Mitigating Deafness in Multiple Beamforming Antennas

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Abstract— **Deafness is considered as a major medium access problem arising due to directional communication in beamforming antennas. In this paper, we provide a novel algorithm for mitigating deafness (AMD) in such antennas. The algorithm extends the directional virtual carrier sensing mechanism by dynamically maintaining parameters for every beam. AMD can easily be implemented with the existing medium access control (MAC) protocols for multiple beamforming antennas. Simulation results show that considerable performance gains can be achieved when the proposed algorithm is employed by the existing MAC schemes.**

Keywords- Beamforming antennas, deafness, medium access control, wireless ad hoc networks.

I. Introduction

Traditional wireless ad hoc networks use omnidirectional antennas for communication, which adversely affects the network capacity in a multihop scenario because of poor spatial reuse [1]. Therefore, researches have suggested using beamforming antennas that have a greater potential to enhance the overall network capacity [2]. Beamforming antennas divide the omnidirectional space around them into angular sectors called beams and data communication occurs only in the respective beams. A multiple beamforming antenna is capable of forming several beams and can initiate simultaneous transmissions (or receptions) in those beams. However, problems due to deafness and hidden terminals often arise with beamforming antennas due to the inability of a node to sense other ongoing transmission(s) in the neighborhood. These problems do not arise in omnidirectional communication when both physical and virtual carrier sensing is used, as in the IEEE 802.11 DCF [3]. The omnidirectional communication of control messages, however, limits the spatial reuse and blocks the data communication in the neighborhood which could have progressed concurrently. Hence, it is required to balance the tradeoff between the conflicting requirements.

In the past, researches have suggested various schemes to handle deafness in single beamforming antennas. In [4], two MAC schemes are presented. The first scheme employs omnidirectional transmission of clear to send (CTS) packets, while the second scheme proposes omnidirectional transmission of request to send (RTS) packets if none of the beams is blocked. A scheme similar to IEEE 802.11 DCF virtual carrier sensing is presented in [5] for directional antennas referred to as directional virtual carrier sensing (DVCS). The DVCS mechanism is used in DMAC [6] to maximize spatial reuse. Elbatt et al. [7] evaluated various mechanisms of sending control packets, viz. omnidirectional, directional and hybrid of two. They also proposed piggybacking beam indices in control packets to inform the neighbors which beam may be used for initiating their own RTS packets. In [8], authors have laid down mode selection criteria for single beamforming antennas but no specific algorithm was proposed. However, in all these schemes, if any beam of the node is blocked due to physical or virtual carrier sensing, the control packets are transmitted directionally to avoid interference with ongoing communications. Thus, deafness is still unresolved. Various other schemes are based on busy tones [9, 10] and circular sweeping of all beams [11] or a subset of beams [12] for sending control packets. While the former requires additional channel for busy tones, the latter incurs sweeping delays.

Recently, two approaches have been exploited to handle deafness in multiple beamforming antennas. In MMAC-NB [13], control packets are transmitted in all free beams. While in ESIF [14], cross-layer information and DVCS mechanism is used to send control packets only in beams with potential transmitters for that node. However, in MMAC-NB unnecessary control packets are transmitted, while in ESIF deafness is handled partially and in a complicated manner using cross-layer information.

In this paper, we propose a novel algorithm for mitigating deafness (AMD) in beamforming antennas. The algorithm can easily be implemented with MMAC-NB and ESIF to enhance their performance. The rest of the paper is organized as follows. In section II, we give an overview of the deafness problem and the existing MAC protocols for multiple beamforming antennas. We propose our algorithm in Section III. The performance evaluation is done in Section IV. Section V concludes the paper.

II. Overview

A. *The Deafness Problem*

Deafness arises when a transmitting node is unaware of the busy state of its intended receiver. As a result, the transmitting node repeatedly makes attempts to communicate with its receiver and is unsuccessful. This results in the transmission backoff, with backoff interval getting doubled for each unsuccessful attempt, thereby increasing the network delays.

This work has been supported in part by the Ohio Board of Regents, Doctoral Investment Funds and National Science Foundation Grant BES-0529063

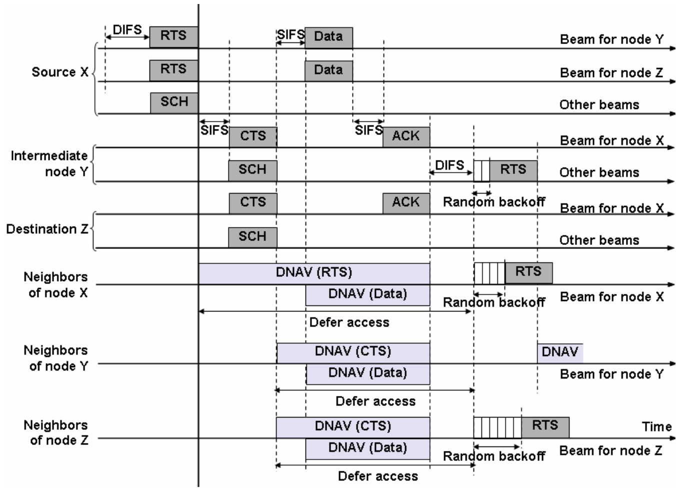


Figure 1. Basic operation of MMAC-NB

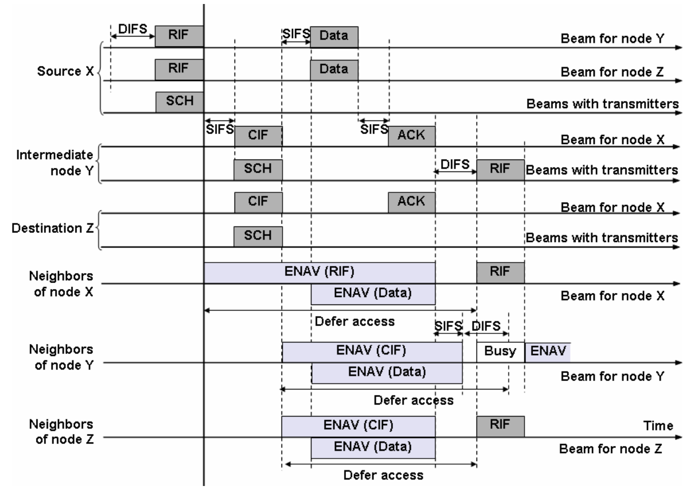


Figure 2. Basic operation of ESIF

These retransmission attempts may also interfere with the ongoing communication at the receiver. Further, once the number of retransmission attempts crosses its upper limit, route is considered as broken and a fresh route discovery is initiated. Thus, deafness greatly affects the network performance not only at the medium access layer but also at the higher layers.

B. MMAC-NB

Multiple beam omnidirectional MAC with Node-based Backoff (MMAC-NB) is an IEEE 802.11 DCF based scheme for multiple beamforming antennas [13]. The scheme employs proactive approach to handle deafness by transmitting control packets in all available beams[1]. While RTS and CTS messages are transmitted in respective beams, scheduling (SCH) packets are transmitted in remaining beams. Also, DVCS mechanism is used to maintain its *Directional Network Allocation Vector* (DNAV) table. DNAV essentially stores the duration required to defer access in a particular beam. The protocol also maintains common backoff interval for all its beams so as to facilitate concurrent packet transmissions (CPT) by the node and is the first on-demand MAC protocol to support CPT with multiple beamforming antennas. The basic operation of this protocol is illustrated in Fig. 1.

C. ESIF

Explicit Synchronization via Intelligent Feedback (ESIF) is the first attempt to achieve concurrent packet receptions (CPR) with on-demand MAC protocol for multiple beam antennas [14]. It uses embedded feedback to synchronize neighboring nodes and thus allows nodes to receive (or transmit) multiple packets simultaneously in different beams. In ESIF, contention window based backoff after the DIFS wait is removed to facilitate CPR and common backoff for all beams is used to achieve CPT. Furthermore, cross layer information is used to send scheduling packets in active receiver routes[2] thus alleviating deafness and hidden terminals, and at the same time minimizing the chances of blocking data communication between other nodes as with MMAC-NB. Fig. 2 illustrates the basic operation of ESIF protocol. ESIF maintains ENAV, *ESIF Network Allocation Vector*, a concept that extends DNAV to stores additional parameters required for its operation.

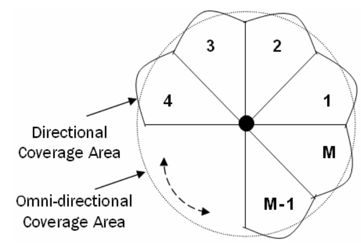


Figure 3. The antenna model

D. Antenna Model

We consider a wide azimuth switched-beam smart antenna comprised of multiple beam antenna array [15]. Each antenna array has M elements and is capable of forming non-overlapping sectors spanning an angle of $2 /M$ radians so as to collectively span entire space as shown in Fig. 3. A conical beam shape is assumed and benefits of nulling or the impact of side-lobe interference are not considered. Also, we focus on gains obtained from spatial reuse rather than range extension. Hence, the range of omni-directional and directional coverage area is same. Carrier sense is performed directionally, i.e., the medium is sensed only in desired beams before initiating the transmission. In idle mode, the receiver scans all its beams for valid transmissions. The direction of incident energy is used to determine the appropriate beam for reception of data and calculating the Angle of Arrival (AoA) of the received signal [16]. Thus, a collision occurs only if a node receives interfering energy in the *same beam* in which it is actively receiving.

III. PROPOSED ALGORITHM

AMD dynamically maintains two parameters for every beam as its input. These parameters are in addition to other parameters stored in DNAV or ENAV table. The two parameters are:

- *isRTSReceived*: This parameter is set to true whenever a node receives a RTS for itself in this beam. This keeps a record of whether a node has transmitter for itself in this beam or not. This parameter can be used to find active-receiver-routes exploited in ESIF.

[1]The beams that are not blocked by carrier sensing mechanism.
[2]This implies transmitting SCH packets in beams having transmitters.

- *isCTSReceived*: This parameter is set to true whenever a node receives a directional CTS in this beam and the control message is not intended for it. We assume that a node can distinguish between a directional CTS and an omnidirectional CTS meant for scheduling purposes. A simple way to achieve this to send RTS/CTS messages in designated beams, while sending another control message for scheduling (SCH) in all other beams as in MMAC-NB and ESIF.

Using the above parameters, the AMD algorithm concludes the following:

- The control messages are transmitted in all the beams which are unblocked and whose *isRTSReceived* parameter is set to true. This is to make all the potential transmitters aware of future data communication by this node. This also ensures fairness in cases where two or more transmitter lie in common beam of the receiver as in Fig. 4(a).
- If the beam selected for data transmission has *isCTSReceived* parameter set to true then the RTS/SCH is transmitted in all the unblocked beams. This is to ensure fairness in cases where two routes overlap with each other as in Fig. 4(b).

Please note that the algorithm does not require any cross layer information and thus can easily be implemented in existing protocols based on DVCS mechanism. Also, the above algorithm does not eradicate the deafness problem completely, as the beams required to send control messages may be blocked by DNAV, or the intended receiver of scheduling message may be currently busy.

IV. Performance Evaluation

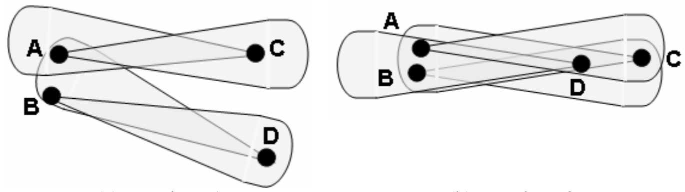
A. Sample Scenarios

We implement AMD for the MMAC-NB and ESIF to compare the performance of protocols with and without AMD. We compare the protocols for the two cases as illustrated in Fig. 4. The topology in Fig 4(a) depicts the scenario, where omnidirectional communication of control messages degrades the performance of the system by causing collisions at the receiver. On the other hand, Fig 4(b) depicts the scenario when omnidirectional communication of control message is required to prevent the deafness problem.

B. Simulation Setup

The simulation is written in PARSEC [17], a C-language based discrete event simulator. Some important simulation parameters are listed in Table I. Packet generation at source nodes is modeled as Poisson process with specified mean arrival rate. The simulations are run for various random seeds and the results statistically averaged out for five iterations each running for hundred simulation seconds. The maximum buffer at each node is 30 packets after which arriving packets are dropped. Also, each packet has a *lifetime* of 30 packet durations[3] after which the packet is considered as dead and is dropped, thus placing an upper bound on the network delays in all protocols.

[3]One packet duration is the time required to transmit one data packet at the given data rate.



(a) Topology 1 (b) Topology 2

Figure 4. Sample topologies

TABLE I. Simulation Parameters

Parameter	Value
Data rate	2 Mbps
Data packet size	2000 bytes
Control Packet size	45 bytes
ACK size	38 bytes
DIFS duration	50 microseconds
SIFS duration	10 microseconds
Short retry limit	7
Long retry limit	4

C. Results and Observations

We observe that omnidirectional transmission of control messages results in performance degradation of MMAC-NB as compared to AMD-MMAC-NB. This is clearly observed in Fig. 5. Throughput obtained in MMAC-NB is low due to collisions occurring at node D from transmissions by nodes A and B. Since node A transmits RTS message in all beams, oblivious to the ongoing communication between nodes B and D, transmission by node A interferes with that of node B. This occurs due to inherent deafness caused in directional communication. This results in increased retransmission attempts by nodes A and B, as evident from Fig. 6. This in turn increases the packet delay in the network as shown in Fig. 7. However, the topology has no effect on ESIF as control messages are sent only in routes with potential transmitters.

For topology 2, we observe in Fig. 8 that performance of both the protocols remain unaffected even after using AMD. While AMD still yields optimal performance with MMAC-NB, there is no performance improvement with ESIF. This is due the fact that ESIF employs localized synchronization, resulting in both the transmitters to begin their transmission at the same time that lead to collisions at the receiver. This is an inherent limitation of ESIF protocol and not of AMD. However, AMD does make the implementation of ESIF protocol much simpler by removing cross layer dependencies for transmitting control messages.

V. Conclusions

We have proposed an elegant distributed algorithm to mitigate deafness in beamforming antennas by extending the DVCS concept. The algorithm adds two more parameters to the DNAV or ENAV table which are maintained dynamically by the medium access control layer. The algorithm is implemented for two medium access protocols MMAC-NB and ESIF for multiple beam antennas. While performance improvements are observed for MMAC-NB scheme, implementation of ESIF is made simpler by using this algorithm.

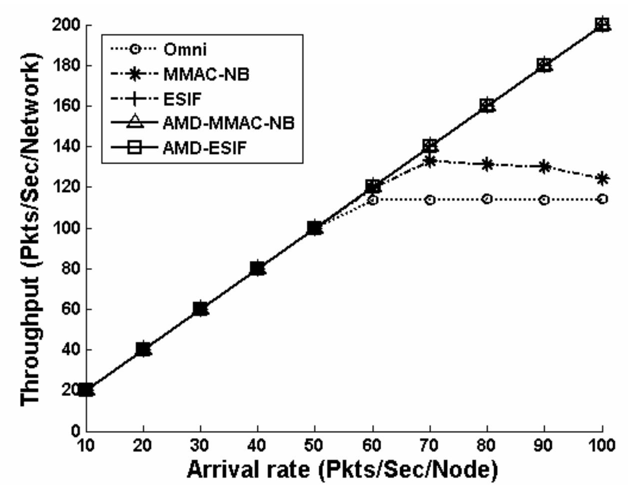


Figure 5. Throughput performance for topology 1

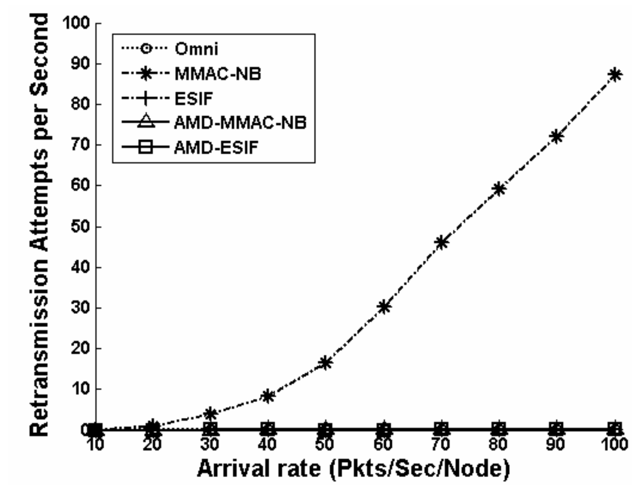


Figure 6. Retransmission attempts made by transmitting nodes in topology 1

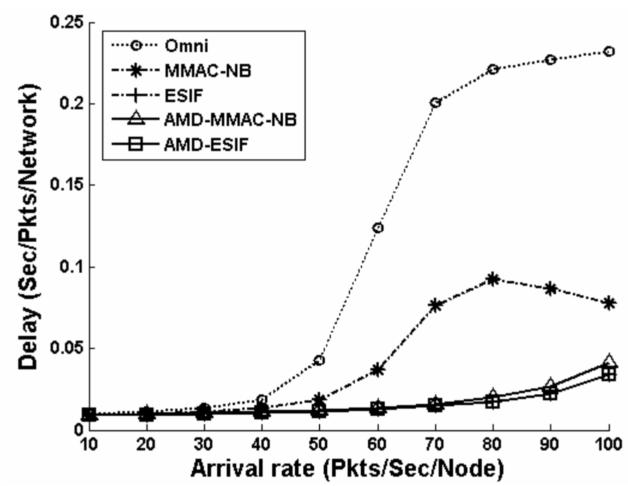


Figure 7. Per packet delay in topology 1

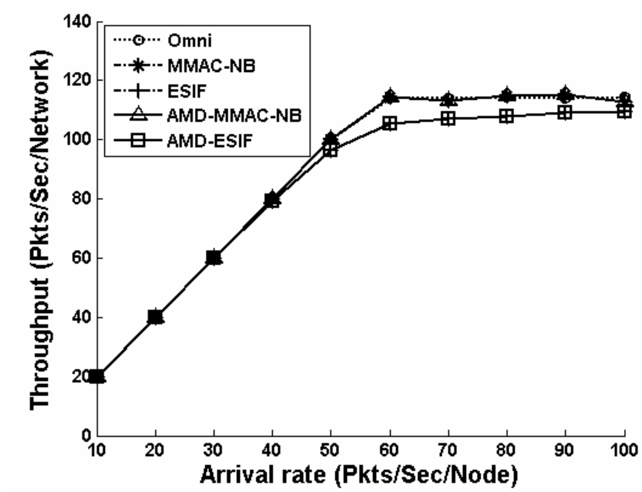


Figure 8. Throughput performance for topology 2

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