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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.

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, and HD digital cameras, under fixed topologies [4,5,13,15,18]. 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 [9,11,12,19]; (2) approaches that notify potential senders [8,17]; 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

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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).
- We have shown that DA-MAC significantly outperforms the existing techniques in terms of various performance indices (in Section 5) and presented our conclusions in Section 6.

2. Related work

According to the taxonomy mentioned in Section 1, the schemes in [9,11,12,19] 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, [11,12,19] used multiple control frames. Although these approaches have multiple RTS/CTS overheads, they do not completely resolve the deafness problem. Fig. 1 is an example of the deafness problem that occurred in [9,11,12,16,19]. 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 Fig. 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.

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

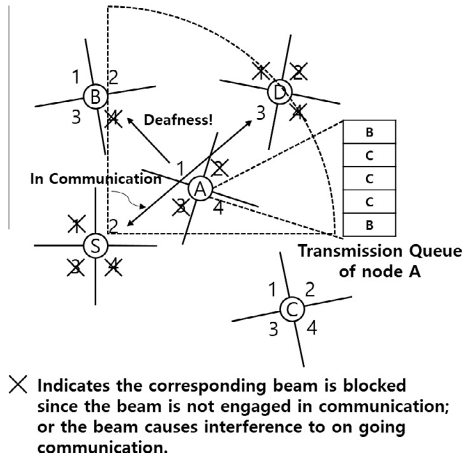

Fig. 1. An example of the deafness problem (4 antenna beams).

Instead of transmitting multiple DRTS/DCTS frames, the schemes in [8,17] 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 [17] 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 Fig. 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 transceivers 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 simultaneously transmit a tone signal omni-directionally to let the other neighboring 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 Fig. 1, their scheme still cannot resolve the deafness problem. For instance, node *A* transmits DRTS to *B* using beam 1. Then,