MDA: An Efficient Directional MAC scheme for Wireless Ad Hoc Networks

Hrishikesh Gossain, Carlos Cordeiro, and Dharma P. Agrawal

OBR Center for Distributed and Mobile Computing
Department of ECECS, University of Cincinnati – Cincinnati, OH 45221-0030
(hgossain, cordeicm, dpa)@ececs.uc.edu

Abstract – This paper addresses the issue of deafness and hidden terminal problem in a Mobile Ad Hoc Networks (MANETs) using directional antennas. To minimize these effects, we propose a MAC protocol for directional Antennas (MDA) which employs an enhanced directional network allocation vector (NAV) scheme and, a novel technique of Diametrically Opposite Directions (DOD) transmission of RTS and CTS. We compare MDA with IEEE 802.11 and two recently proposed directional MAC protocols and results show that MDA outperforms these protocols in the majority of scenarios investigated. We also point out that the performance does depend on the network topology and the traffic pattern.

1. INTRODUCTION

Use of directional antennas is getting increasing acceptance in wireless systems. With directional antennas both transmission range and spatial reuse can be substantially enhanced by having nodes concentrate transmitted energy only towards their destination’s direction, thereby achieving higher signal to noise ratio (SNR). However, use of directional antennas in MANETs creates new types of hidden terminal problems [3] and node deafness [4, 7]. In addition, fundamental issues such as determination of a node’s neighbors have to be properly handled [4]. 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. In such an event, X perceives Y to have moved out of its range, thereby signaling its routing layer to take actions, hence affecting the network throughput. Deafness and hidden terminal issues have been extensively studied in [3] a one hop scenario but no solution has been provided.

In this paper, we introduce a MAC protocol for Directional Antennas (MDA) for use in wireless ad hoc networks. MDA addresses the hidden and deaf node problem by employing a novel scheme of selective diametrically opposite directional (DOD) transmission of RTS and CTS, where these packets are transmitted only through the antennas with neighbors. Here, we argue that the way sweeping (sweeping the packet sequentially in all antenna beams) of RTS/CTS is performed has a significant impact on the performance of the MAC scheme. We then show that the DOD procedure defined in MDA is a special case of sweeping which maximizes the non-overlapping coverage area, while ensuring no collision among RTS and CTS, and hence is observed to be a more suitable approach for directional antennas than sweeping. In addition, MDA implements an Enhanced Directional Network Allocation Vector (EDNAV) which allows a significant spatial reuse compared to existing directional NAV schemes.

We have conducted an extensive performance evaluation of MDA and have compared it with two prominent directional MAC protocols, and the IEEE 802.11 standard. Results indicate that MDA surpass all MAC protocols in the majority of scenarios.

The rest of this paper is organized as follows. In Section 2 we first discuss the related work on MAC protocols for directional antennas followed by a description of our antenna model in Section 3. Next, Section 4 thoroughly describes our proposed MDA protocol and how it overcomes the problems discussed. Simulation study and comparison of MDA with three other MAC protocols including IEEE 802.11 is given in Section 5. Finally, this paper is concluded in Section 6 highlighting some open problems and future research plan.

2. MOTIVATION AND RELATED WORK

In [8], a variation of RTS/CTS mechanism of IEEE 802.11 adapted for use with directional antennas is given. This protocol sends the RTS and CTS packets omnidirectionally in order to enable the transmitter and receiver to locate each other, and sends the DATA and ACK packets in directional mode. A MAC protocol that sends a directional RTS and an omnidirectional CTS is presented in [5]. 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. [6] proposes the use of Directional Virtual Carrier Sensing in which directional RTS and CTS transmissions are employed. Here, it is assumed that the transmitter knows the receiver’s location. Similar to [5], RTS packets are transmitted omni-directionally in case location information is not available. Finally, [3] studies the problems that arises due to use of 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 (DD) links between the transmitter and the receiver.

In [5, 7, 8] at least one omnidirectional transmission of a control packet is employed, hence limiting the coverage area. In [3, 9] a protocol called Directional MAC (DMAC) is proposed that employs directional transmission of RTS and CTS. Similar to the previous schemes, it assumes nodes’ locations are known a priori. In DMAC, a single RTS is transmitted towards the destination which, in turn, responds back with CTS. This protocol also suffers from deafness and hidden node problems as described in [4].

To overcome the shortcomings in DMAC, it is proposed in [4] a scheme of sweeping of RTS. Destination then sends back a single directional CTS packet towards the source. We refer to this scheme as Circular RTS MAC (CRM). While CRM does not assume prior neighbor’s location availability, it prevents node deafness in the neighborhood of the transmitter only. Also if the destination node does not reply back with a CTS (due to a collision/deafness), 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. Finally, [3, 4, 5, 6] propose the concept of Directional Virtual Carrier Sense (DVCS) and Directional Network Allocation Vector (DNAV). Here we show that this scheme has some limitations and propose an Enhanced DNAV (EDNAV) approach.

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3. PRELIMINARIES

3.1 The Antenna Model

We have implemented a complete and flexible directional antenna module at the Network Simulation (NS – version 2.26) [1]. This model possesses two separate modes: Omni and Directional. This may be seen as two separate antennas: an omni-directional and a steerable single beam antenna which can point towards any specified directions [3]. In principle, both the Omni and Directional modes may be used to transmit or receive signals. In Omni mode, a node is capable of receiving signals from all directions with a gain of $G^2$. While idle (i.e., neither transmitting nor receiving), a node stays in Omni mode when using our proposed protocol. 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 Directional mode, a node can point its beam towards a specified direction with gain $G^2$ (with $G^2$ typically greater than $G^3$). 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 termed as sweeping. In the sweeping process, we assume there is only carrier sensing delay in beamforming in various directions. This model has been widely studied in the literature [3, 4, 8, 9]. To simplify modeling of antenna side lobes, we assume that energy contributed to the side lobes is uniformly distributed in a circular area with a very small gain value. Finally, we assume that all nodes use the same directional antenna patterns and can maintain the orientation of their beams at all times [8].

4. THE PROPOSED MDA PROTOCOL

4.1 Determination of Neighbors’ Location

One important component in the design of MDA is the precise determination of the antenna beam through which a given neighbor can be reached. In MDA we use an efficient method of both establishing and maintaining a directional neighbor table (DNT). DNT is established during the route discovery phase. Routing control packets such as RREQ and RREP facilitate neighbor resolution. Any neighboring node $Y$ which receives a packet from $X$ at beam $i^\text{th}$ can easily comprehend that it needs to send a packet on its $j^\text{th}$ beam in order to communicate with $X$. Similarly, with the RREP packet, node $X$ can also resolve node $Y$ to one of its antenna beams. In addition, similar to [2] MDA employs MAC layer snooping for maintaining the DNT. By setting the MAC in a promiscuous mode, a node overhears all the traffic in its vicinity. By simply overhearing these packets, a node updates its DNT as well as track new neighbors in its surroundings. An important aspect of this procedure is it also allows a node to determine if any of its sectors have any neighbors at all.

4.2 The Diametrically Opposite Directional RTS and CTS

MDA uses an efficient form of RTS and CTS transmission called the Diametrically Opposite Directional (DOD) procedure. To better illustrate the DOD procedure let us take an example and analyze Figures 1(a) and 1(b). In these figures, the shaded area represents the region which is not covered by a RTS/CTS transmission between nodes $S$ and $R$ when employing DMAC and CRM, respectively. A closer look reveals that the shaded area actually represents the deafness region. In other words, nodes sitting in this region receive neither the RTS nor the CTS packets originated from node $S$ or $R$, respectively, and hence become deaf to their communication. As we can see from Figures 1(a) and 1(b), the deafness region in CRM is considerably smaller than DMAC (in DMAC RTS-CTS is sent only towards destination directions) as it employs sweeping of RTS. However in CRM, as there is no sweeping of CTS, part of the region around node $R$ defines the deafness region as shown in Figure 1(b).

One possible solution to handle these problems would be to apply a sweeping of both RTS and CTS. However, not only the delay would considerably increase (and throughput decrease) but the coverage area of the RTS and CTS would considerably overlap, thus leading to a high number of collisions. In MDA, the DOD transmission of RTS and CTS is optimized by sending these packets only through those sectors where neighbors are found. As we know, this information is obtained through the neighbors’ location procedure (Section 4.1).

The DOD RTS/CTS mechanism in MDA works as follows. Initially, assume that all nodes have the same number of antenna beams equal to $M$, and that node $S$ has a packet to be sent to its neighbor node $R$ through beam $A_{SR}$. If $A_{SR}$ is not idle, the backoff procedure is initiated similar to IEEE 802.11. Otherwise, the sender node $S$ has to ascertain a few key points. Firstly, it needs to determine through how many of its sectors (called DOD sectors), say $D$, besides the one it communicates with the receiver $R$ it has to transmit a DOD RTS. To illustrate this procedure, please refer to Figure 1(c). First of all, right before sending a RTS to $R$ node $S$ needs to estimate the antenna beam $A_{RS}$ used by $R$ to reach $S$. By simple mathematics, we can see that node $S$ can easily figure out $A_{RS}$ given that it knows $A_{SR}$ (through the neighbor information) as follows. The antenna beam $A_{SX}$ a node $X$ uses to communicate with node $Y$ can be used to derive the beam $A_{XY}$ which is used by $Y$ to communicate with $X$. If $M$ is even, node $X$ can easily determine node $Y$’s receiving antenna beam by:

$$A_{XY}(A_{ST},M) = \begin{cases} A_{ST} + \frac{M}{2}, & \text{if } A_{ST} < \frac{M}{2} \\ A_{ST} - \frac{M}{2}, & \text{otherwise} \end{cases}$$

(1)

On the other hand, if $M$ is odd a more general model can be employed which relies on the angle of arrival (AoA) [6], and is given by:

$$A_{XY}(A_{ST}) = 360^\circ \times \frac{A_{ST} + 180^\circ}{M}$$

(2)

For simplicity, however, from now on we consider $M$ as even. Basically, equation (1) is used to shift a node’s transmitting antenna beam and obtain the receiving node’s antenna beam. Applying equation (1) to the scenario of Figure 1(c), node $S$ finds that $A_{RS}$ is equal to 3. With this information, node $S$ then makes its DOD-RTS$_{End}$ as also equal to 3, while its first DOD RTS$_{Start}$ is antenna 2. After this procedure, node $S$ then sets $D$ to two; as it may possibly send DOD RTS through two beams, namely, 2 and 3. A similar mechanism is employed in for CTS (with DOD-CTS$_{End}$ = 1 and DOD CTS$_{Start}$ = 4) and a careful examination of Figure 1(c) shows that it ensures a non overlapping coverage by RTS-CTS packets. Now, out of these D DOD sectors, MDA has to determine how many have neighbors and are idle. Let $K_S$ be the resulting number of beams (e.g., $K_S = 2$ in Figure 1(c)). Node $S$ then sends its RTS towards node $R$. Once node $R$ receives the RTS from node $S$, it carries out the same procedure. Similarly, let $K_R$ be the resulting number of beams calculated by node $R$ (e.g., $K_R = 2$ in Figure 1(c) corresponding to beams 4 and 1).
An important aspect in the design of MDA is that the first RTS is always transmitted in the sector where its intended neighbor is located, and the DOD transmission of RTS and CTS is only initiated once the RTS/CTS handshake between the communicating nodes is successfully completed.

Upon reception of an RTS packet in step (1), the receiver proceeds similar to IEEE 802.11. That is, it waits for a period of time equal to SIFS and sends back a CTS as shown by step (2). Only after the RTS/CTS handshake is completed and the channel is reserved in their direction, will both sender and receiver nodes simultaneously initiate the DOD transmission of their RTS and CTS packets, respectively, to inform their neighbor nodes. This simultaneous DOD transmission of RTS and CTS is observed to save time and effectively takes care of the hidden node problem and deaf nodes at both the neighborhood of the sender and receiver. The concurrent DOD procedure is illustrated in Figure 1(c) by step (3). Although there is still a small deafness region in MDA, this looks to be the smallest possible deafness region so that the collision probability does not increase.

One issue still remains is how to synchronize sender and receiver again to carry out DATA/ACK transmission. To this end, the sender node $S$ includes its value of $K_S$ in its RTS, that is, $K_S$, and the receiver node $R$ includes $K_R$ in its CTS back to node $S$. Through $K_S$, node $R$ is able to determine the exact point in time when node $S$ will have finished its DOD transmission of RTS and hence will start transmitting DATA. Similarly, node $S$ with $K_S$ can precisely tell the moment node $R$ will be ready and waiting for DATA transmission. Clearly, the DOD procedure works extremely well in uniformly distributed networks when $K_S$ is equal or approximately equal to $K_R$ or even when there is a very small discrepancy in their difference. When there is a large difference between $K_S$ and $K_R$, one node will eventually have to wait until its corresponding node is ready. Steps (4) and (5) in Figure 1(c) depict the DATA/ACK transmission.

### 4.3 The Enhanced Directional NAV (EDNAV)

Directional NAV (DNAV) scheme proposed in [5] is a simple extension of IEEE 802.11 NAV concept and is employed to handle issues of hidden terminal problem in directional environment. Essentially, DNAV is a table that keeps track for each direction the communication path between the transmitter and the receiver (first RTS/CTS handshake), the DNAV is to be modified. The DT is comprised of two components: a DNAV mechanism which is manipulated differently from previous schemes, and a Deafness Table (DT) which is used to handle deafness scenarios. Whenever a node has a packet to be sent over one direction, both DNAV and DT are consulted. On the other hand, upon reception of a packet the node will either modify its DNAV or its DT, not both. If the node lies in the communication path between the transmitter and the receiver (first RTS/CTS handshake), the DNAV is to be modified. The DT is modified whenever the node receives either a DOD RTS/CTS, that is, once the RTS/CTS handshake is over. In this case, the node is certain not to lie within the communication path of the ongoing transmission.

In MDA we incorporate an Enhanced DNAV (EDNAV) scheme comprised of two components: a DNAV mechanism which is manipulated differently from previous schemes, and a Deafness Table (DT) which is used to handle deafness scenarios. Whenever a node has a packet to be sent over one direction, both DNAV and DT are consulted. On the other hand, upon reception of a packet the node will either modify its DNAV or its DT, not both. If the node lies in the communication path between the transmitter and the receiver (first RTS/CTS handshake), the DNAV is to be modified. The DT is modified whenever the node receives either a DOD RTS/CTS, that is, once the RTS/CTS handshake is over. In this case, the node is certain not to lie within the communication path of the ongoing transmission.

The idea behind EDNAV is to differentiate between deafness and collision scenario, which is not possible by using DNAV alone.

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**Figure 1** – Coverage range in DMAC, CRM and MDA, and RTS/CTS/DATA/ACK exchange in MDA

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**Figure 2** – DNAV limitations and the DT table

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### 5. PERFORMANCE EVALUATION

We have implemented a directional antenna module in NS (version 2.26). This module covers most of the aspects of a directional antenna system including variable number of antenna beams, and different
gain values for different number of antenna beams among others. As for the protocol support, we have implemented DMAC, CRM, and MDA and compare their performance to omni-directional IEEE 802.11.

For the simulations that follow, we have considered CBR traffic sources at data rates of 100 Kbps, 200 Kbps, 400 Kbps, 600 Kbps, 800 Kbps, 1000 Kbps, 1200 Kbps, and 1600 Kbps. In addition, we evaluate DMAC, CRM and MDA for four, eight, and twelve antenna beams with transmission ranges of 370, 550, and 710 meters, respectively. For IEEE 802.11, the transmission range is set to 250 meters. Also, in all the scenarios, we consider a 2 Mbps network. It is to be noted that in the following analysis we have enhanced DMAC with prior knowledge of its neighbor’s location.

For the space limitations, we present results only for the gain by spatial reuse and gain by increased coverage range of directional antenna system. For a complete simulation results please refer to [1].

5.1 Random Topology

5.3.1 Gain by Spatial Reuse

We first evaluate the performance of different MAC protocols when all nodes are within radio range of each other. Given that the shortest transmission range is 250 meters in case of IEEE 802.11, all the nodes are confined within a circle of 250 meters diameter in the network topologies evaluated here. By doing so, we plan to evaluate the spatial reuse gain provided by directional antennas as compared to omni-directional antennas. In the next section, we will focus on the gain by increased coverage range.

We consider a scenario comprised of 16 nodes randomly distributed. We have run a total of 10 random topologies and the results presented here are the average of their individual results. In each scenario, we randomly select five nodes as source, which then randomly select five other nodes as destinations. As a result, some nodes can act as both source and destination which may lead to deafness.

5.3.1.1 Aggregate Throughput

Figures 3(a), 3(b), and 3(c) show the aggregate throughput of each directional MAC schemes when nodes possess four, eight, and twelve antenna beams. Intuitively, IEEE 802.11 performance is practically the same when all stations are within the radio range of each other. Given all the nodes are within the radio range of each other, IEEE 802.11 does not suffer from deafness, does not have any sweeping delay and all the flows tend to share the channel. On the other hand, by randomly selecting source and destination nodes leads to situations where a single node is both source and destination, hence increasing the chances of deafness in DMAC. In Figure 3(a), we observe that MDA outperforms all other schemes including IEEE 802.11. It is also interesting to note that CRM performance is inferior to IEEE 802.11. CRM spends a lot more time than MDA performing the sweeping. In addition, it often happens that when a transmitter node using CRM is performing its sweeping, one of its RTS happened to collide at its intended receiver with some other sweeping of RTS carried out by other nodes. Thus, many circular RTS transmissions end up being useless while they still prevent neighbors from transmitting for the entire duration.
When the number of antennas increases from four to eight and twelve (Figures 3(b) and 3(c)), we see that MDA performance is further enhanced by increased spatial reuse. As for CRM, its throughput is again below that of IEEE 802.11. On the other hand, the performance of DMAC improves with the increment in the number of antenna beams. This can be attributed to the fact that a higher number of antenna beams leads to more room for spatial reusability, although it also increases the chances of deafness as nodes are reachable through different antenna beams. This is why the performance of DMAC is still close to IEEE 802.11 as the increase in spatial reuse is offset by increased deafness.

5.3.2 Gain by Increased Coverage Range

Contrary to the previous section, here we focus on the second side which forces packets to wait longer in the queue for CRM. As expected, the directional MAC protocols considerably outperform IEEE 802.11 performing best overall.

6. CONCLUSIONS AND FUTURE WORK

In this paper we have considered the problem of medium access control for ad hoc networks employing directional antennas. We have discussed the shortcomings of existing work and have proposed a new MAC protocol for Directional Antennas (MDA) that implements unique mechanisms, including simultaneous diagnostically opposite directional transmissions of RTS and CTS packets, an optimized form of sweeping, and an enhanced DNAV mechanism. Through our extensive performance evaluation, we have observed that MDA performs better than IEEE 802.11 and existing directional MAC protocols such as DMAC and CRM in all scenarios except in the linear topology. The linear topology case is particularly degrading to all directional MAC protocols, but MDA is still observed to perform best in terms of all directional MAC protocols considered, with IEEE 802.11 performing best overall.

REFERENCES