A Directional MAC Protocol with Deafness Avoidance in Ad Hoc Networks

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SUMMARY This paper addresses the issue of deafness in MAC (Medium Access Control) protocols for wireless ad hoc networks using directional antennas. Directional antennas are expected to provide significant improvements over omni-directional antennas in ad hoc networks, such as high spatial reuse and range extension. Recently, several MAC protocols using directional antennas, typically referred to as directional MAC protocols, have been proposed for ad hoc networks. However, directional MAC protocols inherently introduce new kinds of problems arising from directivity. One major problem is deafness, caused by a lack of state information of neighbor nodes, whether idle or busy. This paper proposes DMAC/DA (Directional MAC with Deafness Avoidance) to overcome the deafness problem. DMAC/DA modifies the previously proposed MAC protocol, MDA (MAC protocol for Directional Antennas), to reduce the number of control messages and also maintain the ability to handle 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. The experimental results show that DMAC/DA outperforms existing directional MAC protocols, such as DMAC (Directional MAC) and MDA, in terms of throughput, control overhead and packet drop ratio under the different values of parameters such as the number of flows and the number of beams. In addition, qualitative evaluation of 9 MAC protocols is presented to highlight the difference between DMAC/DA and existing MAC protocols.

key words: ad hoc networks, medium access control, directional antennas, directional MAC protocol, deafness

1. Introduction

Omni-directional antennas are used in most of the previous works on wireless ad hoc networks [1]. Traditional MAC (Medium Access Control) 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]. On the other hand, 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, typically referred to as directional MAC protocols, have been proposed recently.

However, directional MAC protocols inherently introduce new kinds of problems related to directional transmissions as identified in [4]. Deafness problem is one of the major problems and it appears in most of 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.

This paper proposes DMAC/DA (Directional MAC with Deafness Avoidance) to handle the issue of deafness in directional MAC protocols for wireless ad hoc networks. DMAC/DA modifies the previously proposed MAC protocol, MDA (MAC protocol for Directional Antennas) [5], to reduce the number of control messages and maintain the ability to handle deafness at the same time. In DMAC/DA, each node maintains a neighbor table, and 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. WTS frames are transmitted only through those sectors where potential transmitters are located to reduce the control overhead. We evaluate our protocol through extensive simulation study with different values of parameters such as the number of flows and beamwidth. The experimental results show that DMAC/DA outperforms existing directional MAC protocols in terms of throughput, control overhead and packet drop ratio.

2. Related Work

IEEE 802.11 DCF [2] is a contention-based protocol of CSMA/CA (Carrier Sense Multiple Access with Collision Avoidance). The RTS and CTS control frames relieve the hidden-terminal problem through the NAV (Network Allocation Vector). However, it wastes a large portion of the network capacity by preserving the wireless media over a large area as discussed in [3].

Recently, several directional MAC protocols have been proposed for wireless ad hoc networks. In [4], Choudhury et al. propose DMAC (Directional MAC) in which all frames are transmitted and received directionally, and physical and virtual carrier sense functions are also performed direction-
ally. In this paper, we refer to this protocol as DMAC with DPCS (Directional Physical Carrier Sensing). Directional virtual carrier sensing is realized by DNA V (Directional NA V), a directional version of NA V. They also propose MMAC (Multi-hop RTS MAC) which involves multi-hop RTS to take advantage of the higher antenna gain obtained by directional antennas, and the issues of directional MAC protocols including deafness are discussed but no solution is provided.

In [6], [7], the RTS and CTS frames are transmitted omni-directionally for each Data frame and directional capabilities are utilized only for Data/ACK frames. In [8], RTS is transmitted omni-directionally in order to find the receiver in case location information is not available. Because these protocols employ at least one omni-directional transmission, it restricts the coverage range provided by directional transmissions. Although omni-directional RTS/CTS is one simple solution to avoid deafness by notifying the ongoing communication to all neighbors, any transmissions cannot be initiated until all DNAs are expired in order not to disturb other on-going communications (e.g., [6]). This may reduce the benefits of spatial reuse. In [7], an omni-directional RTS is transmitted if the direction of the intended receiver is not blocked by DNA V. However, this omni-directional transmission of RTS may interfere with the ongoing communications when DNAs are set even in the different directions of the intended receiver.

In [9]–[11], circular directional transmission of periodic hello packets is utilized to obtain node information that is located farther away from the omni-directional transmission range, and to exploit the increase of the transmission range. Takata et al. [12] 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.

Several recent directional MAC protocols attempt to overcome the issue of deafness. In [5], [13], [14], in-band solutions that use additional control frames to alleviate the deafness problem are proposed. These protocols are illustrated in Sect. 4.2.

Choudhury and Vaidya [15] propose ToneDMAC, 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). They then propose the tone-based feedback mechanism, called ToneDMAC, to neighbors of communicating node in order to distinguish deafness from congestion as the reason for communication failure. ToneDMAC needs a dedicated control channel to transmit tones as well as a data channel.

Wang et al. [16] propose SYN-DMAC to address the issues of directional MAC protocols including deafness for ad hoc networks with clock synchronization. This scheme requires that nodes are synchronized to identify the timing structure.

Solutions of directional MAC problems other than deafness such as location information staleness and directional hidden- and exposed-terminal problems are proposed in [17], [18]. 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 [11]–[13].

3. Antenna Model

We assume that each node is equipped with a switched beam antenna system which is comprised of $M$ fixed beam patterns [4]–[18]. 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 the Omni mode, a node receives signals from all directions with gain $G_o$. While idle (i.e., neither transmitting nor receiving), a node waits for signals in the Omni mode to receive frames from other nodes. After a signal is sensed in the 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 $G_d$ ($> G_o$).

4. Deafness Problem

4.1 Problem Description

As discussed in [15], the deafness problem leads to unproductive retransmissions and the wastage of the wireless channel. Figure 1 illustrates deafness situations where directional links are indicated by arrowed lines, and there are three flows (i.e., A to B, B to C, and C to D). We consider

Fig. 1  Deafness situations.
DMAC with DPCS [4] to explain deafness. Assume that nodes A and B have packets to be sent at the beginning of the sequence in Fig. 1. Each of these nodes points its beam towards the intended receiver and performs backoff in the Directional mode. In this case, node B sends RTS to C first. Node A is unaware of the communication between node B and node C because A does not overhear the directional signals between B and C. While B is communicating with C, A attempts to communicate with B, but it fails because B has its beam pointed towards C, and B is deaf with respect to A. Then, node A backs off and repeatedly attempts to communicate. Even though B completes packet delivery to C, B keeps its beam towards C during backoff periods to deliver the next packet, and remains deaf to A. It may result in a packet drop at A after unproductive retransmissions. Deafness problem also appears in the neighborhood of the receiver. If node E attempts to communicate with C while C is receiving Data from B, it suffers from deafness.

Another problem of deafness is the wastage of the wireless channel. After the completion of the communication between B and C, a packet is generated at C. Node C switches to the Directional mode and sends the packet to D. After the communication between C and D, C becomes idle and switches back to the Omni mode because there is no packet in its queue. Node B, however, cannot detect the completion of the communication between C and D by both physical and virtual carrier sensing. Node B thus cannot initiate a transmission immediately because it has a longer backoff time due to the fact that the contention window is doubled for each retransmission, and the wireless channel remains unused during this period.

Because of these situations, the deafness problem leads to excessive packet drops, longer delay, wastage of the wireless channel, and unfairness. As a result, the throughput of DMAC with DPCS degrades significantly as shown in Fig. 2.

Deafness problem does not appear when each node is equipped with the omni-directional antenna because A can overhear the signal from B when B is communicating with C, and A does not try to initiate any transmissions. On the other hand, in DMAC, the RTS and CTS frames are transmitted in the restricted area and each node cannot acquire the on-going transmission information of neighborhoods. Therefore, deafness is mainly caused by a lack of state information of neighbor nodes, whether idle or busy.

4.2 Solutions in Related Work

To solve the deafness problem, several directional MAC protocols introduce additional control frames to inform neighboring nodes of imminent communication. Figure 3 shows the examples of frame exchange in directional MAC protocols. In Circular RTS MAC (CRM) [13] (Fig. 3(B)), multiple directional RTS frames are transmitted consecutively in a circular way to notify the on-going communication to neighbor nodes. While it prevents deafness at the transmitter side, deafness at the receiver side may appear. Moreover, if node B does not reply with CTS and node A cannot transmit Data frame, the neighboring nodes of A, which receive RTS and set DNA V, also cannot initiate their own transmissions for the reserved entire duration, and it results in serious wastage of the wireless channel. To handle deafness at the receiver side, Circular RTS and CTS MAC (CRCM) [14] (Fig. 3(C)) 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 [5] (Fig. 3(D)), multiple directional RTS and CTS frames are transmitted simultaneously 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 for neighbors, which do not intend to communicate with A or B, to acquire the disjoint node information (for neighbors such as nodes C and J in Fig. 3). Furthermore, there is a deafness region not covered by the DOD procedure because it is carried out from the next beam to the opposite beam in order to reduce the number of transmitted control frames. Therefore, if node D intends to communicate with A, it may experience deafness. Obviously, there is a fundamental tradeoff between deafness avoidance using control frames and the overhead reduction using the optimized control frame transmission mechanism. This paper addresses this tradeoff.

4.3 Deaf Zone

The deaf zone is defined as the area that is not covered by the frame exchange between communicating nodes, originally defined by Choudhury and Vaidya. If a node is located within the deaf zone, it may experience deafness. We define the deaf zone ratio as the ratio of the deaf zone over the whole coverage area. We calculate the deaf zone ratio of DMAC, CRM, and MDA. Because the deaf zone ratio of CRCM is almost zero, it is omitted here.

The whole coverage area of a communicating pair is obtained by [19].
Frame exchange in directional MAC protocols, where active links are A-B, D-A, F-A, and I-B.

Fig. 3

\[ W(r) = 2\pi R^2 - 2R^2 q\left(\frac{r}{2R}\right), \]

where \( R \) is the transmission range, \( r \) is the distance between the communicating nodes, and that \( q(t) = \arccos(t) - t \sqrt{1-t^2} \).

The covered area of DMAC is given by

\[ C_A(r) = \theta R^2 - \frac{r^2 \tan(\frac{\theta}{2})}{2}, \]

where \( \theta \) is the beamwidth.

The probability density function of the distance \( r \) is

\[ f(r) = \frac{2r}{R^2}, \quad 0 \leq r \leq R. \]

Therefore, we can calculate the average deaf zone ratio of DMAC

\[ D_A = \int r^2 R^2 \left(1 - \frac{C_A(r)}{W(r)}\right) dr. \]

The covered area of CRM \( C_B(r) \) is \( \pi R^2 \) and the average deaf zone ratio of CRM is given by

\[ D_B = \int r^2 R^2 \left(1 - \frac{C_B(r)}{W(r)}\right) dr. \]

Similarly, the covered area of MDA when the DOD procedure is carried out from the next beam through the opposite beam is

\[ C_D(r) = \pi R^2 - \frac{\theta}{2} R^2 + \frac{\theta}{2}(R - r)^2. \]

Thus, the average deaf zone ratio of MDA is equal to

\[ D_D = \int r^2 R^2 \left(1 - \frac{C_D(r)}{W(r)}\right) dr. \]

When the transmission range \( R \) is 500 m and the beamwidth \( \theta \) is \( \pi/3 \), the deaf zone ratio of DMAC, CRM, and MDA are 0.76, 0.22, and 0.14, respectively. Therefore, if the nodes are randomly placed according to a two-dimensional uniform distribution, 14 percent of neighbor nodes may still experience deafness in MDA.

5. DMAC/DA

In this section, we propose DMAC/DA protocol, an optimized control frame transmission mechanism to overcome the deafness problem and to solve the tradeoff mentioned in the previous section. The details of DMAC/DA are presented next.

5.1 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 1 shows the structure of neighbor table (example of A’s neighbor table in Fig. 3(E)). The record of Table 1 means that A can transmit 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. This field is updated by each reception of the Data frame addressed to itself. 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 transmission exceeds a certain threshold value, $T_{th}$, it is removed from the table. The optimal value of the threshold depends on the mobility and the traffic pattern. The effect of the threshold on the traffic pattern is evaluated in Sect. 6.

5.2 Protocol Description

We use Fig. 3 (E) to explain the procedure of DMAC/DA. In DMAC/DA, each idle node stays in the Omni mode. 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 [15]. When the node senses a signal in backoff periods, it performs the beam scan to determine the direction of the arriving signal. If the estimated direction is in a different direction from that of the intended receiver, then the transmitter continues backing off; otherwise the transmitter considers that channel is busy. If the transmitter receives RTS addressed to it during backoff periods, the transmitter freezes the backoff timer and replies with CTS. It can mitigate unproductive retransmissions due to “persistent deafness” arising from directional physical carrier sensing. However, the wastage of the channel due to deafness is not solved.

If the channel remains idle during backoff periods, node A determines the number of WTS frames $K_A$ (out of $M - 1$) should be transmitted after the successful exchange of RTS and CTS. It checks its own neighbor table and also DNAV table for each beam whether potential transmitters are located and DNAV is not set in its beam. Unlike MDA, all beams except the beam towards B are checked in order to inform all potential transmitters of imminent communication. Note that if DNAV is set in the corresponding beam, this beam is removed from $K_A$ even though there are potential transmitters. $K_A$ 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. If node B receives RTS, it also determines the number of WTS frames $K_B$. Then, node B switches to the Directional mode and sends CTS including $K_B$. Only after the RTS/CTS handshake is successfully completed, A and B send WTS frames simultaneously using the selected beams. Node A transmits WTS frames from the beam that is located just right of the one o’clock position, and node B starts from the beam of the five o’clock position in Fig. 3(E) where the potential transmitters of A are F and D, the potential transmitter of B is I, and the number of beams $M$ is six. WTS frames are sequentially transmitted counter-clockwise to avoid collisions between WTS frames. The frame format of WTS is the same as that of RTS. Duration field of each frame can be decremented accurately because node A can obtain $K_A$ from the CTS and node B vice versa. After both of the nodes complete WTS transmissions, node A sends the directional Data frame and node B sends the directional ACK frame. Both A and B switch back to the Omni mode after the Data/ACK frame exchange.

When the neighbor nodes receive the WTS, these nodes set the sender of the WTS as a deaf node in the deafness duration field of its own neighbor table and defer their own transmissions addressed to the deaf node 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. Figure 4 shows this scenario. This reduces the channel wastage due to unnecessary backoff caused by the deafness problem. Note that DNAV table is not updated by reception of WTS. In Fig. 3(E), while node D receives WTS transmitted by A and refrains from initiating transmission addressed to A, it can communicate with node E without interference between the on-going communication between A and B. DNAV table is updated only when the node receives RTS or CTS.

Differences between DMAC/DA and MDA are summarized as follows.

- In DMAC/DA, WTS frames are transmitted only through those sectors where potential transmitters are located, whereas these frames are transmitted through sectors with neighbors in MDA.
- There is the deaf zone not covered by the DOD procedure in MDA as discussed in Sect. 4.3. On the other hand, the adaptive WTS transmissions can cover all potential transmitters in DMAC/DA.
- In DMAC/DA, if a node fails to communicate with the sender of WTS and the backoff procedure is invoked before receiving WTS, it reselects a new smaller backoff counter for the next attempt.

### Table 1 Neighbor table.

<table>
<thead>
<tr>
<th>ID</th>
<th>Beam Number</th>
<th>Deafness Duration</th>
<th>Link Activity</th>
</tr>
</thead>
<tbody>
<tr>
<td>B</td>
<td>1</td>
<td>–</td>
<td>$B_{RxTime}$</td>
</tr>
<tr>
<td>C</td>
<td>4</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>D</td>
<td>3</td>
<td>$T_D$</td>
<td>$D_{RxTime}$</td>
</tr>
<tr>
<td>E</td>
<td>2</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>F</td>
<td>6</td>
<td>$T_F$</td>
<td>$F_{RxTime}$</td>
</tr>
<tr>
<td>G</td>
<td>2</td>
<td>–</td>
<td>–</td>
</tr>
</tbody>
</table>

![Fig. 4 Handling the wastage of the wireless channel.](image-url)
6. Performance Evaluation

To evaluate the performance of DMAC/DA we developed an event driven simulator. In addition to DMAC/DA, the following six MAC protocols are evaluated in terms of throughput, overhead, packet drop ratio and so on.

- MDA [5]
- CRM [13]
- CRCM [14]
- DMAC with OPCS (Omni-directional Physical Carrier Sensing) [15]
- DMAC with DPCS (Directional Physical Carrier Sensing) [4]
- IEEE 802.11 [2]

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 shortest path. Transmission range of the omnidirectional antenna is 250 m and that of the directional antenna is 500 m. The data size is 1024 bytes and the data rate is 11 Mbps. We do not consider mobility in our simulations. We change the parameters such as the sending rate of each flow, the number of flows, and the 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 specifications [2]. 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 and the number of beams $M$ is six. Figure 5 shows the throughput of seven MAC protocols. As shown in the figure, CRM and CRCM perform lower than IEEE 802.11 because these directional MAC protocols introduce the larger control overhead and increase collisions. Throughput of MDA is higher than DMAC. This is because that MDA mitigates deafness proactively using the DOD procedure although it has the larger control overhead than DMAC. DMAC/DA outperforms others because it reduces the number of control messages compared with MDA, and maintains the ability to handle deafness at the same time.

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

$$RFR = 1 - \frac{N_{CTS}}{N_{RTS}} \quad (8)$$

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. Communication failure factors in directional MAC protocols are classified in [17]. Figures 6 and 7 show the RTS failure ratio and deafness ratio, respectively. Results show that DMAC with DPCS cannot resolve deafness and most of communication failures occur due to deafness. DMAC with OPCS mitigates unproductive retransmissions of RTS and solves the deafness problem.
Deafness ratio of CRM is higher than CRCM because deafness appears due to the transmission of single directional CTS. The circular transmission of CTS, however, incurs large control overhead and reduces spatial reuse of the wireless channel, and thus CRCM achieves the least throughput. 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.

Figure 8 shows the overhead performance. Overhead becomes large when a large number of control bits are transmitted and/or frames are retransmitted. CRM and CRCM have large control overheads due to the circular transmission of RTS/CTS and the increasing of retransmissions. DMAC/DA has lower overhead 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. It can be concluded that DMAC/DA solves deafness properly and increases throughput performance by reducing the control overhead.

Figure 9 shows the average end-to-end delay. DMAC/DA has less delay than MDA. In Fig. 9, 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 increases the end-to-end delay.

Figure 10 shows the packet drop ratio due to exceeding the maximum retry limit. Results show that packet drop in DMAC with DPCS is extremely high due to unproductive retransmissions of RTS caused by the deafness problem. Packet drop ratio of DMAC/DA is lower than others mainly due to overcoming the deafness problem reasonably, and it may prevent the expensive route rediscovery process. Evaluating the impact of deafness on the network layer is included in our future work.

We next evaluate the MAC protocols with different number of flows and that 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 and \( M = 6 \)). Results show that MDA, CRM 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 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.

Figure 12 shows the throughput of directional MAC protocols when the number of beams \( M \) is changed from 4 to 24 (sending rate is 2 Mbps and number of flows is 5). The beamwidth becomes narrower as the number of beams increases, and spatial reuse capabilities are enhanced. CRM
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 relies on the way to distinguish the potential transmitters to solve the deafness problem. Therefore, the performance of DMAC/DA is based on the threshold value, $T_h$, which removes the stale entry of the neighbor table. To evaluate the effect of $T_h$, 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 13 shows the throughput of DMAC/DA when $T_h$ is from 0.001 to 10 (s) (the number of flows is 5 and $M = 6$). Results show that DMAC/DA achieves the highest throughput when $T_h$ is 0.01. When $T_h$ 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 $T_h$ is large, WTS frame is transmitted to the neighbor node even when the flow is no longer active. This deteriorates the throughput performance due to the overhead of WTS transmissions.

Therefore, there is an optimal value of $T_h$, which solves the tradeoff between deafness avoidance and the overhead reduction.

7. Qualitative Evaluation

Table 2 shows the qualitative evaluation of 9 MAC protocols to highlight the difference between the protocols. Deafness handling column in Table 2 represents that the protocol handles deafness proactively or reactively, and handling method column presents its handling method. ToneDMAC requires an additional tone channel and its related hardware, and SYN-DMAC assumes the system-wide synchronization is available, which requires GPS receivers or other synchronization schemes (see [16] and references therein), as indicated in the additional H/W column. Overhead, duration and deaf zone ratio of each protocol are calculated when there is no collision and retransmission, and the data size is 1024 bytes and the number of beams is six. These of DMAC/DA and MDA are adaptively changed according to the distribution of nodes and the traffic pattern. Duration is the time interval which calculates the instant the RTS is transmitted to the instant the ACK frame is received by the transmitter.

8. Conclusion

This paper addressed the issue of deafness in directional MAC protocols and proposed DMAC/DA protocol to handle the deafness problem proactively. DMAC/DA modifies MDA to reduce the number of control messages and also maintain the ability to handle deafness. In DMAC/DA, the WTS frames are simultaneously 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. Simulation results show that DMAC/DA outperforms existing directional MAC protocols in terms of throughput, control overhead and packet drop ratio. Also, the qualitative evaluation of 9 MAC protocols was presented.
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References


Table 2 Qualitative evaluation of 9 MAC protocols.

<table>
<thead>
<tr>
<th>Protocols</th>
<th>Antenna Model</th>
<th>Tx Range</th>
<th>RTS-type</th>
<th>CTS-type</th>
<th>Additional H/W</th>
<th>Deafness Handling</th>
<th>Handling Method</th>
<th>Overhead (ms)</th>
<th>Duration (ms)</th>
<th>Deaf Zone</th>
</tr>
</thead>
<tbody>
<tr>
<td>DMAC/DA [4], [15]</td>
<td>Switched Beam</td>
<td>Directional</td>
<td>Single + Circular</td>
<td>Single + Circular</td>
<td>N/A</td>
<td>Proactive</td>
<td>Adaptive WTS</td>
<td>1.10-1.30</td>
<td>1.61-2.70</td>
<td>0-0.76</td>
</tr>
<tr>
<td>CRM [13]</td>
<td>Switched Beam</td>
<td>Directional</td>
<td>Circular</td>
<td>Single</td>
<td>N/A</td>
<td>Proactive</td>
<td>Circular RTS</td>
<td>1.21</td>
<td>2.71</td>
<td>0.22</td>
</tr>
<tr>
<td>CRCM [14]</td>
<td>Switched Beam</td>
<td>Directional</td>
<td>Circular</td>
<td>Circular</td>
<td>N/A</td>
<td>Proactive</td>
<td>Circular RTS/CTS</td>
<td>1.28</td>
<td>3.37</td>
<td>0</td>
</tr>
<tr>
<td>MDA [5]</td>
<td>Switched Beam</td>
<td>Directional</td>
<td>Single + Circular</td>
<td>Single + Circular</td>
<td>N/A</td>
<td>Proactive</td>
<td>DOD RTS/CTS</td>
<td>1.10-1.22</td>
<td>1.61-2.27</td>
<td>0.14-0.76</td>
</tr>
<tr>
<td>ToneDMAC [16]</td>
<td>Switched Beam</td>
<td>Directional</td>
<td>Single</td>
<td>Single</td>
<td>Tone Channel</td>
<td>Reactive</td>
<td>Out-of-hand Tone</td>
<td>1.09</td>
<td>1.61 + tone</td>
<td>0</td>
</tr>
<tr>
<td>SYN-DMAC [16]</td>
<td>Switched Beam</td>
<td>Directional</td>
<td>Single</td>
<td>Single</td>
<td>Clock</td>
<td>Proactive</td>
<td>Omni Tone/CTS</td>
<td>1.10</td>
<td>One cycle</td>
<td>0.76</td>
</tr>
<tr>
<td>Nasipuri et al’s MAC [6]</td>
<td>Switched Beam</td>
<td>Omni</td>
<td>Single</td>
<td>Single</td>
<td>N/A</td>
<td>Proactive</td>
<td>Omni RTS/CTS</td>
<td>1.09</td>
<td>1.61</td>
<td>0</td>
</tr>
<tr>
<td>IEEE 802.11 [2]</td>
<td>Omni Antenna</td>
<td>Omni Single</td>
<td>Single</td>
<td>Single</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>1.09</td>
<td>1.61</td>
<td>0</td>
</tr>
</tbody>
</table>
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