle, and the time that deafness lasts is compressed to a short duration. However, this scheme requires that nodes are synchronized to identify the timing structure, which is a challenging task in ad hoc networks.

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 Refs. 10), 11).

4. DMAC/DA

In this section, we present DMAC/DA⁷⁾. Deafness is caused because each node is un-

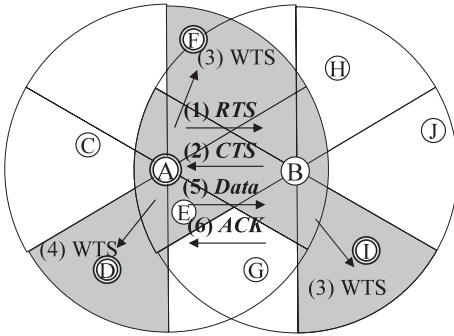


Fig. 2 DMAC/DA.

aware of the on-going communications in a different direction. Therefore, to solve the deafness problem proactively, DMAC/DA uses additional control frames to inform neighboring nodes of imminent communication. In addition, this paper proposes an enhanced version of DMAC/DA, called DMAC/DA with NPN (Next Packet Notification), to reduce the overhead of the control frame transmissions.

4.1 Basic DMAC/DA

In DMAC/DA, each node maintains a neighbor table and it is continuously updated upon overhearing any transmission. In the neighbor table, each node maintains the previous reception time of the Data frame addressed to itself from neighbors. This 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_{DA} , it is removed from the table.

We use Fig. 2 to explain the procedures of DMAC/DA. In Fig. 2, node A is the sender and node B is the intended receiver. In the neighbor table of A, nodes D and F are registered as the potential transmitters. Node I is registered as the potential transmitter of B in the neighbor table of B. The transmitters are denoted by a double circle and other nodes (i.e., receivers and inactive nodes) are denoted by a single circle.

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 OPCS⁶⁾. 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. 2, K_A is set to two. 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. 2 (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. 2, K_B is set to one. Then, node B switches to the Directional mode and sends CTS including K_B (Fig. 2 (2)).

It is only after the RTS/CTS handshake is successfully completed, that A and B send WTS frames simultaneously 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 F, and, at the same time, node B transmits WTS in the direction of I (Fig. 2 (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. 2 (4)).

When the neighbor nodes receive the WTS, these nodes set the sender of the WTS as a busy node and defer their own transmissions addressed to the busy node until the entire data transmission completes.

After both of the nodes complete WTS transmissions, node A sends the directional Data frame and node B sends the directional ACK frame (Fig. 2 (5), (6)). Both A and B switch back to the Omni mode after the Data/ACK frame exchange.

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.

4.2 DMAC/DA with NPN

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 in the head of its queue, 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. 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. Procedures of DMAC/DA with NPN are the same as that of basic DMAC/DA.

5. RI-DMAC

This section presents RI-DMAC⁸⁾, a novel receiver-initiated approach to overcome the deafness problem reactively. RI-DMAC uses the RTR frame to poll a potential deafness node after the completion of every dialog.

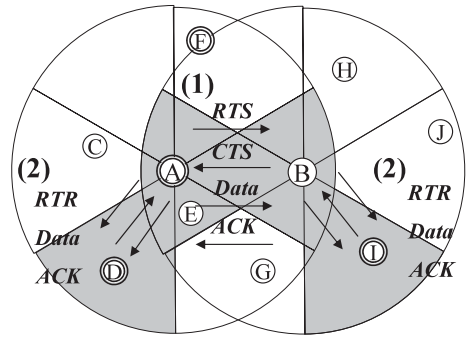
5.1 Polling Table

Each node maintains a polling table to poll a potential deafness node in RI-DMAC. The polling table presents the nodes which have a packet addressed to the node and may experience deafness. To construct the polling table, if there is a packet addressed to the same receiver at the head of its queue, the transmitter appends the size of the next packet to the Data frame header (a 16-bit additional field) for each transmitted packet; otherwise the field is set to zero. When the node receives the Data frame, it checks the frame header and updates its own polling table with its reception time. If the elapsed time of the entry exceeds a certain threshold value T_{RI} , it is removed from the table for handling mobility. Conventional receiver-initiated MAC protocols, such as Ref.19), require the traffic estimator that predicts the packet arrivals of neighbor nodes based on the previous history to poll the neighbors. Unlike these protocols, RI-DMAC does not require the traffic estimator by using a combination of sender-initiated and receiver-initiated operations.

5.2 Polling Scheme

Initially, all nodes operate in sender-initiated mode (SI-mode) using a four-way handshake (Fig. 3 (1)). After exchanging the Data/ACK frames, the transmitter and the receiver check its own polling table to determine whether potential deafness nodes exist. If two or more nodes are registered in the polling table, it also checks its reception time and the least recently transmitted node is selected as a polled node among potential deafness nodes.

If the node selects a polled node, it moves to receiver-initiated mode (RI-mode) (Fig. 3 (2)); otherwise it stays in SI-mode. In RI-mode, the



(1) A-B: SI-mode
 (2) D-A and I-B: RI-mode
 Fig. 3 RI-DMAC.

directional RTR frame addressed to the selected polled node is transmitted when the channel remains idle for DIFS and backoff periods. The duration field of RTR is set according to the packet size registered in its own polling table. When the polled node receives RTR, it immediately transmits the Data frame. A detailed description of RI-DMAC can be found in Ref. 8).

6. Performance Evaluation

6.1 Simulation Model

To evaluate the performance of our proposed MAC protocols, we developed an event driven simulator. The following 9 MAC protocols are evaluated in terms of throughput, overhead, packet drop ratio and so on. For fair comparison, ToneDMAC⁶⁾ and SYN-DMAC¹⁸⁾ are not included in this evaluation because these protocols require the out-of-band tones and clock synchronization, respectively. We evaluate in-band solutions for the deafness problem.

- RI-DMAC⁸⁾
- DMAC/DA⁷⁾
- DMAC/DA with NPN
- MDA¹⁶⁾
- CRM¹⁴⁾
- CRCM¹⁵⁾
- DMAC with OPCS⁶⁾
- DMAC with DPCS⁴⁾
- IEEE 802.11²⁾

We make the following assumptions. A hundred nodes are arranged at random in a square area with dimensions of 1,500 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

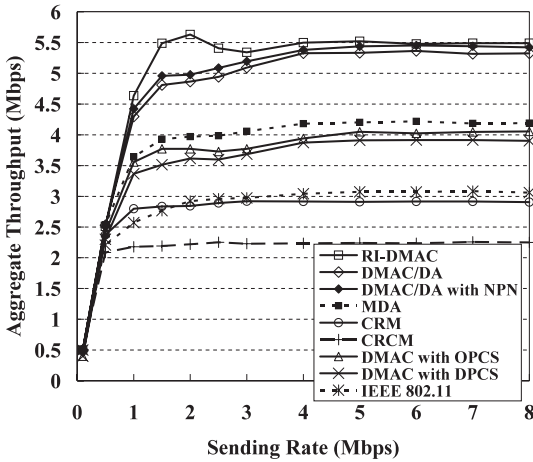


Fig. 4 Aggregate throughput.

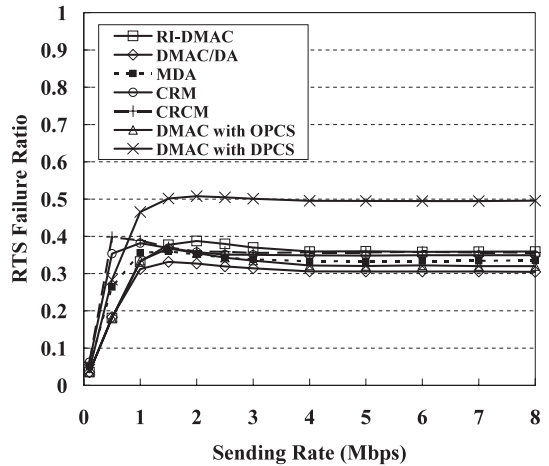


Fig. 5 RTS failure ratio.

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 specifications²⁾. 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.

6.2 Simulation Results

We first evaluate the performance of different MAC protocols when the sending rate of each flow is changed, the number of flows is five, data size is 1,024 bytes, and the number of beams is six. **Figure 4** shows the throughput performance of 9 MAC protocols. As shown in the figure, CRM and CRCM are inferior to IEEE 802.11 because these directional MAC protocols introduce the large control overhead and increase collisions. Throughput of MDA is higher than DMAC. This is because MDA mitigates deafness proactively using selective circular RTS/CTS transmitted through beams with neighbors. 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 a higher throughput than basic DMAC/DA because it reduces the unnecessary WTS transmission compared with basic DMAC/DA based on the next packet in-

formation of neighbor nodes. RI-DMAC outperforms other directional MAC protocols because the proposed polling scheme alleviates deafness using the RTR frame. It is transmitted by the receiver node for inviting the deafness node to transmit its packet, and it reduces control frames compared with a four-way handshake. Obviously, there is a fundamental tradeoff between deafness handling using control frame and the overhead reduction using the optimized control frame transmission mechanism. RI-DMAC balances this tradeoff and achieves the highest throughput.

We next define RTS failure ratio and deafness ratio to confirm the ability to handle deafness of each directional MAC protocol. 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 (and RTR frames in RI-DMAC) towards the intended receiver and N_{CTS} is the number of successful CTS frames (and Data frames in RI-DMAC). Deafness ratio is defined as the ratio of the communication failure due to deafness over the whole communication failure factors⁵⁾. **Figures 5 and 6** 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 indices, results of DMAC/DA with NPN are omitted here. Results show that DMAC with DPCS suffers from deafness and that most of the communication failures occur due to deafness. DMAC with OPCS mitigates unproductive retransmissions of RTS and solves the deaf-

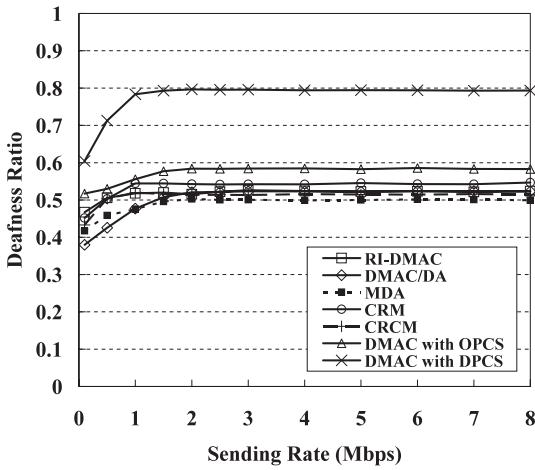


Fig. 6 Deafness ratio.

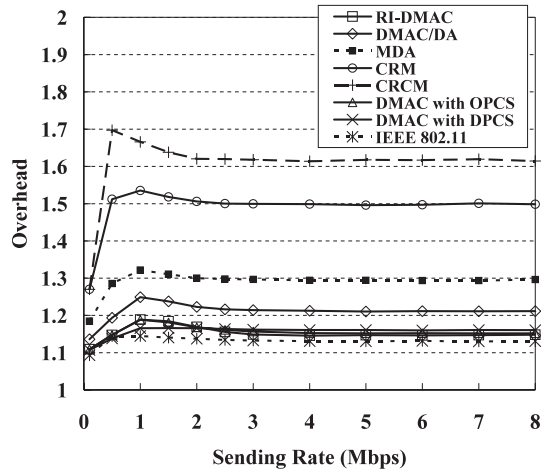


Fig. 7 Overhead.

ness problem partially. Deafness ratio of CRM is higher than CRCM because deafness appears due to the transmission of single directional CTS. As shown in Fig. 6, it may not be possible to completely eliminate the deafness problem. It is interesting to note that deafness accounts for half of the failure factors even in conservative deafness avoidance schemes, such as CRCM and MDA. It implies that the tradeoff between deafness avoidance and spatial reuse is an important problem in directional MAC protocols. RTS failure ratio of DMAC/DA is lower than other directional MAC protocols and the deafness ratio is almost the same as MDA. Although RI-DMAC reactively handles deafness at the specific node, the deafness ratio of RI-DMAC is almost the same as that of DMAC/DA or other conservative schemes.

Figure 7 shows the overhead performance, defined as the average number of bits transmitted to deliver one bit of payload to the receiver at the MAC layer. CRM and CRCM have large control overheads due to the circular transmission of RTS/CTS and the increase of retransmissions. The overhead of DMAC/DA is lower than MDA because WTS frames are transmitted only through those sectors where potential transmitters are located to reduce the control overhead in DMAC/DA, whereas these frames are transmitted to all neighbors in MDA. RI-DMAC has lower overhead than proactive deafness handling schemes because it does not involve circular transmission of control frames.

Figure 8 shows the average end-to-end delay. CRM and CRCM have a longer delay because these protocols not only incur large over-

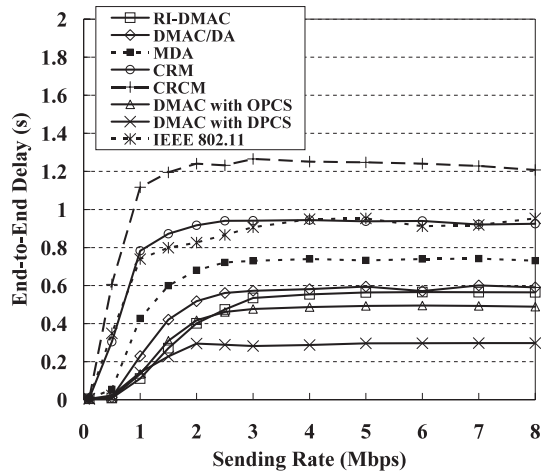


Fig. 8 End-to-end delay.

head but also spend the majority of their time transmitting control frames. It can be observed that DMAC/DA and RI-DMAC have less delay than MDA. This is because our proposed protocols have lower control overhead, and moreover, reduce idle time due to unnecessary back-off caused by deafness. In Fig. 8, results show that DMAC with DPCS outperforms others when the sending rate is high. Note that the results do not include the latency of packets that are dropped due to exceeding the maximum retry limit, which is set to 7 in our simulations, and also the routing overhead is not included. DMAC with DPCS suffers from excessive packet drops caused by deafness, and therefore route discovery procedures may be initiated throughout the network, which increase the end-to-end delay. Evaluating the impact of

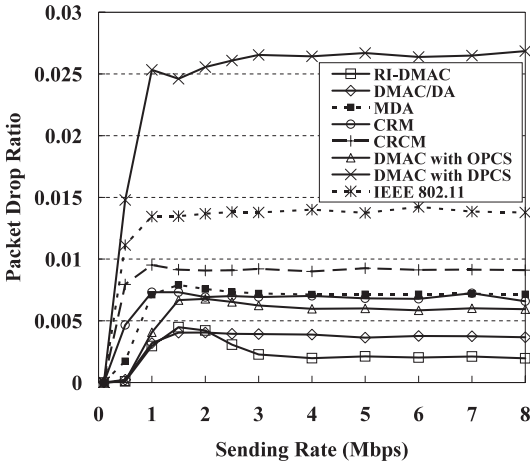


Fig. 9 Packet drop ratio.

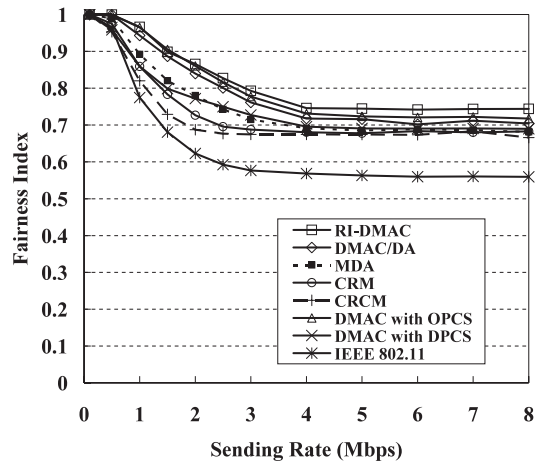


Fig. 10 Fairness index.

deafness on the network layer is projected for our future work.

Figure 9 shows the packet drop ratio due to exceeding the maximum retry limit. Results show that packet drop ratio of DMAC with DPCS is extremely high due to unproductive retransmissions of RTS caused by the deafness problem. Packet drop ratio of RI-DMAC is lower than others mainly due to overcoming the deafness problem reasonably, and it may prevent the expensive route rediscovery process.

As discussed in Ref. 6), the deafness problem also leads to the unfair channel access problem. Figure 10 shows the fairness index of eight MAC protocols. We use the max-min fairness defined in Ref. 20). Assuming the throughput of flow i is x_i , fairness index is calculated by the following expression.

$$f(x_1, x_2, \dots, x_n) = \frac{\left(\sum_{i=1}^n x_i\right)^2}{n \sum_{i=1}^n x_i^2} \quad (2)$$

Results show that RI-DMAC outperforms others in terms of fairness. This is because our sophisticated polling scheme in RI-DMAC selects the least recently transmitted node as a polled node and it solves the long-term and short-term fairness issues²¹⁾.

We next evaluate the MAC protocols with different numbers of flows, data size, and number of beams. Figure 11 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 1,024 bytes and $M = 6$). Results show that MDA, CRM

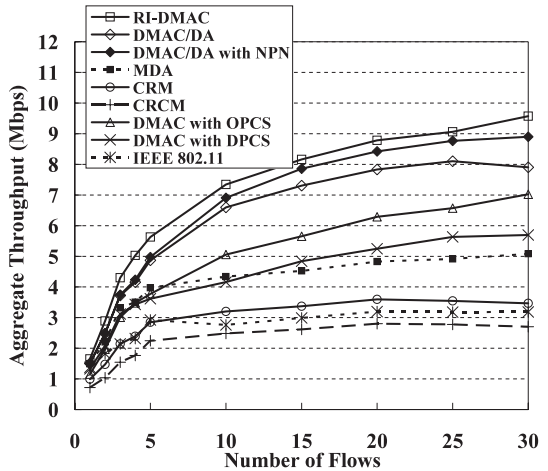


Fig. 11 Effects of the number of flows.

and CRCM cannot increase throughput performance as the number of flows increases because these protocols 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 properly and also for reducing the control overhead.

Figure 12 shows the effects of the data size. (sending rate is 2 Mbps, number of flows is 5

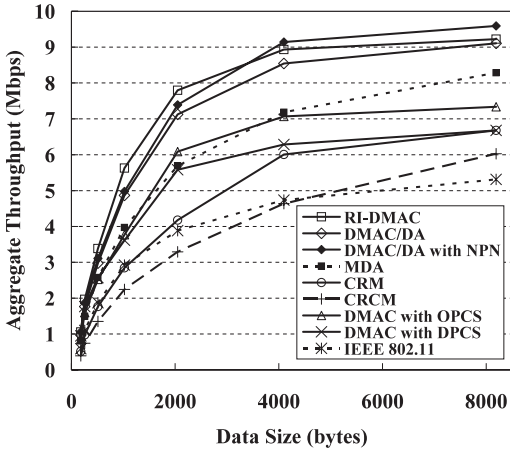


Fig. 12 Effects of the data size.

and $M = 6$). The control overhead relatively becomes small as the data size increases. On the other hand, when the data size is large, the duration that each node experiences deafness is increased and consequently the deafness problem becomes more serious. It can be seen that RI-DMAC outperforms other MAC protocols when the data size is not large. On the other hand, when the data size is large (i.e., more than 4,000 bytes), DMAC/DA with NPN has better performance than RI-DMAC. DMAC/DA with NPN achieves 5% improvement in terms of throughput compared with RI-DMAC when the data size is 8,000 bytes. This is because DMAC/DA with NPN uses multiple WTS frames to solve the deafness problem in all neighbors of communicating nodes which intend to communicate with the sender of the WTS. RI-DMAC solves deafness in one or two neighbor nodes using RTR, and other neighbors, which do not receive RTR, suffer from deafness again for a long time. Therefore, DMAC/DA with NPN has a higher throughput than RI-DMAC when the data size is large.

Figure 13 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 1,024 bytes). The beamwidth becomes narrower as the number of beams increases, and spatial reuse capabilities are enhanced. CRM and CRCM cannot achieve high throughput because the number of control frames increases in proportion to the number of beams. On the other hand, DMAC/DA and RI-DMAC can achieve high throughput due to reducing the number of control messages and consequently

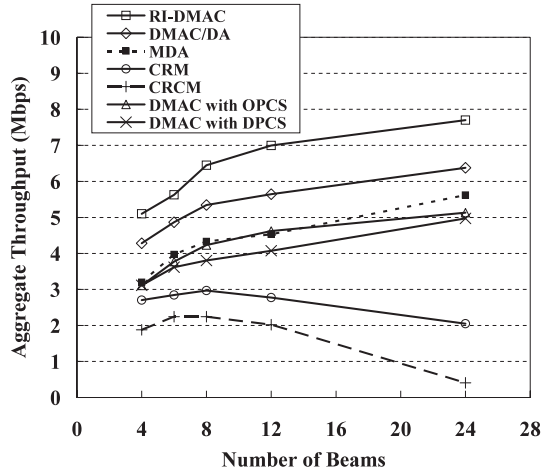


Fig. 13 Effects of the number of beams.

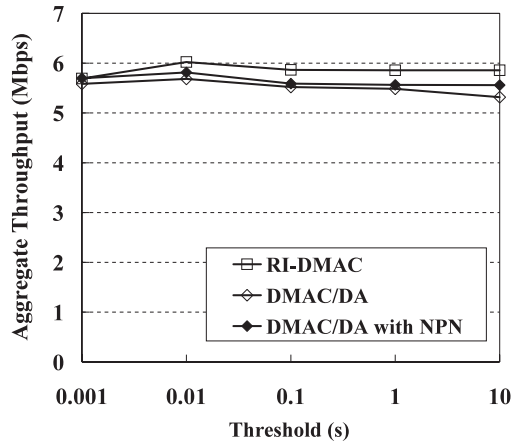


Fig. 14 Effects of the threshold.

allowing simultaneous communications.

Our proposed MAC protocols distinguish the potential transmitters from the neighboring nodes to solve the deafness problem and also reduce the control overhead. DMAC/DA and DMAC/DA with NPN use the neighbor table to do so, and RI-DMAC uses the polling table. When the transmitters are changed frequently, our proposed protocols rely on the threshold value, T_{DA} or T_{RI} , which removes the stale entry of the table. To evaluate the effect of the threshold values, 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. Figure 14 shows the throughput of DMAC/DA,

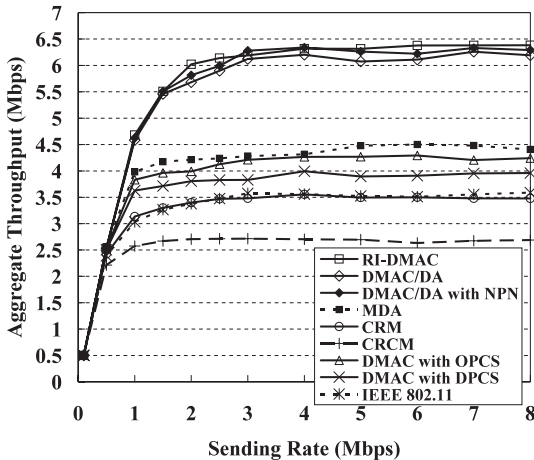


Fig. 15 Throughput in scenario where flows are randomly changed.

DMAC/DA with NPN and RI-DMAC when each threshold is from 0.001 to 10 (s) (sending rate is 2 Mbps, number of flows is 5, data size is 1,024 bytes and $M = 6$). Results show that our proposed protocols achieve the highest throughput when the thresholds are set to 0.01. When the thresholds are 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 or RTR frame is not transmitted to the deleted node and it suffers from deafness. On the other hand, when the thresholds are large, WTS frame or RTR frame is transmitted to the neighbor node even when the flow is no longer active. Although DMAC/DA with NPN and RI-DMAC notify the next packet information, the packet may be dropped due to exceeding the maximum retry limit. This deteriorates the throughput performance due to the overhead of unproductive transmissions. Therefore, there is an optimal value of the threshold, which solves the tradeoff between deafness handling and the overhead reduction. However, as shown in Fig. 14, the different values of the thresholds 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 9 MAC protocols in this scenario is shown in Fig. 15, where the threshold value of 0.01 is used in our proposed protocols. Each protocol achieves a higher performance compared with Fig. 4 because the traffic is distributed and spatial reuse is possible in this scenario. Results show that RI-DMAC has

the highest throughput and DMAC/DA with NPN has almost the same performance as RI-DMAC. It can be concluded that our proposed protocols solve the fundamental tradeoff between deafness handling and spatial reuse.

7. Conclusion

This paper presented DMAC/DA and RI-DMAC, which are proactive and reactive handling of deafness, respectively. In addition, we proposed DMAC/DA with NPN, enhanced DMAC/DA using the next packet notification. Simulation results show that RI-DMAC outperforms existing directional MAC protocols in terms of throughput, control overhead and packet drop ratio in the majority of scenarios investigated, especially when the numbers of flows and beams are large (e.g., up to 100% improvement compared with MDA). Results also show that DMAC/DA with NPN has a higher throughput than basic DMAC/DA because it reduces the overhead involved in unnecessary transmission of WTS frames, and that DMAC/DA with NPN has a higher throughput than RI-DMAC when the data size is large (e.g., up to 5% improvement compared with RI-DMAC when the data size is larger than 4,000 bytes).

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