Tradeoff between Spatial Reuse and Deafness Avoidance in Directional MAC Protocols for Ad Hoc Networks

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Abstract Directional antennas have great potential such as high spatial reuse and range extension. However, deafness is a crucial problem, caused by a lack of state information of neighbor nodes. This paper proposes two directional MAC protocols, DMAC/DA (Directional MAC with Deafness Avoidance) and RI-DMAC (Receiver-Initiated Directional MAC), to handle the deafness problem. DMAC/DA uses WTS (Wait To Send) frames to notify the on-going communication to potential transmitters that may experience deafness. RI-DMAC handles deafness reactively using a combination of sender-initiated and receiver-initiated operations. The experimental results show that our proposed protocols outperform existing directional MAC protocols in terms of throughput, control overhead and RTS failure ratio.

Keyword Ad Hoc Networks, Medium Access Control, Directional Antennas, Deafness Problem

1. Introduction

In the previous works on ad hoc networks [1], omni-directional 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 omni-directional antennas and these protocols lead to inefficient use of the wireless channel and consequently deteriorate the throughput in ad hoc networks as discussed in [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.

Directional MAC protocols, however, inherently introduce new kinds of problems related to directional transmissions as identified in [4, 5]. 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 [6], the deafness problem leads to unproductive retransmissions and the wastage of the wireless channel. To avoid the deafness problem, several conventional directional MAC protocols use additional control frames to inform neighboring nodes of imminent communication. However, these protocols introduce large control overhead, and consequently reduce the spatial reuse efficiency. Therefore, there is a fundamental tradeoff between spatial reuse and deafness avoidance.

This paper presents two directional MAC protocols, DMAC/DA (Directional MAC with Deafness Avoidance) [7] and RI-DMAC (Receiver-Initiated Directional MAC) [8], to solve the tradeoff between spatial reuse and deafness avoidance. DMAC/DA is a proactive handling method for deafness. 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. 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. The experimental results show that our proposed MAC protocols outperform existing directional MAC protocols in terms of throughput, RTS failure ratio and control overhead in the majority of scenarios investigated.

2. Related Works

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 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 (Directional Network Allocation Vector), 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 [9, 10] 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 et al. [11] 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. Jakllari et al. [12] 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 [13], Gossain et al. propose MDA (MAC protocol for Directional Antennas). In MDA, multiple directional RTS and CTS frames are transmitted sequentially 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. However, it is unnecessary to notify the imminent communication to neighbors, which do not intend to communicate with the transmitter or the receiver.

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. Obviously, there is a fundamental tradeoff between deafness avoidance and the overhead reduction. This paper addresses this tradeoff in in-band solutions.

Choudhury and Vaidya [6] 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). 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.

We assume that each node is equipped with a switched beam antenna system which is comprised of $M$ fixed beam patterns [4-15]. 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 [14, 15].

3. DMAC/DA

In this section, we present DMAC/DA [7]. Deafness is caused because each node is unaware of the on-going communications in the 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.

3.1. 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 as well as neighbor ID and beam number. 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 $T_h$, it is removed from the table.

We use Fig. 1 to explain the procedures 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 $K_A$ of 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 whether potential transmitters are located and DNAV is not set in its beam. In the case of Fig. 1, $K_A$ is set to two because nodes D and E 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. 1 (1)). If node B receives RTS, it also determines the number $K_B$ of beams, in which potential transmitters exist. In the case of Fig. 1, $K_B$ 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. 1 (2)). Only after the RTS/CTS handshake is successfully completed, 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. 1 (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. 1 (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. 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. 1 (5, 6)). Both A and B switch back to the Omni mode after the Data/ACK frame exchange.

3.2. 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 properly 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 appends a 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 $Th$, it is removed from the table for handling mobility.

4. RI-DMAC

This section presents RI-DMAC [8], 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.

4.1. 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 in the head of its queue, the transmitter appends a 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 $Th$, it is removed from the table for handling mobility.

4.2. Polling Scheme

Initially, all nodes operate in sender-initiated mode (SI-mode) using a four-way handshake (Fig. 2 (1)). After exchanging the Data/ACK frames, the transmitter and the receiver check its own polling table 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. 2 (2)); otherwise it stays in SI-mode. In RI-mode, the 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. This reduces the channel wastage due to unnecessary backoff.
5. Performance Evaluation

To evaluate the performance of our proposed MAC protocols, 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 shortest path. Transmission range of the omni-directional antenna is 250 m and that of the directional antenna is 500 m. The number of beams is six (60 degree beamwidth). 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, and data size. Other parameters not described in this paper, such as the interframe space and the contention window size, follow the IEEE 802.11 specifications.

We first evaluate the performance of different MAC protocols when the sending rate of each flow is changed, the number of flows is five, and data size is 1024 bytes. Fig. 3 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 that 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 higher throughput than basic DMAC/DA because it reduces the unnecessary WTS transmission compared with basic DMAC/DA based on the next packet information of neighbor nodes. RI-DMAC outperforms other directional MAC protocols because the proposed polling scheme alleviates deafness using the RTR frame transmitted by the receiver node for inviting the deafness node to transmit its packet and reduces control frames compared with a four-way handshake. RI-DMAC balances the tradeoff between spatial reuse and deafness avoidance, and achieves the highest throughput.

We next define RTS failure ratio and deafness ratio to confirm the ability for handling deafness of each directional MAC protocol. Deafness ratio is defined as the ratio of the communication failure due to deafness over the whole communication failure factors [5]. Figs. 4 and 5 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 per-
performance metrics, results of DMAC/DA with NPN are omitted here. The results show that DMAC with DPCS suffers from deafness and that the most of communication failures occur due to deafness. DMAC with OPCS mitigates unproductive retransmissions of RTS and solves the deafness 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. 5, 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 spatial reuse and deafness avoidance is an important problem in directional MAC protocols. RTS failure ratio of DMAC/DA is lower than other directional MAC protocols and deafness ratio is almost the same as MDA. Although RI-DMAC reactively handles deafness at the specific node, deafness ratio of RI-DMAC is almost same as that of DMAC/DA or other conservative schemes.

Fig. 6 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 increasing of retransmissions. 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.

We next evaluate the MAC protocols with different number of flows and data size. Fig. 7 shows the aggregate throughput when the number of flows is changed from 1 to 30 (sending rate of each flow is 2 Mbps and data size is 1024 bytes). The results show that MDA, CRM and CRCM cannot increase throughput performance as the number of flows increases because these protocols 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. 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 to transmit WTS frames properly and also reduce the control overhead.

Fig. 8 shows the effects of the data size (sending rate is 2 Mbps and number of flows is 5). 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. When the data size is large (i.e., more than 4000 bytes), to the contrary, 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 8000 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 higher throughput than RI-DMAC when the data size is large.

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, $Th$, 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. Fig. 9 shows the throughput of DMAC/DA, 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, and data size is 1024 bytes). The 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. The throughput of 9 MAC protocols in this scenario is shown in Fig. 10, where the threshold value of 0.01 is used in our proposed protocols. The results show that RI-DMAC has the highest throughput and DMAC/DA with NPN has the almost same performance as RI-DMAC. It can be concluded that our proposed protocols solve the fundamental tradeoff between deafness handling and spatial reuse.

6. 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. The simulation results show that RI-DMAC outperforms existing directional MAC protocols in terms of throughput, control overhead and RTS failure ratio in the majority of scenarios investigated (e.g., up to 100% improvement compared with MDA). The results also show that DMAC/DA with NPN has 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 4000 bytes).

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