Deafness-aware MAC Protocol for Directional Antennas in Wireless Ad Hoc Networks

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Abstract

The use of directional antennas is a promising technique for the provision of high-speed wireless local and personal area networks such as IEEE 802.11ac, IEEE 802.11ad, and IEEE 802.15.3c. In this paper, we propose a new directional MAC protocol for wireless ad hoc networks that is referred to as deafness-aware MAC (DA-MAC). Although a significant number of directional MAC protocols have been proposed, they have not comprehensively resolved the deafness problem. Our proposed DA-MAC protocol can distinguish the deafness problem from collisions by employing logical data and control channels. We provide a discrete-time Markov chain model to analyze the impact of deafness for both an existing technique and DA-MAC. Through extensive simulations, we show that our DA-MAC protocol can significantly outperform the other existing techniques with respect to the throughput, deafness duration, energy consumption, and transmission fairness.

Keywords: Directional MAC, deafness problem, and collision

1. Introduction

In the near future, wireless technologies that support even greater data throughput than IEEE 802.11n over short distance will emerge in order to eliminate wires between multimedia devices such as uncompressed HDTV, high volume storage, HD digital cameras, etc., under fixed topologies [4, 5, 14, 17, 20]. One of the core technologies in which industries are interested is directional antennas, through which consumer devices can obtain benefits, namely better spatial reuse and a longer transmission range. For this reason, standardization organizations such as IEEE 802.11ac, IEEE 802.11ad, and IEEE 802.15.3c have focused a great deal of attention on MAC protocols using directional antennas (or *directional MAC*).

Despite these merits, directional MAC protocols are known to suffer from a deafness problem that reduces the throughput of the network. The deafness problem occurs if a node does not answer a directional RTS (DRTS) frame addressed to it. Consequently, the originator of the DRTS will try more DRTS frames, thus increasing the contention window, during which time the messages to other nodes are blocked.

According to our taxonomy, the existing solutions to the deafness problem can be classified as (1) approaches using multiple control frames [9, 11, 13, 21]; (2) approaches that notify potential senders [8, 19]; and (3) tone-based approaches [1, 6]. The approaches using multiple control frames try to solve the deafness problem by disclosing the transmission information to all of the neighboring nodes. The nodes receiving the control frame understand that there is an upcoming communication and delay their communication in order to avoid deafness. Instead of transmitting multiple control frames, the approaches that notify potential senders exploit a local table that maintains the potential senders who have previously transmitted an advance notice. The advance notice informs the receiver that the sender will transmit data in the next available time so that the sender can minimize deafness duration. The tone-based approaches try to distinguish deafness from a collision using one or more tone signals. Unfortunately, none of these three approaches have comprehensively resolved the deafness problem (as will be described in Section 2).

The contribution of this paper can be summarized as follows:

- We have classified the existing schemes and identified their limitations (in Section 2),
- We have proposed a new directional MAC that is referred to as deafness-aware MAC (DA-MAC) to completely resolve the deafness problem by distinguishing deafness from a collision (in Section 3). To the best of our knowledge, DA-MAC is the first protocol that can completely rectify the deafness problem,
- We have provided a discrete-time Markov chain model to analyze the impact of deafness for both an existing technique and DA-MAC. We have shown that the impact of deafness is critical to the overall performance in the existing technique but can be greatly relaxed in DA-MAC (in Section 4), and
- We have shown that DA-MAC significantly outperforms the existing techniques in terms of various performance in-

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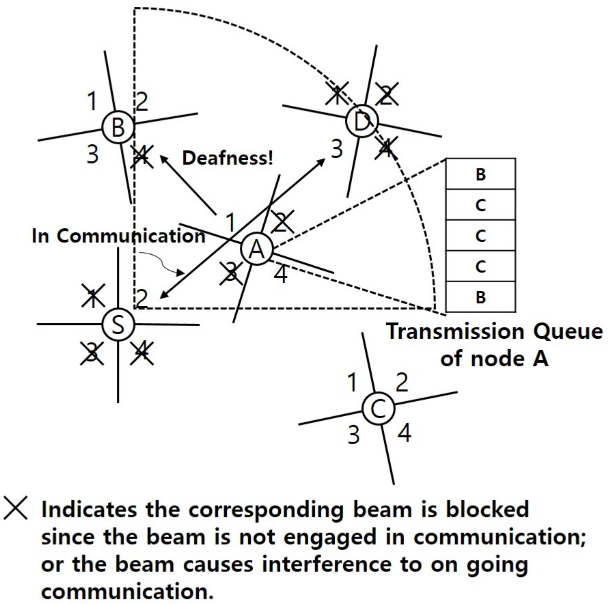

Figure 1: An example of the deafness problem (4 antenna beams).

dices (in Section 5) and presented our conclusions in Section 6.

2. Related Work

According to the taxonomy mentioned in Section 1, the schemes in [9, 11, 13], and [21] are multiple control frame approaches. In [9], authors proposed the circular RTS/CTS MAC (CRCM) scheme where a transmitter and receiver pair sequentially transmits multiple control frames (DRTSs and DCTSs, respectively) using all of the antenna beams. If a nearby node overhears that control frame, the corresponding beam of the node is blocked.[1] Since the control frames are transmitted in all directions near the sender and the receiver, the neighboring nodes are aware of the ongoing communication. Likewise, [11, 13] and [21] used multiple control frames. Although these approaches have multiple RTS/CTS overheads, they do not completely resolve the deafness problem. Figure 1 is an example of the deafness problem that occurred in [9, 11, 13, 18] and [21]. Suppose that node *S* has data for *D*. Node *S* then transmits DRTS frames to *D* and its neighboring nodes. Accordingly, node *D* and its neighbors answer with DCTS frames. During exchange of these control frames, beams that cause the interference to *S* and *D* are blocked, just as beam 4 of node *B* is blocked in Figure 1. Now, if node *A* has data for *B*, node *A* will send DRTS frames to *B* and its neighbors. However, node *B* will not receive the DRTS frame because beam 4 is blocked, causing a deafness problem.

Instead of transmitting multiple DRTS/DCTS frames, the schemes in [8] and [19] exploit an approach that notifies potential senders. In [8], authors proposed the advance notice directional MAC (AN-DMAC) using an additional RTS (A-RTS) frame to notify potential senders to wait until another node finishes its transmission in order to avoid deafness. The scheme in [19] uses the ready-to-receive (RTR) frame once a node finishes a transmission to another node so that the receiving node receives data from its potential senders and minimizes the deafness duration. Even though the above schemes try to reduce the deafness duration and avoid the deafness problem by notifying potential senders, they are not always successful. Again, as in Figure 1, although node *A* will transmit the advance notice information to *B*, node *B* cannot receive the DRTS frame since nodes *S* and *D* are already in communication, and thus *B*'s beam 4 is blocked, causing a deafness problem.

From the above observation, we conclude that the fundamental solution to the deafness problem is to identify whether or not a node encounters deafness. Recognizing deafness is not an easy task because the sender does not know why the DCTS frame is not received, either because of deafness or a collision. One method to distinguish the deafness from a collision is proposed in [1, 6].

In [1], authors proposed the dual sensing directional MAC (DSDMAC) using two tranceivers for transmitting data frame and tone signal separately. In their scheme, when a sender transmits data frame to a receiver, the sender and receiver also simulataneously transmit a tone signal omni-directionally to let the other neigboring nodes aware of an ongoing communication. The use of the tone is as follows: if a sender wants to communicate with its receiver, it starts sending a DRTS frame. If a DCTS is not delivered at the sender within a predefined time, the sender initiates tone detection process. If the sender cannot detect any tone, it concludes that there is a collision at the DRTS; otherwise, it concludes that the receiver is busy for ongoing communication. However, in Figure 1, their scheme still cannot resolve the deafness problem. For instance, node *A* transmits DRTS to *B* using beam 1. Then, if *A* does not receive a DCTS from *B*, it tries to detect a tone at beam 1. However, node *A* cannot detect any tone at beam 1 because node *B* is not engaged in communication and *B*'s beam 4 is blocked. As a result, node *A* concludes that there is a collision at the transmitted DRTS and it tries to continuously transmit DRTS frame to *B*.

The scheme in [6] tries to distinguish deafness from a collision using a tone signal. In that scheme, the sender and receiver omni-directionally transmit a tone after their communication. Once a node experiencing the deafness problem receives a tone, the node is aware that a destination node cannot deliver DCTS to the source because neighbor nodes are engaged in communication using the same medium (receiver's corresponding beam is blocked). For instance, in Figure 1, once node *A* receives the tone from node *S* or *D*, node *A* will realize that it did not receive the DCTS from node *B* because *B*'s beam 4 is blocked by communication between *S* and *D*. The problem in this scheme is that node *A* will be aware of the deafness only after *S* and *D* finish their communication. If the communication time between *S* and *D* increases, the deafness problem will become more severe.

As explained previously, the existing techniques have not comprehensively resolved the deafness problem. If we can provide a method in which node *A* can realize in advance that nodes

[1] The blockage means the corresponding beam of the node cannot be used for transmission in this paper.

S and D are engaged in communication, we can resolve the deafness problem. In other words, if A is aware that beam 4 of node B is blocked in advance, it can communicate with other node instead of B. For instance, node A can check its transmission queue and start to send the next frame in order to increase the throughput (e.g., in Figure 1, there is a data frame to node C in the transmission queue of node A).

3. The DA-MAC Protocol

3.1. Basic Assumptions and System Model

In this paper, we assume a single channel scenario[2]. This single channel is further divided into two logical channels: a data channel ω_D and a control channel ω_C. We assume these two channels do not interfere with each other. Therefore, the same frame can be transmitted simultaneously through the two channels. To increase the data throughput, we assign more subcarriers to the data channel than the control channel. Details regarding the physical layer design are beyond the scope of this paper.

Also, we assume that each node is equipped with a switched beam antenna system where M beam patterns are ideally non-overlapping in order to cover all directions. All beams can be simultaneously used to provide an omni-directional receiving function or they can be individually switched for reception in a specific direction. The switched beam antenna system is operated by a controller that keeps track of the directions with the highest SNR. The controller then informs the higher layers about the sector of the received signal. Switching within the antenna controller can be achieved using very fast analog CMOS multiplexers/demultiplexers, which have a transition time of less than 217 ns [22], less than the signal propagation delay. Therefore, the short inter-frame space (SIFS) defined in the 802.11 standard is long enough for the antenna to be switched between transmitting and receiving modes. For directional communication, a node is assumed to be able to transmit over a specific beam whose range contains the destination node. We also assume that, when a node transmits using one beam, the other beams cannot receive due to the use of a single channel[3]. We further assume that each node exploits beam table caching (BTC) as in the recent existing techniques [2, 16, 21]. Using BTC, each node knows its corresponding beam index at which its one-hop neighbors are located. A one-time pairwise exchange of the beam table is sufficient for static and fixed networks, while frequent exchanges are necessary for dynamic networks.

In our DA-MAC protocol, only the DRTS and DCTS frames are exchanged on the control channel, while all of the DRTS/DCTS/DATA/ACK frames are exchanged on the data channel (The rationale behind this approach is described in Section 3.2).

If a sender has data to transmit, it transmits a DRTS frame to the receiver on both channels over the beam on which the receiver is located. The receiver of the DRTS responds with a DCTS on both channels and continuously senses the control channel while using the data channel to receive data. Note that, since the DATA frame is transmitted only over the data channel, the sender (receiver) can detect the signal from the control channel during transmission (reception). After a successful transmission, the receiver transmits an ACK to the sender on the data channel.

3.2. Distinguishing Deafness from Collision

The reason for using both data and control channels to transmit DRTS is to distinguish deafness from a collision. Let us apply our DA-MAC protocol to the example in Figure 2 (the same scenario as in Figure 1). Initially (at $t = t_1$), we assume that no communication occurs in the network (Figure 2(a)). The beam tables show that nodes A and B are listening omni-directionally on both channels. Suppose that node S has data for node D. S simultaneously transmits a DRTS frame on both the data (solid line) and control (dashed line) channels (Figure 2(b)). Then, nodes A and B receive the DRTS frames using beam 3 and beam 4, respectively, since these are the beams from which the highest SNR is measured. Because the receiving DRTS frame's destination is D, A's beam 3 and B's beam 4 are blocked, as in Figure 1, only on the data channel, while they are still in the listening state on the control channel. In our DA-MAC, only beams on the data channel are blocked in order to distinguish deafness from a collision. As a response to the DRTS, node D sends a DCTS frame to S on both of the channels (Figure 2(c)), and nodes S and D are engaged in communication (Figure 2(d)). Now, if node A has data for B, it transmits a DRTS frame on both channels (Figure 2(e)). Observe that the channel states for A's beam 1 show transmission (Tx). Even if node B cannot receive the DRTS frame on the data channel (since B's beam 4 on the data channel is blocked), *it can still hear the DRTS frame on the control channel* because B's beam 4 on the control channel is in the listening state. Therefore, the state of B's beam 4 on the control channel shows the receiving state (Rx). Node B then replies to A with a DCTS frame on the control channel (Figure 2(f)). Since node A receives the DCTS frame only on the control channel and not on the data channel, *it can determine that node B is in a deaf state*. Normally, the DRTS is received on both of the channels.

Now, if there is a collision in the DRTS frame at node B (Figure 2(e)), then the DRTS frame will not be received at node B on either channel since the DRTS frame on the data channel has also experienced collision. Therefore, no DCTS frame will be transmitted to node A. Then, *node A can determine that there has been a collision.*

[2] If we employ multiple channels, the system throughput will significantly increase. However, we are interested in the network throughput improvement rectifying the deafness problem in the case of a single channel.

[3] However, if two channels are involved, as in our scheme, transmission in one channel does not necessarily mean that reception in the other channel is not possible

[4] When a node overhears a DRTS frame (or DCTS frame), it should set directional network allocation vector (DNAV) timers per sector. It should block all of its sectors for the duration of communication.

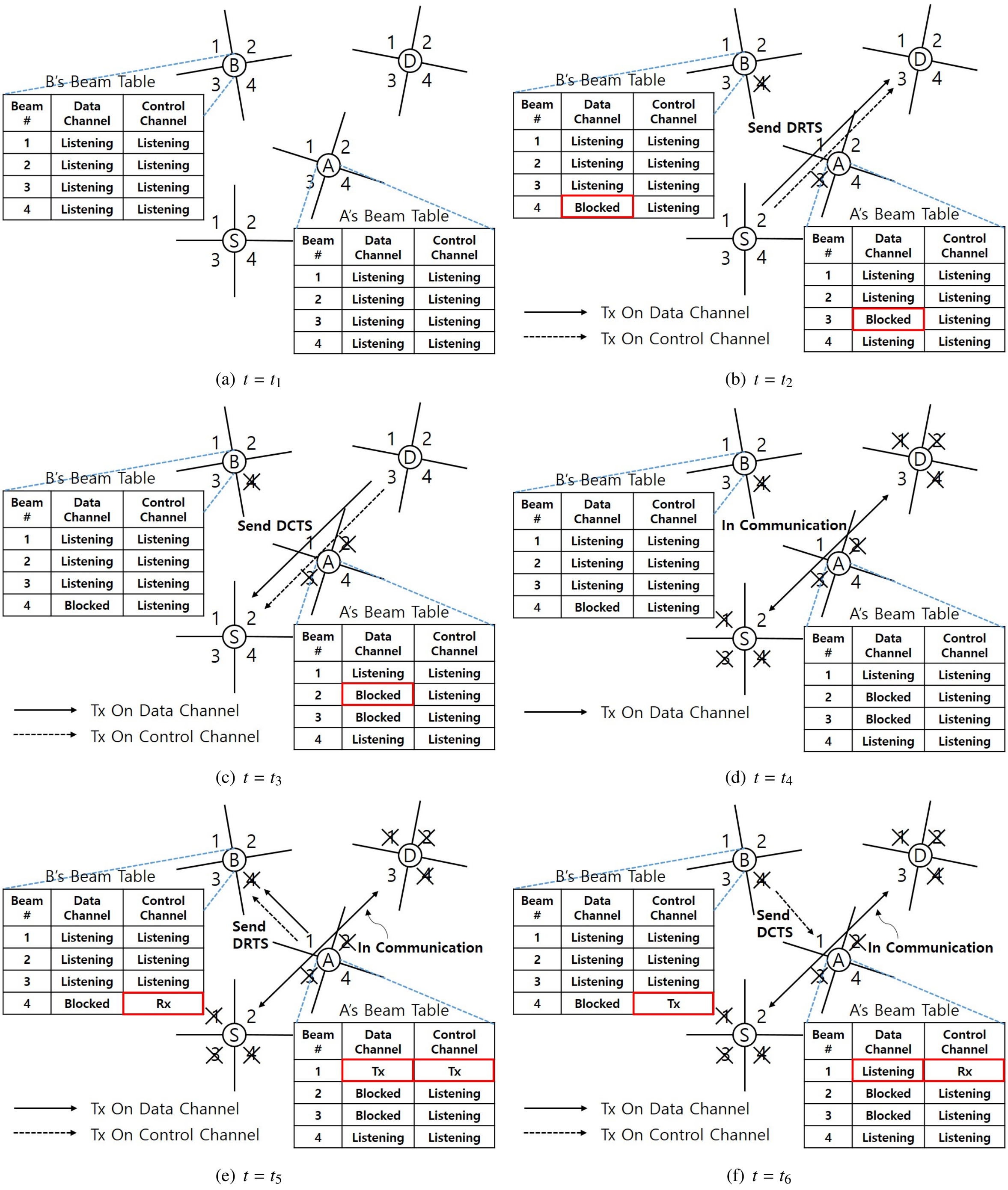

Figure 2: Resolution of the Deafness Problem in the DA-MAC Protocol ($t_1 < t_2 < t_3 < t_4 < t_5 < t_6$).

3.3. Protocol Description

Section 3.2 showed the exemplary behavior of our DA-MAC in rectifying the deafness problem. In summary, the DA-MAC provides the following features:

- **Deafness-awareness**: The sender is able to detect an actual network failure by distinguishing deafness from a collision.
- **Queue Scheduling**: If the sender is aware that the receiver is in the deaf state, it can start to communicate with another idle node, improving the aggregate throughput.[5]
- **Reducing Control Overhead**: The sender and receiver do not transmit the DRTS or DCTS frame to their neighbors. Eliminating the control frame overhead to all neighbors

[5] If a sender tries to transmit to a deaf node, the transmission will be suspended until the receiver recovers from deafness (*head of line*). However, in our scheme, the sender can transmit the next frames instead of transmitting the head of line frame [13, 21].

Algorithm 1: The DA-MAC Algorithm

```
1:  loop
2:      if Data to send then
3:          Set Contention Window in [0, CW_max];
4:          if (Φ_D==IDLE) and (Φ_C==IDLE) then
5:              Transmit a DRTS on both ω_D and ω_C only to the receiver,
6:              and set timer; // Control overhead can be reduced
7:          end if
8:      end if
9:      if Frame received then
10:         if (F_D==DRTS and F_C==DRTS) then {normal case}
11:             Transmit a DCTS on both ω_D and ω_C;
12:         else if (F_D==NONE and F_C==DRTS) then {in communication}
13:             Transmit a DCTS on ω_C; // in deaf state
14:         else if (F_D==DCTS and F_C==DCTS) then {normal case}
15:             Transmit a DATA frame on ω_D, and set timer;
16:         else if (F_D==NONE and F_C==DCTS) then {deafness}
17:             Delay transmission by DNAV^4; // found the receiver deaf
18:             Schedule Tx of next frame to other node; // Queue Scheduling
19:         else if (F_D==DATA and F_C==NONE) then {normal case}
20:             Send ACK;
21:         end if
22:     end if
23:     if Timer expired then {Node does not receive frame}
24:         if Node transmitted DATA then
25:             Retransmit frame and set timer;
26:         else if Node transmitted DRTS then
27:             CW_max ⇐ CW_max * 2 and go to step 4;
28:         end if
29:     end if
30: end loop
```

can further increase the aggregate throughput.[6]

Algorithm 1 shows the pseudo code for the DA-MAC algorithm. Let Φ_D and Φ_C denote the states of ω_D and ω_C, respectively. Also, let $\mathcal{F}_\mathcal{D}$ and $\mathcal{F}_C$ be received frames on ω_D and ω_C. In the DA-MAC, if a node has data to transmit, it sets the contention window in the range of $[0,CW_{\max}]$, where $CW_{\max}$ is the maximum contention window size. The node then performs clear channel assessment (CCA) and backoff, as in the CSMA/CA. If the node finds that both the data and control channels are idle (e.g., Φ_D==IDLE and Φ_C==IDLE), it transmits a DRTS frame on both channels and sets the retransmission timer (lines 5–6). Note that the node does not transmit the DRTS frame to all of its neighbors, so the control frame overhead is reduced.

If the node receives one DRTS frame on each of the data and control channels (line 10), the node considers it a normal case (i.e., neither collision nor deafness). The node then responds to the sender of the DRTS with a DCTS frame on both channels. If the node receives two DCTS frames (line 14), it starts to transmit the data frame only on the data channel and sets the retransmission timer. After successful reception of the data (line 19), the node transmits the ACK frame.

On the other hand, the node might not receive any frames on the data or control channel (line 24) since two DRTS frames can collide on either channel. In this case, the sender's retransmission timer will expire (line 26), and the sender retransmits the DRTS frames on both channels after the backoff duration of range $[0,CW_{\max})$ has expired.

If the node is communicating with another node, it can receive only one DRTS frame on the control channel (line 12) because the data frame is transmitted only on the data channel. The node then replies to the sender with a DCTS frame only on the control channel. At that time, different from the above case, the timer for DCTS is not set since this DCTS informs the sender of the DRTS being transmitted.

If the DCTS is not delivered to a sender node, the sender will retransmit the DRTS frames (lines 5–6). Once the sender receives the DCTS frame on the control channel (line 16), it can determine that the node is in a deaf state. Then, the sender delays the transmission using DNAV [7] in the corresponding beam. If the sender has more data for another destination, it can start such communication during the DNAV duration (lines 17-18). As a result, the aggregate throughput can be improved.

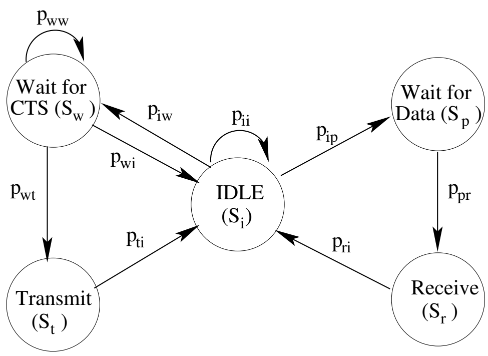

Figure 3: State diagram of the original DMAC protocol.

4. Impact of Deafness

4.1. Analysis of original DMAC

In this section, we use a mathematical approach to study the impact of deafness in the original DMAC protocol [10]. To evaluate the impact of deafness, we analyze the deafness probability and the aggregate throughput (the average information payload transmitted in a slot time over the average duration of a slot time) with the discrete-time Markov chain (DTMC) model assuming a finite number of nodes. We discuss one such model that obtains saturated throughput. Therefore, we assume that all nodes always have data to send. In the original DMAC protocol, a node uses a 4-handshake mechanism (DRTS-DCTS-DATA-ACK) to communicate. We also assume that all of the control frames except the DRTS frame are always delivered successfully to the destination node. Figure 3 shows the state transition process of a node represented by a discrete-time Markov chain model. Let the steady-state probabilities of the Markov chain be denoted by S_i, S_w, S_t, S_p, and S_r, and let the time periods

[6]The schemes in [11, 21, 13, 19] and [8] include an additional control frame that is sent to their neighbors.

[7]The sender uses the DNAV parameter included in the DCTS frame.

during which a node is in the corresponding states be T_i, T_w, T_t, T_p, and T_r where i, w, t, p, and r represent states of 'idle,' 'wait for CTS,' 'transmit,' 'wait for Data,' and 'receive,' respectively.

Then, we need to derive the transition and steady-state probabilities. First, we obtain the steady-state probabilities from Figure 3 as

$$\begin{aligned} S_w &= p_{iw} S_i + p_{ww} S_w, \\ S_t &= p_{wt} S_w, \\ S_p &= p_{ip} S_i, \\ S_r &= p_{pr} S_p, \quad \text{and} \\ S_i &= p_{wi} S_w + p_{ti} S_t + p_{ri} S_r + p_{ii} S_i. \end{aligned} \tag{1}$$

Next, we need to calculate the transition probabilities p_{iw}, p_{ww}, p_{wt}, p_{ip}, p_{pr}, p_{wi}, p_{ti}, p_{ii}, and p_{ri}. We define each transition probability as

$$\begin{aligned} p_{iw} &= P\{\text{Node transmits a DRTS frame}\}, \\ p_{ww} &= P\{\text{Node does not receive a DCTS frame}\}, \\ p_{wt} &= P\{\text{Node receives a DCTS frame}\}, \\ p_{ip} &= P\{\text{Node receives a DRTS frame}\}, \\ p_{pr} &= P\{\text{Node receives a data frame}\}, \\ p_{wi} &= P\{\text{The retransmission limit is exceeded}\}, \\ p_{ti} &= P\{\text{Node transmits an ACK frame}\}, \\ p_{ii} &= P\{\text{Node overhears other's frame}\}, \quad \text{and} \\ p_{ri} &= P\{\text{Node receives an ACK frame}\}. \end{aligned} \tag{2}$$

Since it is assumed that all of the frames except the DRTS frame are delivered successfully, p_{pr}, p_{ti}, and p_{ri} are 1. First, we can derive p_{iw} as

$$p_{iw} = \tau_1, \tag{3}$$

where τ_1 denotes the probability that a node transmits in the first backoff stage. This can be calculated using the backoff Markov chain model from [3],

$$\tau_1 = \frac{2(1-2p)(1-p)}{(1-2p)(W_0+1) + pW_0(1-(2p)^m)}. \tag{4}$$

τ_1 depends on p and W_0, which denote the conditional collision probability and maximum backoff window size for stage 0, respectively. However, in the general DMAC protocol, the network node has deafness probability P_d. For this reason, we replaced p with P_f, where P_f is the probability of network failure and is given by $P_f = p + P_d$. Then, the collision probability p can be calculated as:

$$p = 1 - (1-\tau)^{N_r-2}, \tag{5}$$

where N_r is the number of senders in an idle receiver's omni-directional range.

Next, we can derive p_{ip} as

$$p_{ip} = p_1 p_2 p_3, \tag{6}$$

where

$$\begin{aligned} p_1 &= P\{\text{Sender transmits a DRTS frame}\}, \\ p_2 &= \left\{\begin{matrix}\text{No nodes in a receiver's omni-directional} \\ \text{range initiate a transmission}\end{matrix}\right\}, \text{ and} \\ p_3 &= P\{\text{Receiver's beam is not blocked}\}. \end{aligned}$$

Let τ denote the probability that a node transmits in a random slot time for all backoff stages. Then, we can obtain

$$\begin{aligned} p_1 &= \tau_1 \quad \text{and} \\ p_2 &= (1-\tau)^{N_r-2}. \end{aligned}$$

Since we assume that all senders are uniformly distributed in a given topology, the probability of blockage of a specific beam for receiving the sender's frame is $1/M$. Then, we can derive p_3 as:

$$p_3 = 1 - \frac{1}{M}. \tag{7}$$

Therefore, p_{ip} is given by

$$p_{ip} = \tau_1 (1-\tau)^{N_r-2} \left(1 - \frac{1}{M}\right), \tag{8}$$

where M is the number of beams. τ can be calculated as the following,

$$\tau = \frac{2(1-2p)}{(1-2p)(W_0+1) + pW_0(1-(2p)^m)}. \tag{9}$$

Similarly, we can derive p_{wt} as

$$p_{wt} = (1 + \tau_1 - \tau)^{N_r-2} \left(1 - \frac{1}{M}\right). \tag{10}$$

Finally, we can obtain p_{wi} as

$$\begin{aligned} p_{wi} &= P\left\{\begin{matrix}\text{Sender does not receive any response} \\ \text{within retransmission limit } k\end{matrix}\right\} \\ &= (P_f)^{k+1}, \end{aligned} \tag{11}$$

and p_{ww} can be computed as

$$p_{ww} = 1 - (1 + \tau_1 - \tau)^{N_r-2}(1 - \frac{1}{M}) - (P_f)^{k+1} \tag{12}$$

since $p_{wi} + p_{wt} + p_{ww} = 1$.

By solving the balance equation for the steady-state proba-

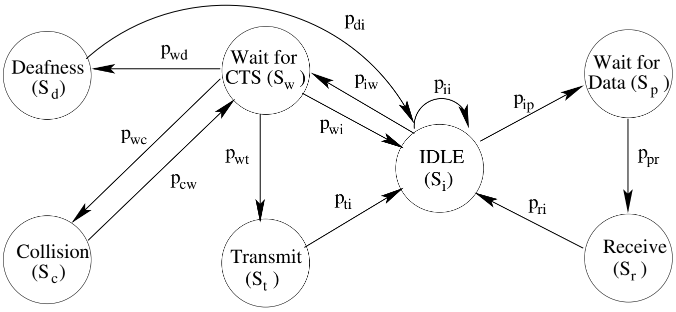

Figure 4: State diagram of the DA-MAC protocol.

bilities, we can obtain each steady-state probability as

$$S_w = \frac{\tau_1}{1 - p_{ww}} S_i = \frac{\tau_1}{(1 + \tau_1 - \tau)^{N_r - 2}(1 - 1/M) + (P_f)^{k+1}} S_i \quad (13)$$

$$S_t = \frac{\tau_1 (1 - \tau)^{N_r - 2}(1 - 1/M)}{1 - p_{ww}} S_i = \frac{\tau_1 (1 - \tau)^{N_r - 2}(1 - 1/M)}{(1 + \tau_1 - \tau)^{N_r - 2}(1 - 1/M) + (P_f)^{k+1}} S_i \quad (14)$$

$$S_p = \tau_1 (1 - \tau)^{N_r - 2} \left(1 - \frac{1}{M}\right) S_i = S_r. \quad (15)$$

In (15), $S_p = S_r$ since $p_{pr} = 1$.

Thus, according to (13) – (15), all of the steady-state probabilities are expressed as S_i, which is finally determined by imposing the normalization condition that simplifies to

$$S_w + S_t + S_p + S_r + S_i = 1. \quad (16)$$

4.2. Analysis of the DA-MAC

In this section, we analyze the proposed DA-MAC protocol with an approach similar to that used in Section 4.1. Figure 4 shows the state transition process of a node. Unlike the original DMAC protocol, the DA-MAC protocol can distinguish deafness from a collision. Therefore, the collision state and the deafness state are newly added in Figure 3. If a node detects deafness at its destination, it moves to the deafness state and ceases its transmission, i.e., it does not retransmit DRTS frames even if the maximum retransmission limit is not reached. Afterward, the node moves to the idle state. On the other hand, if the node detects a collision of its DRTS frame, it moves to the collision state and tries to retransmit DRTS frames after exponential backoff. From the DTMC in Figure 4, we derive the steady-state probabilities as

$$\begin{aligned} S_w &= p_{iw} S_i + p_{cw} S_c \\ S_t &= p_{wt} S_w \\ S_p &= p_{ip} S_i \\ S_r &= p_{pr} S_p \\ S_d &= p_{wd} S_w \\ S_c &= p_{wc} S_w, \text{ and} \\ S_i &= p_{wi} S_w + p_{ti} S_t + p_{ri} S_r + p_{ii} S_i \end{aligned} \quad (17)$$

where newly added c and d represent states of 'collision' and 'deafness,' respectively.

Most transition probabilities are the same as those in the original DMAC except the following newly defined or modified transition probabilities:

$$\begin{aligned} p_{wt} &= P\{\text{Node receives one DCTS frames on each channel}\}, \\ p_{ip} &= P\{\text{Node receives one DRTS frames on each channel}\}, \\ p_{wd} &= P\{\text{Node receives a DCTS frame on the control channel}\}, \\ p_{wc} &= P\{\text{Node does not receive a DCTS frame}\} \quad (18) \\ p_{di} &= P\left\{\begin{matrix}\text{Node is aware that the destination is} \\ \text{in the deaf state}\end{matrix}\right\}, \text{ and} \\ p_{cw} &= P\{\text{Node retransmits a DRTS frame}\}. \end{aligned}$$

p_{iw}, p_{ip}, p_{wt} and p_{wi} are the same as those in the original DMAC. Also, since it is assumed that all of the frames except the DRTS frame are delivered successfully, p_{pr}, p_{ti}, and p_{ri} are 1. Furthermore, $p_{di} = 1$ since the node tries to communicate with the other idle node once deafness occurs. Similarly, $p_{cw} = 1$ because the node tries another DRTS after the collision occurs.

Firstly, we consider that p_{wc} is

$$p_{wc} = p_4 p_5, \quad (19)$$

where

$$\begin{aligned} p_4 &= P\{\text{Transmitted frame collision}\} \text{ and} \\ p_5 &= P\{\text{Sender does not exceed the retransmission limit}\}. \end{aligned}$$

Therefore,

$$p_{wc} = \left\{1 - (1 - \tau)^{N_r - 2}\right\}\left(1 - (P_f)^{k+1}\right). \quad (20)$$

Similarly to p_{ww} of the original DMAC, we can calculate p_{wd} as

$$p_{wd} = (1 - (P_f)^{k+1})(1 - \tau)^{N_r - 2} - (1 + \tau_1 - \tau)^{N_r - 2}(1 - 1/M) \quad (21)$$

since $p_{wc} + p_{wt} + p_{wd} + p_{wi} = 1$.

Finally, we also calculate the steady-state probability of each state as

$$S_p = \tau_1(1-\tau)^{N_r-2}\left(1-\frac{1}{M}\right)S_i = S_r,$$
$$S_w = \frac{\tau}{1-\{1-(1-\tau)^{N_r-2}\}\left(1-(P_f)^{k+1}\right)}S_i,$$
$$S_t = \frac{\tau_1(1-\tau)^{N_r-2}\left(1-\frac{1}{M}\right)}{1-\{1-(1-\tau)^{N_r-2}\}\left(1-(P_f)^{k+1}\right)}S_i, \quad (22)$$
$$S_d = \frac{(1-(P_f)^{k+1})(1-\tau)^{N_r-2}-(1+\tau_1-\tau)^{N_r-2}(1-1/M)}{1-\{1-(1-\tau)^{N_r-2}\}(1-(P_f)^{k+1})}S_i, \text{ and}$$
$$S_c = \frac{\tau_1\left\{1-(1-\tau)^{N_r-2}\right\}\left(1-(P_f)^{k+1}\right)}{1-\{1-(1-\tau)^{N_r-2}\}\left(1-(P_f)^{k+1}\right)}S_i.$$

4.3. The Deafness Probability and Throughput

Let *DRTS, DCTS, DATA*, and *ACK* denote the bit sizes of the DRTS, DCTS, DATA, and ACK frames in bits, respectively. Since we assume a full buffer model for each node, there is no waiting time for data arrival from the upper layer. Time is require only for the backoff process at stage 0 in the carrier sense. Therefore, similar to [3], the expected time in the idle state, denoted by $E[T_i]$, can be calculated as

$$E[T_i] = DIFS + \alpha\frac{W_0+1}{2} + \frac{DRTS}{\eta}, \quad (23)$$

where α denotes a backoff slot time duration, and W_0 is the maximum backoff window size for stage 0. Also, η denotes the data rate.

In the original DMAC, a sender remains in the "wait for CTS" state before receiving a DCTS frame or retransmitting a DRTS frame. As in Figure 3, there are three states to which the "wait for CTS" state progresses. If the sender receives a DCTS frame, it moves to the "transmit" state. However, the sender tries to retransmit a DRTS frame in the "wait for CTS" state when a receiver does not reply with CTS due to collision or deafness. Also, it moves to the "idle" state when the sender reaches the maximum retransmission limit.

Hence, the expected waiting time in the "wait for CTS" state $E[T_w]$ for the original DMAC can be calculated as

$$E[T_w] = E_w[T_w]\times p_{ww} + E_t[T_w]\times p_{wt} + E_i[T_w]\times p_{wi}, \quad (24)$$

where $E_w[T_w]$, $E_t[T_w]$, and $E_i[T_w]$ denote the conditional expectation of T_w given that the sender does not receive a DCTS frame within $k-1$, that the sender receives a DCTS frame within k, and that the sender reaches the maximum retransmission limit k, respectively.

In the case that the sender does not receive a DCTS frame within the $k-1$ stage for the original DMAC, the sender waits for backoff stages from 1 to $k-1$ after the retransmission timer has expired and retransmits a DRTS frame. Hence, $E_w[T_w]$ for the original DMAC is given by

$$E_w[T_w] = \sum_{i=1}^{k-1}\left[i(p_{ww})^i\left\{\delta+\alpha\frac{W_i+1}{2}+DIFS+\frac{DRTS}{\eta}\right\}\right]+\delta, \quad (25)$$

where W_i denotes the maximum backoff window size for stage i, and δ denotes the *TxTimer* defined as the retransmission timer for DRTS. Note that the last δ in (25) implies the time delay after the initial DRTS is transmitted until the retransmission timeout is expired.

In the case that the DRTS frame is successfully delivered to the receiver within k retransmission trials, however, the sender waits until a DCTS is received after SIFS for backoff stages from 1 to k. Hence, $E_t[T_w]$ for the original DMAC can be computed as the following:

$$E_t[T_w] = \sum_{i=1}^{k}\left[i(p_{ww})^i\left\{\delta+\alpha\frac{W_i+1}{2}+DIFS+\frac{DRTS}{\eta}\right\} + \left\{SIFS+\frac{DCTS}{\eta}\right\}\right] + SIFS + \frac{DCTS}{\eta}. \quad (26)$$

In the case that the sender reaches the maximum retransmission limit k, the sender only waits for retransmission timer expiration. Hence, $E_i[T_w]$ for the original DMAC can be given by $E_i[T_w] = \delta$.

On the other hand, in the DA-MAC, there are four states to which the "wait for CTS" state moves, as shown in Figure 4. If a sender does not receive any DCTS frames on either channel (collision), it moves to the "collision" state. Similarly, the sender moves to the "deafness" state when the sender receives a DCTS frame only on the control channel (deafness). The sender moves to the "transmit" or "idle" states when it receives a DCTS frame on each channel and when it reaches the maximum retransmission limit k, respectively.

Hence, $E[T_w]$ for the DA-MAC can be calculated as

$$E[T_w] = E_c[T_w]\times p_{wc} + E_d[T_w]\times p_{wd} + E_t[T_w]\times p_{wt} + E_i[T_w]\times p_{wi}, \quad (27)$$

where $E_c[T_w]$ and $E_d[T_w]$ denote the conditional expectation of T_w given that the sender does not receive any DCTS frames on either channel and that the sender receives only one DCTS frame on the control channel, respectively.

In the case that the sender does not receive any DCTS frames on either channel within $k-1$ stages for the DA-MAC (collision), the sender waits δ for each retransmission and moves to the "collision" state. Hence, $E_c[T_w]$ for the DA-MAC is given by

$$E_c[T_w] = \sum_{i=1}^{k-1}\left\{i(p_{wc})^i\delta\right\}+\delta. \quad (28)$$

In the case that only one DRTS frame is successfully delivered through the control channel to the receiver within k retransmission trials (deafness), the sender waits until the DCTS is received after SIFS for backoff stages from 1 to k. Hence, $E_d[T_w]$ for the DA-MAC can be calculated as the following:

$$E_d[T_w] = \sum_{i=1}^{k}\left[i(p_{wc})^i\left\{\delta + SIFS + \frac{DCTS}{\eta_c}\right\}\right] + SIFS + \frac{DCTS}{\eta_c}. \tag{29}$$

Different from the original DMAC, we assign different data rates for data channel (η_d) and that for control channel (η_c) in the proposed scheme. Note that we assign η for data rate in the original DMAC. For fair comparison between the original DMAC and the DA-MAC, we set $\eta = \eta_d + \eta_c$.

In the case that DRTS frames are successfully delivered to the receiver on both channels within k retransmission trials, the sender waits until two DCTS frames are received after SIFS for backoff stages from 1 to k. Since two DCTS frames are transmitted simultaneously, the time for delivering two DCTS frames is $DCTS/\eta_c$.[8] Hence, $E_t[T_w]$ for the DA-MAC can be calculated as $E_t[T_w] = E_d[T_w]$.

In the case the sender reaches the maximum retransmission limit k, the sender only waits for retransmission timer expiration. Hence, $E_i[T_w]$ in the DA-MAC is same as in the original DMAC.

If the sender receives only one DCTS frame on the control channel, it moves to the "deafness" state. In the deafness state, the sender ceases its transmission and moves to the idle state immediately in order to transmit the other frame. Hence, $E[T_d]$ is equal to 0. On the other hand, when the sender does not receive any DCTS frames on either channel within k stages, the sender waits for backoff stages from 1 to k and retransmits two DRTS frames in the "collision" state. Hence, $E[T_c]$ can be calculated as:

$$E[T_c] = \sum_{i=1}^{k}\left[i(P_{wc})^i \times \left\{\alpha\frac{W_i+1}{2} + DIFS + \frac{DRTS}{\eta_c}\right\}\right]. \tag{30}$$

The times spent in the other states $E[T_t]$, $E[T_p]$, and $E[T_r]$ are given, respectively, by

$$E[T_t] = 2SIFS + \frac{DATA + ACK}{\eta}, \tag{31}$$

$$E[T_p] = SIFS + \frac{DCTS}{\eta} \text{ (for original DMAC)}, \tag{32}$$

$$E[T_p] = SIFS + \frac{DCTS}{\eta_c} \text{ (for DA-MAC)}, \tag{33}$$

$$E[T_r] = 2SIFS + \frac{DATA + ACK}{\eta} \text{ (for original DMAC) and,} \tag{34}$$

$$E[T_r] = 2SIFS + \frac{DATA + ACK}{\eta_d} \text{ (for DA-MAC).} \tag{35}$$

Lastly, we can derive the deafness probability for the original DMAC and the DA-MAC protocols as

[8] Basically, the data rate of the control channel is less than that of the data channel. Therefore, transmission delay for DCTS is determined by the delay on the control channel.

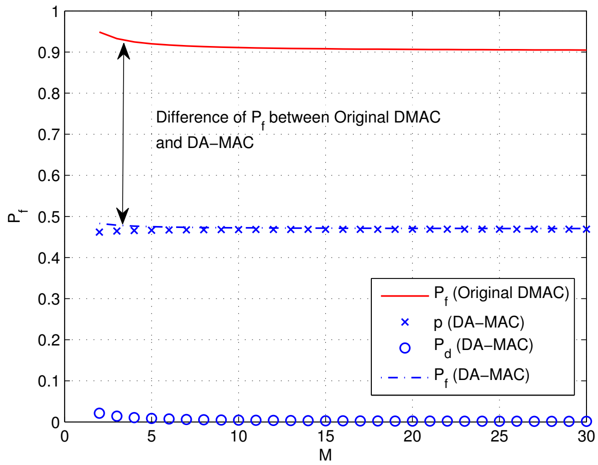

Figure 5: Probability of network failure vs. the number of beams (N_r=4 and full buffer)

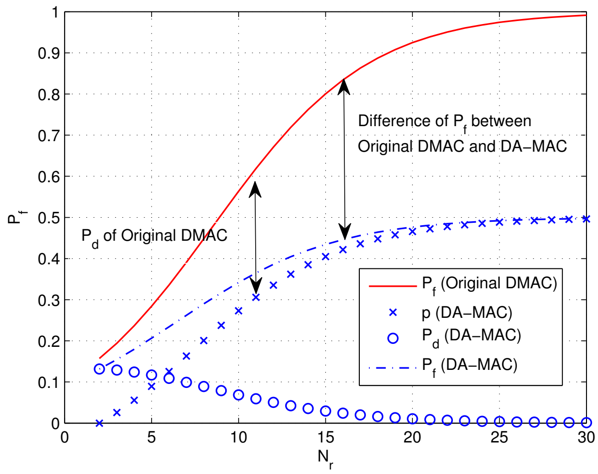

Figure 6: Probability of network failure vs. the number of senders in a receiver's omni-directional range (M=4 and full buffer)

$$P_d = \begin{cases} \dfrac{\{S_wE[T_w]\}}{\begin{Bmatrix} S_wE[T_w] + S_iE[T_i] + \\ S_tE[T_t] + S_rE[T_r] + \\ S_pE[T_p] \end{Bmatrix}} \text{(for original DMAC)} \\ \dfrac{\{S_dE[T_d]\}}{\begin{Bmatrix} S_wE[T_w] + S_iE[T_i] + \\ S_tE[T_t] + S_rE[T_r] + \\ S_pE[T_p] + S_dE[T_d] + S_cE[T_c] \end{Bmatrix}} \text{(for DA-MAC)} \end{cases} \tag{36}$$

Also, we can calculate the network throughput using an approach similar to that in (36). Then, the throughput of a network

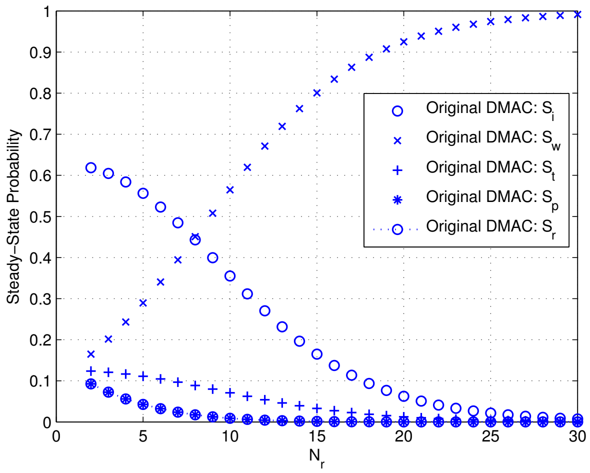

Figure 7: State probability vs. the number of senders in a receiver's omni-directional range for DMAC (M=4)

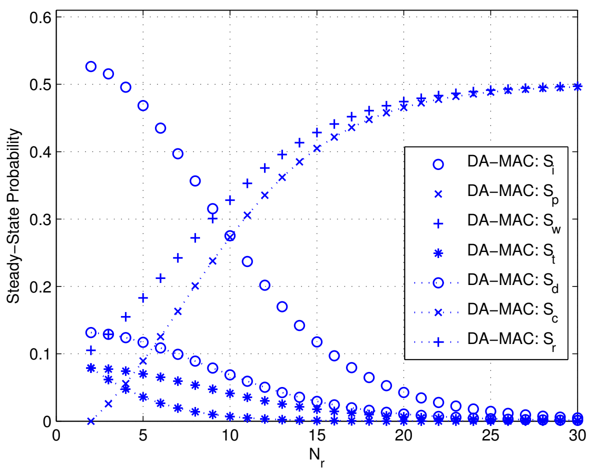

Figure 8: State probability vs. the number of senders in a receiver's omni-directional range for DA-MAC (M=4)

with N nodes is given by

$$TH = \begin{cases} \dfrac{\left\{NS_r E[P]\right\}}{\left\{\begin{matrix} S_w E[T_w] + S_i E[T_i] + \\ S_t E[T_t] + S_r E[T_r] + \\ S_p E[T_p] \end{matrix}\right\}} \text{(for original DMAC)} \\ \dfrac{\left\{NS_r E[P]\right\}}{\left\{\begin{matrix} S_w E[T_w] + S_i E[T_i] + \\ S_t E[T_t] + S_r E[T_r] + \\ S_p E[T_p] + S_d E[T_d] + S_c E[T_c] \end{matrix}\right\}} \text{(for DA-MAC),} \end{cases} \quad (37)$$

where $E[P]$ is the average payload size of a data packet.

From (36) and (37), we now analyze the impact of deafness when applying the original DMAC and our proposed DA-MAC. In our analysis, we set $DRTS$, $DCTS$, and ACK to 16 bytes and $DATA$ to 1024 bytes. Also, we set $SIFS$ and $DIFS$ to 10μs and 50μs, respectively. m, η, η_d and η_c are set to 7, 54Mbps, 53.5Mbps and 0.5Mbps, respectively.

Figure 5 shows P_f when varying the number of beams. As shown in the figure, P_f is much higher in the original DMAC than in our DA-MAC. Since the original DMAC cannot distinguish deafness from collision, P_f includes network failure due to both deafness and collision. On the other hand, since our DA-MAC protocol can distinguish between the two, we observe how P_d and p contribute to P_f. As in the figure, P_d is negligible and independent of the number of beams over most of the range of the x-axis in the DA-MAC. This is obvious since deafness is present even if in the presence of beams. The difference in P_f between the original DMAC and the DA-MAC is about 0.45 over most of the range of the x-axis. This implies that P_d of the original DMAC greatly affects network failure if assuming equal p, as in the DA-MAC. If $p = 0.45$, we estimate that $P_d \approx 0.5$ for the original MAC.

Figure 6 shows P_f versus the number of senders in a receiver's omni-directional range. P_f increases as the number of senders increases for both schemes. In the original DMAC, P_f rapidly increases at sender numbers greater than to 5 and is saturated at a value of 1. This is because S_w overwhelms the entire steady state probabilities, as shown in Figure 7 (refer to (36)). As explained above, we can estimate P_d of the original DMAC. As in the figure, we observe that P_d of the original DMAC rapidly increases (the gap between the solid line and 'x') as N_r increases. This implies that the major contributing factor to network failure is deafness in the original DMAC. In our DA-MAC, on the other hand, P_d can be approximated as 0 when N_r is greater than 20. This implies that there are non-negligible steady state probabilities other than deaf state. As observed in Figure 8, the steady-state probabilities of S_c and S_w are 0.5, respectively, and S_d becomes 0 when there are a large number of nodes. Since $P_d = 0$, the major factor of P_f is p when N_r is greater than 20.

The throughput performance of the proposed scheme will be discussed in section 5 with simulation results.

5. Performance Evaluation

In this section, we evaluate the performance of the DA-MAC protocol using the OPNET simulator. The simulation parameters are listed in Table 1 and are similar to those in [6]. Also, each node has a randomized orientation of the beams in our simulation. To measure the effectiveness of the DA-MAC protocol, we evaluated the following performance metrics.

- **Deafness Duration:** the time between the first transmission of the DRTS frame and its corresponding DCTS frame,
- **Aggregate Throughput:** total data traffic in bits transferred successfully from all nodes divided by time,

Table 1: Simulation parameters

Parameters	Value
Omni-directional Communication Range	150m
Directional Communication Range	300m
$CW_{\max}$	1024
Backoff Slot Size	0.02msec
Packet Size	512Bytes
Data Rate at the Data Channel (DA-MAC)	53.5Mbps
Data Rate at the Data and Control Channels (CRCM, AN-DMAC, and Tone-DMAC)	54Mbps
Data Rate at the Control Channel	0.5Mbps
Energy Consumption	9.6mW/sec(busy) [7] 3.0mW/sec (idle) [7]
Traffic Load from a Node with an Omni-directional Antenna	6Mbps

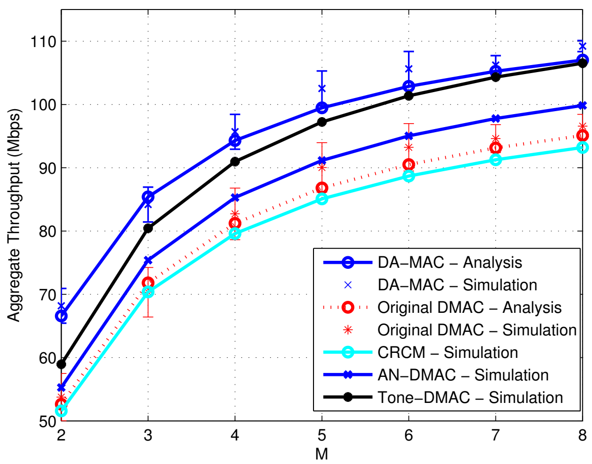

Figure 9: Aggregate throughput vs. the number of beams (N_r=4, $N = 2N_r$ and full buffer).

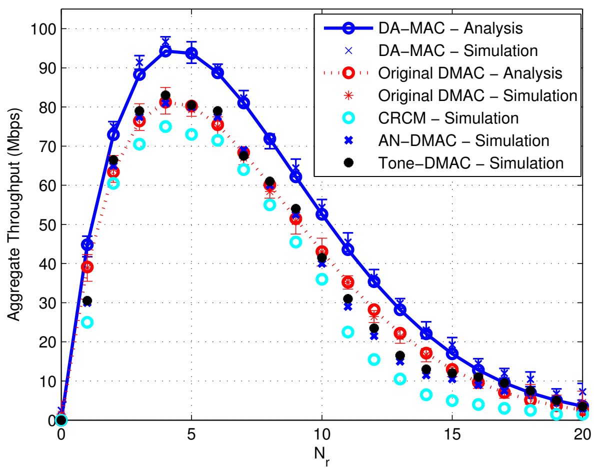

Figure 10: Aggregate throughput vs. the number of senders in a receiver's omni-directional range (M=4, $N = 2N_r$ and full buffer).

Table 2: The Deafness Duration (11Mbps, N = 20, and M = 4)

DA-MAC	Tone-DMAC	CRCM	AN-DMAC
0.8msec	4msec	16msec	18.3msec

- **Energy Consumption per Frame:** total energy consumption from all nodes divided by the number of transmitted frames, and

- **Jain's Fairness Index:** the square of the average of x_i divided by the average of x_i^2, where N denotes the number of nodes and x_i is the throughput for the ith connection.

$$J(x_1, x_2, \cdots, x_N) = \frac{\left(\sum_{i=1}^{N} x_i\right)^2}{N \sum_{i=1}^{n} x_i^2}$$

To verify the analytical results in section 4, we compare them with simulation results. For this comparison, we developed the simulation model that all nodes are located in a square 500 × 500m^2 topology. Also, all receivers are located in the transmission beam range of all senders. This is due to fact that the analytical model uses the throughput formula given in (37) with respect to N_r, which is constant for all senders. The receivers, however, are randomly deployed in the overlapped beams of all senders.

Figure 9 and Figure 10 show the comparison between analytical and simulation results of the aggregate throughput when varying the number of beams and the number of senders in a receiver's omni-directional range, respectively (additionally, we provide simulation results for CRCM, AN-DMAC, and Tone-DMAC). We note that the analytical results closely agree, with the simulation results. We also observed that the aggregate throughput increases as the number of beams increases for all schemes. This is because a narrower beam stimulates spatial reuse in the DMAC protocol. Actually, in the real world, a number of beams are not feasible due to high costs. However, Figure 9 shows that our proposed scheme performs well in extreme situations. The aggregate throughput achieves the best performance when the number of nodes is 4. This is mainly because increasing the number of nodes increases the interference of each ongoing communication. Moreover, our proposed scheme outperforms other schemes with lower data rates for the data channel (53.5Mbps vs. 54Mbps) by reducing the deafness duration.

To evaluate the effectiveness of DA-MAC, we compared the performance of the DA-MAC with those of the CRCM [9], AN-DMAC [8], and Tone-DMAC [6] using OPNET simulator. In the simulation model used to compare with the other protocols, all nodes are randomly deployed in a square 1500 × 1500m^2 topology according to a uniform distribution.

Table 2 shows the deafness duration for 20 nodes. As can be seen from the table, the DA-MAC protocol significantly reduces the deafness duration compared with the other schemes. Especially, the DA-DMAC reduces the response time to 80% of that of the Tone-DMAC [6] and 96% of that of AN-DMAC [8].

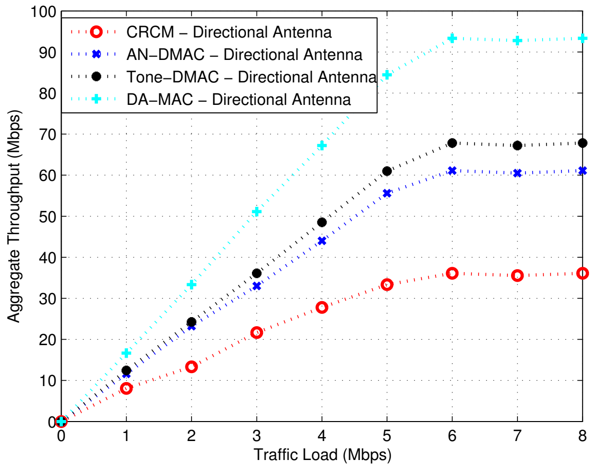

Figure 11: Aggregate throughput vs. traffic load (N=20 and M=4).

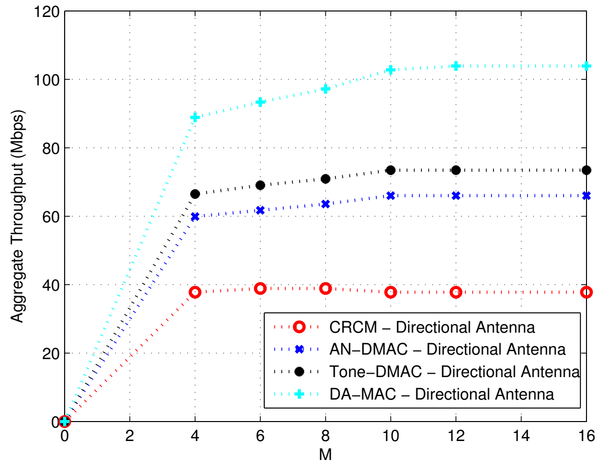

Figure 13: Aggregate throughput vs. the number of antennas (N=20 and traffic load = 6Mbps).

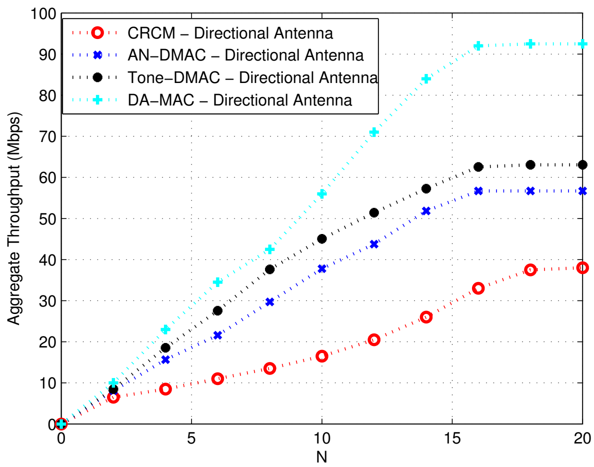

Figure 12: Aggregate throughput vs. the number of nodes (M=4, traffic load = 6Mbps).

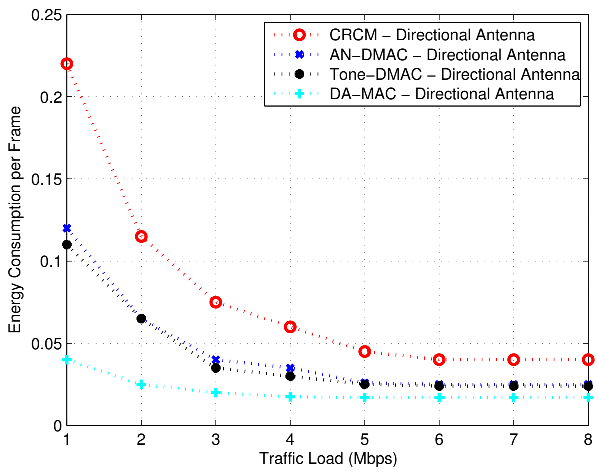

Figure 14: Energy consumption per frame vs. traffic load (N=20 and M=4).

This is because a sender that identifies a deaf node can immediately try another idle node.

Figure 11 shows the aggregate throughput versus the traffic load. As shown in the figure, the aggregate throughput increases as the traffic load increases. The aggregate throughput of DA-MAC achieves the best performance of all compared schemes. This is because DA-MAC can detect the deaf node, as shown in the previous performance of the deafness duration, and thus DA-MAC does not waste transmission opportunities to other nodes.

Figure 12 shows the aggregate throughput versus the number of receiver nodes in the sender range. As shown in the figure, the aggregate throughput increases as the number of receiver nodes in the sender range increases for all of the schemes. However, the aggregate throughput of DA-MAC achieves the best performance of all compared schemes. CRCM has the worst performance due to the significant control frame overhead. The slope of the aggregate throughput in DA-MAC is much higher than in the other schemes because the deafness problem frequently occurs in the other schemes.

Figure 13 shows the aggregate throughput versus the number of antennas. As shown in the figure, the aggregate throughput increases as the number of beams increases because a narrower beam stimulates the spatial reuse in the DMAC protocol. As a result, nodes have more apportunity to transmit simultaneously. The aggregate throughput of the DA-MAC achieves the best performance of the compared schemes. One interesting finding is that the aggregate throughput in the CRCM scheme is saturated at around 39 Mbps due to the use of many additional control frames.

Figure 14 shows the energy consumption per frame versus the traffic load where the traffic load varies from 1 to 8 Mbps. As shown in the figure, the energy consumption decreases as the traffic load increases. This is because there is more overhead for carrier sensing per frame at the lighter load. We observe that DA-MAC is the most energy-efficient among the given

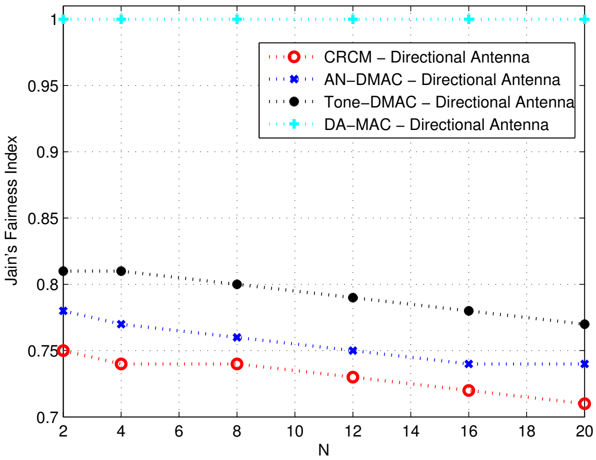

Figure 15: Jain's fairness index vs. the number of nodes (M=4 and traffic load = 6Mbps).

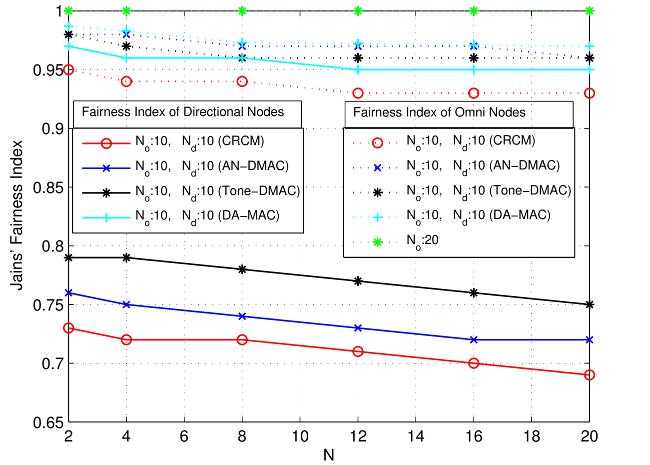

Figure 17: Jain's fairness index vs. the number of nodes (M=4, traffic load = 6Mbps, N=N_o+N_d=20, solid lines show the fairness index of directional nodes, and dashed lines show the fairness index of omni nodes).

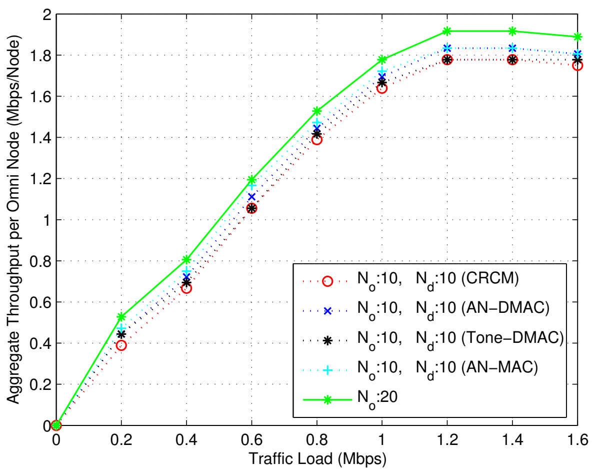

Figure 16: Average throughput per omni node vs. traffic load (N=N_o+N_d=20, M=4, N_o is the number of omni nodes, and N_d is the number of directional nodes).

schemes. Despite the use of two channels, our scheme has the benefit of energy-efficiency.

Figure 15 shows the Jain's fairness index versus the number of nodes when $M = 4$ and the traffic load is 6Mbps. In this simulation, all nodes use a directional antenna. As shown in the figure, all nodes have equal opportunity to send data in our DA-MAC scheme. However, in the other three schemes, nodes do not have the same opportunity since some nodes suffer from the deafness problem. The nodes experiencing the deafness problem suffer reduced throughput by retransmitting unnecessary DRTS frames to deaf receivers and incrementing the backoff window. This violates the fairness among all nodes. On the other hand, the DA-MAC scheme can choose the next receiver in the transmit queue and maintain similar transmission opportunities among all nodes, with a fairness of 1.

Additionally, to verify the backward-compatibility, we applied a heterogeneous topology by deploying nodes with an omni-directional antenna (*omni nodes*) and nodes with a directional antenna (*directional nodes*). We measured the throughput degradation of omni nodes in the presence of directional nodes with various directional MAC schemes compared with the case that all nodes are equipped with an omni-directional antenna (*homogeneous case*). Figure 16 shows the average throughput per omni node versus the traffic load. As shown in the figure, the throughput degradation is about 0.06–0.15 Mbps for the homogeneous case with an omni-directional antenna (i.e., $N_o = 20$). The proposed scheme experiences the smallest amount of throughput degradation because the DA-MAC uses a single beam to transmit its control frame, while the other three schemes use more beams for control frame transmission. The CRCM scheme shows the worst performance since it sequentially sends multiple control frames in all directions.

In Figure 17, we measured the Jain's fairness index of omni nodes and directional nodes in a heterogeneous topology. As expected, we observed that fairness indices of omni nodes for all directional MAC schemes decrease about 2–7% compared with the homogeneous case (i.e., $N_o = 20$). However, the proposed scheme maintains a fairness level comparable to the homogeneous case regardless of node type (96–98% for omni nodes and 95–96% for directional nodes). On the other hand, the fairness index of directional nodes in the other directional schemes decreases as the number of nodes increases due to the deafness problem (about 15–25% degradation compared with the DA-MAC).

6. Conclusion

Most of the existing DMAC protocols in ad hoc networks attempt to solve the deafness problem by using techniques with multiple control frames, advance notification of potential senders, or a tone. However, the existing techniques still suffer from the deafness problem. We conclude that the fundamental solution to the deafness problem is identifying whether a node encounters deafness. In this paper, we proposed a DA-MAC protocol that distinguishes deafness from a collision by exploiting two channels (data and control). Informed by the different responses to a DRTS frame based on the two channels, the DA-MAC sender can identify normal, deafness, and collision cases. The proposed DA-MAC has the following features:

- **Deafness-awareness**: The sender is able to detect an actual network failure by distinguishing deafness from a collision.

- **Queue Scheduling**: If the sender is aware that the receiver is in a deaf state, it can start to communicate with another idle node, thus improving the aggregate throughput.

- **Reducing Control Overhead**: The sender and receiver do not transmit the DRTS and DCTS frames to their neighbors. Eliminating the control frame overhead to all of the neighbors can further increase the aggregate throughput.

The performance evaluation shows that the DA-MAC outperforms the existing schemes in terms of the aggregate throughput, the deafness duration, energy consumption per frame, and transmission fairness.

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