The Deafness Problems and Solutions in Wireless Ad Hoc Networks using Directional Antennas

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Abstract – This paper addresses the issue of deafness in directional antennas for wireless ad hoc networks. Deafness is caused when a node *X* repeatedly attempts to communicate with node *Y* but is unsuccessful, because *Y* is presently tuned to some other antenna beam. In this paper, we first outline different factors which contribute to such deafness in directional antennas and its significant impact on network performance. We then propose two schemes to overcome deafness scenarios which are transparent to the underlying directional MAC protocol in use. In addition, we also claim that IEEE 802.11 Short Retry Limit (SRL) needs a special handling in directional environment because of the presence of deafness. We have done a detailed performance evaluation of our schemes with different directional MAC protocols running over switched beam antennas and the initial results are found to be very promising.
Keywords: MAC, Deafness, Directional Antennas, MANETs.

1. INTRODUCTION

Most of the existing research on ad hoc networks typically assumes the use of omni-directional antennas by all nodes. Such an example is the IEEE 802.11 medium access control (MAC) [1] protocol which appears to efficiently solve the issues of this type of environment. However, due to the omni-directional nature of transmissions, network capacity is considerably limited. For example, the distribution of energy in all directions other than the intended direction not only generates unnecessary interference to other nodes, but also decreases the potential range of transmissions. With directional communications, on the other hand, both range and spatial reuse can be substantially enhanced, by having nodes concentrate transmitted energy only towards their destination's direction. On the receiving side, directional antennas enable a node to selectively receive signals only from the certain desired direction, thereby increasing the signal to interference and noise ratio (SINR).

Traditional MAC protocols that have been designed under the omni-directional assumption [1, 2] are no longer suitable for use over directional antennas. The design of an efficient MAC protocol for directional antennas is then a crucial issue and needs extensive investigation. In directional antennas, new types of hidden node problems arise [3]. In addition, fundamental issues such as node deafness and the determination of neighbors' locations have to be properly handled [4, 13]. Deafness is defined as the phenomenon when a node X is unable to communicate with node Y, as Y is presently beamformed in a different direction. As explained here, deafness is a serious issue in directional antennas as it may considerably impact performance. A study of the deafness issue is given in [3] but no solution is provided. In this paper, we have studied the deafness issue in detail outlining different factors which contribute to deafness and its impact in a switched beam antenna system. We have also proposed two proactive approaches to handle deafness scenarios, wherein a node willing to send an RTS[1] first estimates if its destination is deaf to the antenna beam being used to reply the CTS. If so, it defers the transmission of its RTS. This estimation is done based on its destination's location information and knowledge of ongoing transmissions in its neighborhood. To this end, we have assumed that nodes are aware of the location information of its neighbors, as in [3, 12]. Also, our proposed schemes are transparent to the type of the MAC scheme being used. By type of MAC scheme we mean the way control packets (RTS/CTS) are sent. If an RTS is sequentially sent through all antenna beams, it is referred to as omni-directional RTS (ORTS), whereas it is referred as directional RTS (DRTS) if it is sent only towards its intended destination (as in DMAC[3]). Similarly, CTS may be OCTS or DCTS. In addition, in proposed MAC extensions, we have tuned IEEE 802.11 Short Retry Limit (SRL) for directional environment. A source node X now tries to learn if the absence of a reply from some destination Y was because of deafness; and if so, it handles SRL differently.

The rest of this paper is organized as follows. We will first discuss the existing work in the directional MAC layer protocols in Section 2. In Section 3 we outline the antenna model used in this paper followed by a brief description of IEEE 802.11. Section 4 thoroughly describes deafness phenomenon in directional antenna, followed by a discussion of its impact on network performance in Section 5. Section 6 discusses our proposed enhancements. Comprehensive simulation study of different MAC protocols with and without our scheme is then presented in Section 7. Finally, this paper is concluded in Section 8 highlighting some open problems and future research.

2. RELATED WORK

The majority of research in the area of directional antennas has focused on broadband and cellular networks [5, 6, 7]. In the context of wireless ad hoc networks, research is still at its infancy. In general for ad hoc networks, two models for MAC protocols for directional antennas can be identified. In the first

[1] *In IEEE 802.11 Distributed Coordination Function (DCF)[1], to address the hidden terminal problem, DATA transmission is generally preceded by an RTS (Request to Send) and CTS (Clear to Send) handshake.*

model [8], each node is equipped with *M* antennas whose orientations can be maintained at any time, regardless of the node's movement. In this model, it is assumed that nodes have directional reception capability. Most recent research adopts this model [3, 4, 8]. In the second model [9], antennas are always active for receiving and thus transmissions to different antennas in the same node results in collision. Some MAC proposals for directional antennas assume this model [10]. In this work, we consider the first model.

The adaptation of the IEEE 802.11 MAC in [8] sends the RTS and CTS packets omni-directionally in order to enable the transmitter and receiver to locate each other, while it sends the DATA and ACK packets in directional mode. A MAC protocol that sends a directional RTS and an omni-directional CTS is presented in [11]. Here, it is assumed that the transmitter knows the receiver's location, so that it can send the RTS directionally. In case location information is not available, the RTS is transmitted in omni mode in order to find the receiver. In [12] it is proposed the use of Directional Virtual Carrier Sensing (DVCS) in which directional RTS and CTS transmissions are employed. This protocol also assumes that the transmitter knows the receiver's location. Similar to [11], RTS are transmitted omni-directionally in case location information is not available. The concept of DVCS and Directional Network Allocation Vector (DNAV) mechanisms are proposed in [3, 4, 11, 12]. DNAV is an extension to the NAV concept used in IEEE 802.11 for directional antennas. Essentially, DNAV is a table that keeps track for each direction (beam) the time during which a node must not initiate a transmission in that direction.

Finally, [3] studies the problems associated with using directional antennas and proposes a MAC protocol to take advantage of the higher gain obtained by directional antennas. This protocol employs a scheme of directional multihop RTS transmissions so as to establish directional-directional links between the transmitter and receiver. An assumption of this scheme is that the transmitter must know the entire path to the intended receiver so that the RTS packet can be routed. In addition, it suffers from deafness and hidden node problems [4].

To overcome the shortcomings in DMAC, a scheme of circular directional transmission (i.e., sweeping) of RTS coupled with a single directional CTS packet is employed in [4]. We refer to this scheme as Circular RTS MAC (CRM). While CRM does not assume prior neighbor's location availability, it does not satisfactorily prevent node deafness and collisions. First of all, CRM only prevents deafness in the neighborhood of the transmitter. Another serious problem with CRM is in the design of its RTS/CTS handshake. For example, if the destination node does not reply back with a CTS (due to a collision), nodes in the neighborhood of the transmitter which correctly receive the circular RTS will not be able to initiate any transmission as their DNAV is set. Clearly, this degrades the network capacity.

3. PRELIMINARIES

3.1 Antenna Model

We have implemented a directional antenna module in Network Simulator (NS – version 2.26), which possesses two separate modes: Omni and Directional. This may be seen as two separate antennas: an omni-directional and a single switched beam antenna which can point towards any specified directions [3]. The Omni mode is used only to receive signals, while the Directional mode is used for transmission as well as reception.

In Omni mode, a node is capable of receiving signals from all directions with a gain of G^o. While idle (i.e., neither transmitting nor receiving), a node stays in Omni mode. As soon as a signal is sensed, a node can detect the direction through which the signal is strongest and goes into the Directional mode in this particular direction.

In Directional mode, a node can point its beam towards a specified direction with gain G^d (with G^d typically greater than G^O). In addition, the gain is proportional to number of antenna beams (i.e., inversely proportional to the beamwidth) given that more energy can be focused on a particular direction, thus resulting in increased coverage range. A Node provides coverage around it by a total of M non-overlapping beams. The beams are numbered from 1 through M, starting at the three o'clock position and running counter clockwise. In Directional mode, and at a given time, a node can transmit or receive in only one of these antenna beams. In order to perform a broadcast, a transmitter may need to carry out as many directional transmissions as there are antenna beams so as to cover the whole region around it. This is called sweeping procedure. In the sweeping process, we assume there is negligible delay in beamforming in various directions.

To model antenna side lobes, we assume that energy contributed to the side lobes is uniformly distributed in a circular area. Although energy contributed to the side lobes depends on the actual radiation pattern, which is governed by the configuration and weighting of elements in the antenna array [13], for our simulation we assume that the side lobe gain is fixed and is set to -20dBi. Finally, we assume that all nodes use the same directional antenna patterns and can maintain the orientation of their beams at all times [8].

3.2 The IEEE 802.11

In the IEEE 802.11 [11], the Distributed Coordination Function (DCF) coordinates medium access in ad hoc networks. In DCF, an RTS and CTS handshake precedes DATA communication and the following ACK. DCF in IEEE 802.11 conducts two forms of carrier sensing: physical (by listening to the wireless shared medium) and virtual. Virtual carrier sensing uses the duration field which is included in the header of RTS and CTS frames. This duration field is utilized to set a station's Network Allocation Vector (NAV), which indicates the remaining time the medium is busy with the ongoing transmission. Using the duration information, nodes update their NAVs whenever they receive a packet. The channel is considered to be busy if either physical or virtual carrier sensing (by the NAV) so indicates. Whenever NAV is zero, a station may transmit if the physical sensing allows.

The area covered by the transmission range of the sender and receiver is reserved for data transfer, and hence other nodes cannot initiate transmission while communication is in progress. Given this fact, this region is referred to as *silenced region*. By using the RTS and CTS handshake to silence the nodes in the *silenced region*, IEEE 802.11 almost [20] overcomes the hidden terminal problem [18, 19].

4. THE DEAFNESS PROBLEM

In general, deafness is caused when a node X repeatedly attempts to communicate with node Y, but is not successful, because Y is presently tuned to some other antenna beam. At each unsuccessful attempt, the backoff interval is doubled hence degrading network performance. Deafness may also occur if Y's DNAV is set in the direction of X and hence it is unable to reply with a CTS. In this section we outline different scenarios which may cause deafness. We refer to Figure 1 for illustration purposes and assume an ongoing communication between nodes S and R. Obviously, severity of deafness depends on the specific MAC protocol under consideration; hence we also explain which protocol is more susceptible to what kind of deafness. We have classified directional MAC protocols into four categories based on how they transmit the RTS/CTS: ORTS-OCTS, ORTS-DCTS, DRTS-OCTS, and DRTS-DCTS.

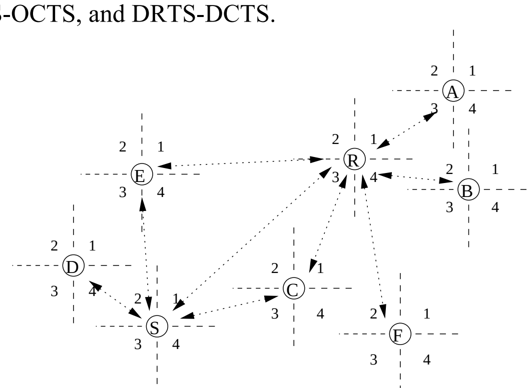

Figure 1: Deafness in Directional Antennas

- ***Destination engaged in communication:*** This kind of deafness problem is more prevalent in DRTS-DCTS protocols like DMAC [3]. DMAC sends RTS and CTS only in the direction of its prospective destinations. Hence, there is no way a third node which is reachable through a different antenna beam will come to know that its intended destination is currently engaged in a communication. In Figure 1, since node S sent its RTS only in antenna 1 (towards node R), there is no way its neighbor node D can determine that S is presently engaged in a communication with R. As a result, if D sends an RTS to S it will not receive any reply as S is presently tuned to beam 1 and hence is deaf to beam 2. Schemes using ORTS-OCTS can better overcome this problem since they try to send RTS and CTS through all beams. ORTS-DCTS and DRTS-OCTS are similar to DMAC with the difference that the impact of deafness is now confined to the neighborhood of the destination or the source side, respectively.

- ***Persistent hearing of DATA:*** This kind of deafness problem occurs in almost all directional MAC protocols. When a node sends RTS/CTS (either directional or omni), all neighbors who receive it set their DNAV accordingly. Whenever the source node starts transmitting DATA, neighboring nodes which are reachable through same antenna beam and are currently idle (e.g., node C in Figure 1) move to directional mode to receive the DATA packet, hence becoming deaf to all other directions. For example, although node C in Figure 1 knows about the communication between S-R as it received the previous RTS/CTS, it still moves to directional mode so as to receive the DATA packet. Therefore, if node F tries to send an RTS to C (beam 4) during the data transmission between S and R, node C will not reply as it is tuned to node S's DATA transmission. This result in a poor spatial reuse and negatively impacts overall system throughput. In Section 6, we will outline a scheme to overcome the persistent hearing of data packet at a destination node.

- ***Precautionary Deafness at the Receiver:*** This is a different variant of the problem discussed above wherein a receiver node avoids sending CTS if it knows that it may result in collision with an ongoing transmission. For example, let us assume that node C wants to send an RTS to node E (reachable through beam 2) and its DNAV is only set in beams 1 and 3 due to ongoing transmission between S and R. Obviously, node C is unaware of the fact that the antenna used by node E to receive packets from C and S is the same. Thus, if node C sends an RTS to E, it will either result in a collision at E or E will avoid sending a CTS back to C as its DNAV in that particular antenna beam is already set. Mostly all directional protocols suffer from this deafness since there is no way a source node can determine if its destination's beam towards him is blocked or not. By assuming neighbor location information availability, in Section 6.1 we will outline a scheme which handles this kind of deafness.

- ***Unheard RTS/CTS:*** Suppose node D wants to communicate with E while transmission is going on between S and R. In this scenario, as S is tuned to antenna beam 1 it will miss the RTS/CTS handshake between D and E (if sent in his direction), and hence will be unaware this future communication. When node S finishes communication with R and if it has any packet to be sent to either node D or E, it will unsuccessfully attempt to communicate with these nodes given that its DNAV is not set towards the corresponding directions. This problem exists in almost all directional MAC protocols and is difficult to handle.

5. IMPACT OF DEAFNESS ON NETWORK PERFORMACE

Deafness not only degrades the performance at the MAC level, but it also considerably affects the performance of higher layers. Whenever a node sends an RTS and does not receive back a CTS, it backoffs (according to IEEE 802.11) and tries to retransmit the RTS at some later time. This amounts to excessive wastage of network capacity in control packet transmission. Larger backoff intervals also result into unfairness wherein a flow completely captures the wireless shared medium. To illustrate this, assume that in Figure 1 two flows are present in the network: flow S-R from nodes S and R, and flow E-S from nodes E and S. We have simulated this scenario and the result of individual flow throughput is shown in Figure 2. As we can see, after a specified sending rate the flow S-R captures the medium forcing the flow E-S to completely shut down. This is because node S becomes deaf in the direction of node E, as the flow S-R is constantly sending packets.

The impact of deafness on the routing layer is also very severe. Each consecutive unsuccessful transmission of a packet (RTS or DATA) at the MAC causes the increment of a variable called Short Retry Limit (SRL). In the IEEE 802.11 standard, an SRL threshold is maintained (with default value equal to 7) that controls the number of packets transmission attempts made before a send failure is reported to the routing layer. The way SRL has been set in IEEE 802.11 assumes an omni-directional antenna is in place. If a node is not able to reach its destination in 7 attempts, it reports a route failure to the routing layer which, in turn, initiates a route discovery procedure throughout the network. Clearly, this results in considerable network performance degradation, as route request packets are often flooded. One possible solution would be to increase the value of SRL (e.g., multiply it by the number of antenna beams), but it might not be an efficient solution for two reasons. Firstly, higher values of SRL mean longer delays in discovering the movement of a destination node; secondly, even a higher value of SRL does not guarantee that a route request will not be triggered while it may only delay it. In Section 6.2 we will outline an improved method to handle SRL in directional antenna systems.

The impact of deafness is severe in the route discovery phase as well. This problem is outlined in [4] where a node misses a better route to its destination as one of the nodes in the shortest path was deaf to its route request broadcast packet and hence was not able to reply back.

Finally, deafness may also impact the performance of the transport layer. Deafness may preclude a node from receiving a TCP ACK, for example. Clearly, this negatively impacts TCP performance as it may continuously enter its congestion control mechanisms.

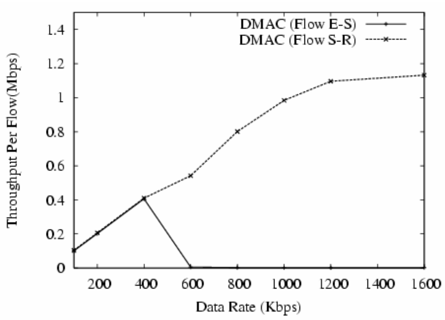

Figure 2: Channel Capture in Deafness Scenarios

6. THE PROPOSED SCHEMES

Although, in practice, it may not be feasible to completely overcome all deafness scenarios as discussed in Section 4, we can certainly minimize its effect. To this end, we propose such enhancements to directional MAC protocols which proactively try to prevent deafness situations.

Our first proposed enhancement attempts to eliminate deafness caused by *persistent hearing of DATA*, and is implemented by smartly handling the RTS/CTS handshake. For example, in Figure 1, after receiving RTS (antenna 3) and CTS (antenna 1), node C sets its DNAV accordingly. During the remaining duration of DATA transmission between S and R, C does not go to directional mode in antenna 3. With this, we are suggesting that node C should become deaf to its antenna beam 3 for duration of node S's DATA transmission. It is to be noted that a similar approach cannot be adopted for antenna 1 (CTS reception antenna). This can be argued by the fact that the ACK transmission duration is very small as compared to that of DATA duration. If node C also becomes deaf in antenna 1, it may miss important control or broadcast packets from other nodes. Note this would not happen in antenna 3 mainly because collisions may occur with ongoing DATA packets.

The implementation of the aforementioned enhancement is very simple. We just added a flag in the DNAV table maintained at each node. This flag basically indicates if the DNAV presently set was originally due to an RTS or not. It is worthwhile to note that this kind of deafness problem affects other nodes only at the antenna beams used by the sender and receiver to communicate (node S's beam 1 and node R's beam 3 in Figure 1). Hence, neighboring nodes receiving an ORTS/OCTS through a different antenna beam do not suffer from this kind of deafness. We have enhanced our protocol with this feature.

In our second proposed enhancement we assume that each node is aware of the location of its neighbors and uses the same number of antenna beams (NUM_ANTENNA_BEAMS)[2]. We also assume that all nodes use the same directional antenna patterns and can maintain the orientation of their beams at all times. Given the location information of its neighbor node Y, a node X can calculate `Antenna(Y,X)`, the antenna used by the neighbor Y to reach X as given in equation (1). In the following subsection we describe how this information can be used to handle deafness.

$$Antenna(Y,X) = \lceil Angle(Y,X) / NUM\_ANTENNA\_BEAMS \rceil \qquad (1)$$

6.1 Estimating Destination Status

Based on RTS/CTS, each node maintains a neighbor transmission table (NTT) for all ongoing transmissions in its neighborhood. The NTT stores the source node address which sent the RTS and the duration of the corresponding transmission. As for the CTS, we have made one modification to its header. CTS now also include the sender address too.

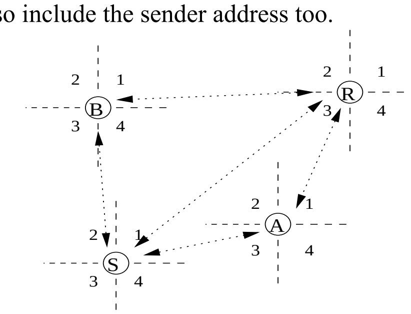

Figure 3: Proactive Handling of Deafness

Given the above modification, if a node X wants to send an RTS to node Y, it first verifies if the DNAV for the antenna beam used by X to reach Y is set. If it is, X defers its transmission. Otherwise, X searches all ongoing transmissions in its neighborhood by checking if the duration field in any entry of its NTT is set. If the resulting set is non-empty, by equation (1) node X calculates the beam its destination node Y is going to use to reply with a CTS, say $A_{Y,X}$. Then, for each node T in the NTT

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[2] *In case number of antenna beams supported by nodes is different, nodes should include their corresponding number of beams in MAC layer packet transmissions. For each neighbor, a node now maintains both its location information and the number of beams supported. This information can now be used in estimating the angle in equation (1).*

whose duration field is set, it verifies if the antenna beam used by T to reach Y, say $A_{T,Y}$, is equal to $A_{Y,X}$. If so, node X determines that a collision may take place and defers sending its RTS for the corresponding duration.

To illustrate this scheme please refer to Figure 3. Let us assume that S and R are presently engaged in a communication and node A wants to communicate with B. First of all, our first enhancement ensures that once the RTS and CTS from S and R is over, node A becomes deaf to antenna beam 3, while it can still receive and reply in antenna beam 1, 2 and 4. Without the second enhancement, if node A sends an RTS towards B, B will not reply as its DNAV is set for beam 4 and hence it is deaf in the direction of A for the duration of the DATA communication between S and R. The second enhancement enables node A to overcome this by determining in advance if it should or not send the RTS. To do so, node A checks if `Antenna(B,A)` is equal to `Antenna(B, S)`. Since A is a neighbor of S, R, and B, it has the location information for all of them and hence can use equation (1) to calculate the corresponding antenna beams. Once determining that `Antenna(B,A)` is the same as `Antenna(B,S)`, node A defers the transmission of its RTS for the corresponding duration field of node S. This prevents unwarranted transmission of RTS from node A. Please note that node A does not need to be a neighbor of both source and destination, so as to calculate the various antenna beams. Being a neighbor of the destination suffices as CTS packets now carry the information about the sender too.

6.2 Handling of SRL in Directional Environment

As outlined in Section 5, in IEEE 802.11 standard, an SRL threshold is maintained (with default value equal to 7 in most of the implementation) that controls the number of packets transmission attempts possible before a send failure is reported to the routing layer. However the absence of reply from a destination may be contributed by several factors. For example in an omni-directional environment, a receiver might not have received RTS correctly (collision), it may be an exposed terminal, its CTS might be lost or it is moved out of the transmission range of the sender. On the other hand, in directional environment, assuming the nodes are static, the main factor which contributes to the increment of SRL is beamforming (*deafness*) of a receiver in a different direction.

Hence it is necessary to identify absence of a reply because of beamforming of a receiver and in those cases special handling of SRL is required. For example, a sender node should not report a broken link error if it can detect that the absence of reply was because of its destinations beamforming in a different direction. However, the question remains how a source node S will know if its destination R is not able to reply because of beamforming. Here we argue that, depending on the type of directional MAC protocol employed, a sender can determine absence of reply because of deafness by continuously listening (MAC layer snooping) the packets in its neighborhood.

In proposed approach, if node B receives an RTS from S, and if it has a packet to sent to S, it resets its SRL as well as its contention window. We argue that resetting of contention window in this case helps node B to reach S, during S post-backoff period. We have incorporated this feature in our proposed enhancements of directional MAC protocols.

7. PERFORMANCE EVALUATION

In addition to the directional antenna module, we have also implemented ORTS-OCTS (referred as OMAC), and DMAC schemes. We used dynamic source routing (DSR) as the routing protocol for our simulation work.

For the simulations that follow, we have considered CBR traffic sources at data rates of 200, 400, 600, 800, 1000, 1200 and 1600 Kbps, and we measure the total network aggregate throughput of all flows. In addition, we evaluate DMAC, OMAC, and the proposed Enhanced DMAC (E-DMAC) and Enhanced OMAC (E-OMAC) schemes, for four and eight antenna beams with transmission ranges of 350 and 550 meters, respectively. To reduce the sweeping overhead in OMAC, in E-OMAC nodes send the RTS-CTS only to beams with neighbors [14]. Also, in all the scenarios we consider a 2 Mbps network with no node mobility. For the radio propagation model, a two-ray path loss model is used. Since DMAC requires prior knowledge of neighbors' location, we have provided all protocols with such information for a fair analysis.

We first evaluate the gain by using the first enhancement alone. To do so, we have created a topology as shown in Figure 4. In this scenario, node B is a neighbor of nodes S and R whereas node A is neighbor of B only. Also, node S sends packets to node R while node A sends packet to node B. Note that the antenna used by S to reach both B and R are same.

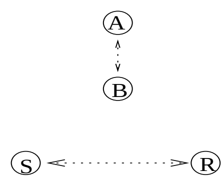

Figure 4: Persistent Hearing of DATA/ACK

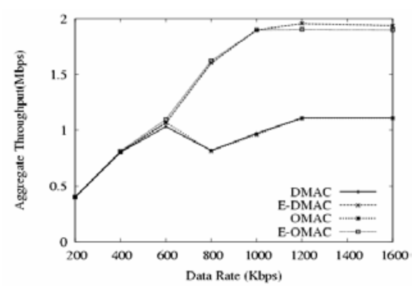

Figure 5: Effect of persistent hearing of DATA/ACK

Figure 5 shows the simulation results obtained for this scenario. Amongst the directional MAC protocols evaluated, E-DMAC performs slightly better than E-OMAC. This is because E-DMAC does not employ circular directional transmission of both RTS and CTS which serves to inform the neighbors of a node about the intended transmission, thus minimizing hidden terminals. In the particular scenario of Figure 4, circular RTS/CTS does not provide any benefit for deafness as `Antenna(S,B)` is the same antenna as `Antenna(S,R)`, and the same is true with respective to node R. As the traffic increases, our proposed enhancement gives a considerable improvement for both the existing schemes. This can be argued by the fact that at lower traffic rate nodes have sufficient time to share the channel without being affected by neighboring transmissions, while it is not true for higher traffic rate.

In addition, Figure 6 shows that the enhanced scheme improves the sharing of the medium as opposed to the original scheme depicted in Figure 2. Although it is worthwhile to note that the improvement depends on the topology under consideration.

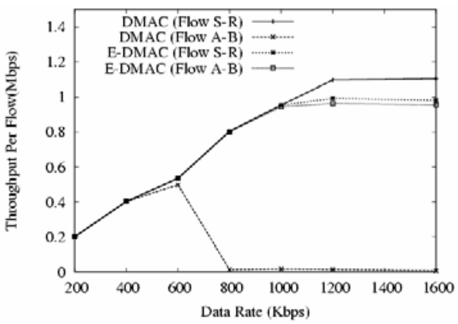

Figure 6: The Enhanced Scheme Prevents Channel Capture

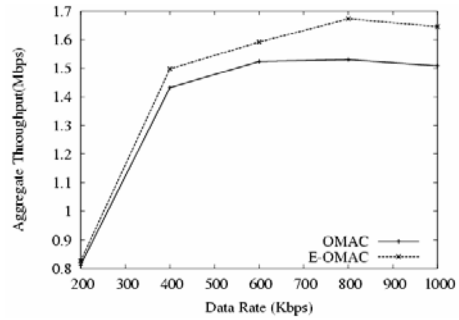

Figure 7(a): Random Topology (4 beams)

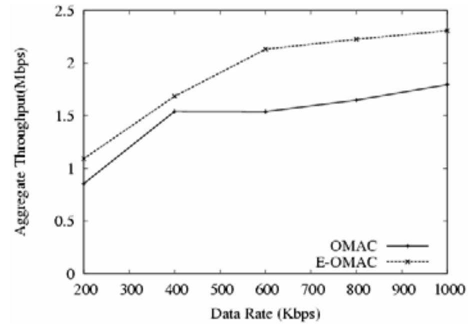

Figure 7(b): Random Topology (8 beams)

We now simulate a topology comprised of 16 nodes distributed in a 4 by 4 grid. Nodes are placed at a distance of 175 meters. We randomly select 4 source and destination nodes. We have simulated a total of 10 scenarios and the results presented here are the average of their individual results. In this set of simulations, we implement both of our enhancement schemes in OMAC. Figures 7(a) and 7(b) show the results when nodes possess four and eight antenna beams respectively. It is to be noted that in DMAC a sender does not employ any kind of sweeping mechanism to tackle deafness in its neighborhood (except the beam at which its destination is), hence we eliminate DMAC in following set of simulation results.

In Figure 7(a), we observe that for four antenna beams the performance improvement gained by using our enhanced schemes is marginal, whereas for eight antenna beams, we obtain a significant performance improvement as shown in Figure 7(b). This is due to the fact that as the number of antenna beams increases, chances of different nodes being at different antenna beams are higher thus increasing the likelihood of deafness scenarios.

8. CONCLUSIONS AND FUTURE WORK

In this paper we have considered the problem of deafness for ad hoc networks employing directional antennas. We have discussed the shortcomings of existing work and have proposed two enhancements. Our enhancements are transparent to type of directional MAC scheme under consideration, and through simulation work we have shown that they provide considerable gain. We also note that the performance gain is dependent of the type of directional MAC protocol under consideration as the severity of deafness depends on the MAC. Finally, it is to be noted that the system performance also depends on the network topology as well as the traffic pattern between nodes. As future work, we plan to incorporate these enhancements into a new directional MAC protocol for ad hoc networks.

ACKNOWLEDGMENTS

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