Directional Medium Access Protocol (DMAP) with Power Control for Wireless Ad Hoc Networks

Aman Arora, Marwan Krunz, and Alaa Muqattash
Department of Electrical and Computer Engineering
The University of Arizona, Tucson, AZ 85721
{amarora,krunz,alaa}@ece.arizona.edu

Abstract— **Protocols for mobile ad hoc networks (MANETs) are often designed with the assumption that nodes are equipped with omnidirectional antennas. Spatial reuse in such networks can be significantly improved by using directional antennas, leading to higher system capacity. This gain is associated with a substantial energy saving that results for beamforming the transmitter and/or receiver antennas in the appropriate directions. However, several medium access problems (e.g., hidden terminal, deafness) resurface when directional antennas are integrated into existing MAC protocols. In this paper, we propose a power-controlled MAC protocol for directional antennas that ameliorates many these problems. Our protocol uses separate control and data channels to reduce collisions. It allows for dynamic adjustment of the data-packet transmission power, such that this power is just enough to overcome interference at the receiver. Simulation results demonstrate that the combined gain from using directional antennas and power control results in significant energy saving and improved throughput performance.**

I. INTRODUCTION

One of the fundamental challenges in designing mobile ad hoc networks (MANETs) is how to increase the overall network throughput while maintaining low energy consumption for packet processing and communications. One approach to increase the throughput is to use directional antennas, which allows for more efficient use of the channel along with other benefits related to increased coverage and lower power consumption. Due to these advantages, directional antennas have been widely deployed in IS-95 and third generation cellular networks [1]. For instance, sectoring provided by directional antennas enables a base station to serve more than one cell, thus improving the capacity of the network. MAC protocols currently used for MANETs with omnidirectional antennas (e.g., IEEE 802.11b [2]) are unsuitable for use with directional antennas. These MAC protocols are designed based on assumptions that are not valid for directional antennas. For instance, one of these assumptions is that nodes have equal reception sensitivity and radiate equal power in all directions. This is the assumption that lies behind using the RTS/CTS exchange for collision avoidance in the IEEE 802.11b prior to data transmission. The argument is, if any node can cause interference at a receiver then it will most likely hear the CTS from that receiver and defer from transmitting. When directional antennas are used, the radiated power and reception sensitivity between any two nodes become a function of the angular orientation of these nodes. Thus, using equal power for RTS/CTS and data packets can no longer prevent all potential interferers from transmitting.

This paper focuses on the design and evaluation of a new MAC protocol for MANETs with directional antennas. The proposed protocol is designed to alleviate the channel access problems associated with previous protocols. Moreover, our protocol addresses the critical issue of energy efficiency in mobile devices by using power control to minimize energy consumption. The remainder of the paper is organized as follows. Section II reviews previous work on MAC protocols for directional antennas. Section III discusses the problems associated with these protocols. Section IV presents our proposed protocol and in Section V we discuss the solutions for the channel access problems. In Section VI we evaluate the performance of the proposed protocol. Finally, we conclude the paper in Section VII.

II. RELATED WORK

MAC protocols for ad hoc networks using directional antennas is a rather recent topic, and has been studied in handful of papers [3] [4] [5] [6] [7] [8] [9] [10]. The authors in [3] proposed using location tables to keep track of directions via which a node can communicate with its neighbors. The RTS is sent directionally, successively in a circular manner to locate the intended receiver. In [4], the authors proposed a protocol that employs directional antennas and extends the concept of virtual carrier sensing to directional virtual carrier sensing. They also introduced the concept of DNAV, wherein a direction and an angular width are also associated with the NAV. The angle of arrival (AOA) estimate was used to set this DNAV for a receiving node. Setting the DNAV excludes a direction from the transmission; however, the node is free to transmit in other directions. The authors also demonstrated the adverse effects of minor lobes on their protocol performance. In [5] the authors have proposed two MAC protocols. The first is similar to protocol in [4]. The other protocol exploits the extended range of directional antennas, wherein a *multi-hop* RTS mechanism is used to beamform two far-off nodes in each other's direction before data transmission. Moreover, the authors of [5] identified the channel access problems that their protocol and other proposed MAC protocols for directional antennas face. These problems and some other channel problems are explained in Section III. The protocol proposed in [6] uses a somewhat complex mechanism, wherein individual nodes maintain neighborhood activity tables. These tables are updated using periodic broadcasts in all directions. Nodes then exchange these tables as data packets. As far as power controlled MAC protocols for directional antennas are concerned, few works have been published in the past on this

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issue. In [10] the authors proposed a power control technique for ad hoc networks. In this scheme, signal-to-interference-and-noise ratio (SINR) estimates are exchanged between nodes using control and data packets and a power reduction factor is updated iteratively.

III. PROBLEMS IN EXISTING MAC PROTOCOLS

A. Hidden Terminal Problems

In a MANET that uses omnidirectional transmissions, the solution for the hidden terminal problem lies in the exchange of RTS/CTS packets before data transmission. Protocols proposed for directional antennas (e.g., [4] [5] [6]) also use an RTS/CTS exchange but with the difference that the RTS/CTS packets are sent directionally. In these protocols, a node listens to the channel omnidirectionally when idle, and it uses directional transmission when sending data packets. These protocols suffer from the following hidden terminal problems [5]:

1) Unheard RTS/CTS due to Busy Node: In Figure 1, suppose that node B is beamformed in the direction of node A. In the meantime, node C exchanges RTS/CTS packets with node D and is sending data to node D. While listening in the directional mode, node B is unable to hear the $C \leftrightarrow D$ RTS/CTS exchange. In this scenario, node B is unaware of the ongoing transmission in its neighborhood. Suppose after the end of the $A \leftrightarrow B$ transmission, node B intends to transmit a packet to node D. Consequently, it sends an RTS to node D. This would result in a collision at node D. The MAC protocols proposed in [4][5][6] suffer from this problem.

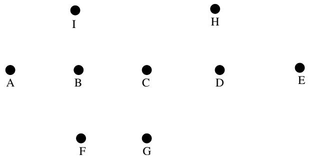

Fig. 1. Topology used to demonstrate the problems in existing MAC protocols.

2) Unequal Gains in Omni and Directional Modes: The protocols in [4][6] use equal power for directional RTS/CTS (DRTS/DCTS) and data packets. This could cause a collision, as explained in the following example.

Suppose in Figure 1 that node C sends a DRTS to node D and node D replies with a DCTS. Nodes C and D beamform in each other's direction, and node C starts transmitting to node D. Meanwhile, node A is in the idle mode listening omnidirectionally and is distant from node D, so it does not hear the DCTS. While this transmission is going on, suppose that node A has data to send to node B, and thus sends a DRTS to node B. It is quite possible that the DRTS from node A will interfere with node D since node A and node D are now beamformed in each other's direction. Roy et. al [5] identified this problem in their protocol but did not provide a solution to it. Also, the MAC protocols proposed in [4][6] do not address this problem.

3) Collisions due to Minor Lobes: Minor lobes represent the power radiated/received in directions other than the intended direction. This power is significant and can lead to the following problem. Consider Figure 1 again. If node B intends to send data to node C, it first sends a DRTS to node C. When C replies with a DCTS, node B starts sending the data packet. Node F is unable to hear the DCTS since it is not located in the direction of the main lobe of node C. Furthermore, assume that the gain of the minor lobes of node C is comparatively small, and node F is listening omnidirectionally. Meanwhile, node F has data for node C, and thus, points its main lobe towards node C. Even though node C has only a minor lobe in the direction of node F, the increased gain of the main lobe of node F could result in a collision at node C. This problem arises due to unequal gains in the directional and omnidirectional modes as in Section III-A.2. However, in this case, the interferer is sending the signal towards the minor lobes of the receiver. This problem remains unresolved in the protocols in [5][4][6].

4) Vulnerable Transmitter: In Figure 1 assume that node F sends a DRTS to node H, and node H replies with a DCTS. Upon receiving the DCTS, node F commences data transmission. This DRTS/DCTS exchange is heard by node C, which sets its DNAV accordingly. Meanwhile, node C intends to send a data packet to node B. Node C's DNAV in the direction of node B is not set and thus, it sends a DRTS to node B and waits for a DCTS while beamformed in B's direction. However, node F has its main lobe pointed towards node C, and node C has finite minor lobe gain in node F's direction. Therefore, the power received from node F at node C may be significant. In this case, if node B replies with a DCTS, then this may cause a collision at the node C. Thus, nodes in the vicinity of a transmitter may not be able to initiate data transmission even in the free directions (directions in which DNAV has not been set) while a nearby transmitter is sending data. A similar problem can arise when a transmitter is expecting an acknowledgement (ACK) following a data-packet transmission.

B. Deafness

Suppose that in Figure 1 node F is transmitting data directionally to node C. While this transmission is going on, node G intends to transmit to node C (assume that G has missed the DRTS/DCTS exchange between C and F, which is possible from the discussion in Sections III-A.1 and III-A.2). Thus, node G sends a DRTS to node C. Since node C is listening directionally facing node F, it is unable to listen to the DRTS from node G. When node G does not receive the DCTS for some time, it transmits another DRTS. Node G will retransmit the DRTS packet over and over again, resulting in wasted network capacity and unfairness (since node G's back off interval would be increased after every failed attempt) [5].

IV. PROPOSED PROTOCOL

A. Assumptions

In designing DMAP, we make the following assumptions: (1) Nodes use out-of-band signaling for control messages; (2) the physical layer at the receiver can accurately estimate the AOA of the received signal and the average interference power and deliver these estimates to the MAC layer on demand; (3) all nodes use directional antennas with identical antenna gains in the main lobe, denoted by G_M; (4) the channel is symmetric, and (5) the channel gain between a pair of nodes is stationary for the duration of the control and ensuing data packets. With regard to first assumption, we assume that the carrier frequencies for the data and control channels are adjacent so that the path loss is identical for both channels. This is needed to enable the estimated path loss from the control channel to be used for power control over the data channel. The fifth assumption is reasonable since the effect of multi-paths on the channel behavior (i.e., small-scale variations) can be mitigated using physical-layer diversity techniques (e.g., RAKE receivers). Therefore, the only parameter of significance in designing power-controlled MAC protocols is the power of the received signal after applying these diversity techniques, which is determined only by the path loss and large-scale variations and not by small-scale variations. Other studies (e.g., [11]) have also made the same assumption.

B. *Protocol Description*

The proposed DMAP is characterized by the following:

- An idle node will listen omnidirectionally to the data and control channels.
- If a node, say T, intends to transmit a data packet, it sends an RTS omnidirectionally at a common fixed power. Since the RTS is sent over the control channel, which is segregated in frequency from the data channel, there is no risk of it colliding with data transmissions.
- When a receiver, say R, receives the RTS, it estimates the AOA. Node R also calculates the path loss (ratio of power transmitted to power received, denoted by L_P). Note that the RTS is not used for setting the DNAV. Now, node R beamforms in the direction of node T and measures the total noise and interference (I_R), which consist of thermal noise power and the multiple access interference (MAI) at the receiver. Node R now calculates the power control factor β (explained shortly) as follows:

$$\beta = \frac{I_R L_P}{G_M^2}. \tag{1}$$

- β is used at node T to determine the transmission power of the data packet. This computed power is just enough to overcome path loss and interference; yet it achieves the required SINR at node R. Notice that G_M^2 represents the energy saving that is achieved due to the directional gain of antennas at the receiver and transmitter.
- Node R includes the value β in the DCTS packet. Before sending the DCTS, the receiver scales up the power of the transmitted DCTS packet (as explained in Section V-B) and then sends DCTS in the direction of node T.
- When node T receives the DCTS, it estimates the AOA of the DCTS and beamforms in the direction of node R. Node T now calculates the required transmission power as:

$$P_T = \beta \cdot \mathrm{SINR}_{th} \tag{2}$$

  where SINR_{th} is the required SINR threshold at node R. If $P_T < P_{max}$, where P_{max} is the maximum transmission power set by the hardware, then node T commences its data transmission. Otherwise, the data transmission is aborted.
- If a node other than node T receives the DCTS, then that node estimates the AOA of the DCTS. Subsequently, that node sets its DNAV on the basis of the estimated AOA in an analogous manner to setting the NAV in the IEEE 802.11b scheme.
- After the data packet is successfully received, node R sends an ACK to node T over the control channel directionally.

V. ADDRESSING CHANNEL ACCESS PROBLEMS

In this section, we discuss how DMAP resolves the channel access problems that afflict other MAC protocols for directional antennas.

A. *Segregation of Data and Control Channels*

Collisions due to unheard RTS/CTS messages (Section III-A.1) and vulnerable transmitter (Section III-A.4) are resolved by using separate data and control channels. For example, in Figure 1 consider the unheard RTS/CTS problem (Section III-A.1) wherein node B is transmitting data to node A. Meanwhile, node C sends a DRTS to node D. Upon receiving the DRTS, node D replies with a DCTS. Although nodes A and B are busy sending/receiving on the data channel, their control channels are idle, and thus, they are able to hear the DCTS from node D. Accordingly, both nodes set their DNAVs. This resolves the unheard RTS/CTS problem mentioned in Section III-A.1. As far as the vulnerable transmitter problem is concerned, separating the control and data channels eliminates entirely the possibility of a collision between data and control messages at the transmitter. Collisions can occur at the transmitter when two control messages reach the transmitter simultaneously. However, this has a low probability of occurrence due to the small size of control messages.

B. *Power Scaling of DCTS Transmissions*

As explained in Sections III-A.2 and III-A.3, the difference in the gains of the omni and directional modes, and also the major and minor lobes increase the likelihood of collisions. Our solution to these problems relies on the fact that with proper power scaling of the DCTS, collisions at a receiver due to asymmetric gains and minor lobes can be eliminated. This is possible if the power of the DCTS is scaled over the maximum power of the *data channel* by a power-scaling factor that ensures that every potential interferer listening omnidirectionally can hear the DCTS. To illustrate the idea and determine the appropriate value of the power-scaling factor, consider Figure 1 again. If node C intends to send a data packet to node D, it first sends an RTS omnidirectionally to node D. Upon receiving the RTS, node D scales the power of its DCTS. The scaling factor is such that the DCTS power received from node D (denoted by P_1) at a potential interferer (say node A) when node A is listening omnidirectionally is equal to the power (denoted by P_2) that node D will receive when node A points its main lobe toward node D. Notice that an interferer pointing its main lobe towards a receiver is the worst-case scenario for reception. Power scaling of the DCTS would ensure that if node A can cause interference at node D, then it would always hear the CTS in advance and set its DNAV accordingly. The powers P_1 and P_2 are given by:

$$P_1 = \frac{K G_O G_D}{r^\alpha}, \quad P_2 = \frac{K G_M G_D}{r^\alpha} \tag{3}$$

where G_O is the omnidirectional gain of node A's antenna, G_D is the directional gain of node D's antenna, G_M is the directional gain of node A's antenna at main lobe, r is the distance between

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A and D, K depends on the transmitted power and wavelength, and α is a constant that depends on the propagation conditions.

Let $P_1\Gamma = P_2$, where Γ is the power scaling factor. From (3) we get:

$$\frac{KG_OG_D}{r^\alpha}\Gamma = \frac{KG_MG_D}{r^\alpha} \Longrightarrow \Gamma = \frac{G_M}{G_O}. \qquad (4)$$

Equation (4) can be expressed in dBi as

$$\Gamma(dBi) = G_M(dBi) - G_O(dBi). \qquad (5)$$

The scaling factor used by node D is simply the difference in gain of the main lobe and gain in omnidirectional mode. Thus, before transmission, node D uses the gain at its main lobe to scale the power of DCTS above the maximum power of the data channel. Unlike the case mentioned in Section III-A.2, the scaling of the DCTS power will ensure that node A will be able to hear the DCTS packet and will set its DNAV, eliminating the possibility of collisions.

To address the problem in Section III-A.3, our solution exploits the minor lobes of the receiver and relies on scaling the power of the DCTS packet. Transmission of DCTS from minor lobes of the receiver at scaled power would prevent potential interferers located in directions other than that of the main lobe from transmitting. Any potential interferer, which is located in a direction other than the main lobe of the receiver, would receive the DCTS in advance and would set its DNAV. This resolves the problem mentioned in Section III-A.3. Deafness, would also be eliminated due to the power scaling of the DCTS. Scaling of DCTS power and segregation of control and data channels would ensure that all potential transmitter would hear the DCTS and thus, would set their DNAVs and defer sending an RTS in the receiver's direction.

VI. PROTOCOL EVALUATION

A. Simulation Setup

We now evaluate the performance of the DMAP protocol and contrast it with the IEEE 802.11b scheme. Our results are based on simulation experiments conducted using CSIM programs (CSIM is a C-based process-oriented discrete-event simulation package). In our simulations, we investigate both the network throughput as well as the energy consumption. For simplicity, data packets are assumed to have a fixed size. Each node generates packets according to a Poisson process of rate λ (same for all nodes). The routing overhead is ignored, as the goal here is evaluate the performance improvements due to the MAC protocol. The other parameters are: directional antenna used is 6 element circular array; data packet size is 2 KB; 802.11b data rate is 2 Mbps; DMAP data and control channel rates are 1.6 Mbps and 400 Kbps respectively; SNR threshold is 6 dB; omnidirectional reception range range is 188 meters.

We consider two types of topologies: *random grid* and *clustered*. In the random grid topology, M mobile hosts are placed across a square area of length 1000 meters. The square is split into M smaller squares. The location of a mobile user is selected randomly within each of these squares. For each generated packet, the destination node is randomly selected from the one-hop neighbors. To generate a clustered topology, we consider an area of dimensions 500×500 (in meters). We let $M = 24$ nodes, which are split into 4 equal groups, each occupying a 100×100 square in one of the corners of the complete area. For a given source node, the destination is selected from the same cluster with probability $1-p$ or from a different cluster with probability p. In each case, the selection from within the given cluster(s) is done randomly.

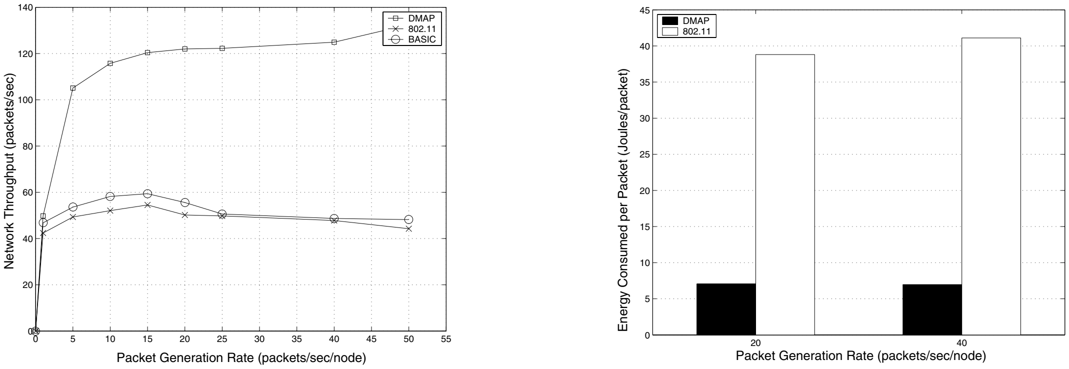
B. Simulation Results

The performance for random grid topologies is shown in Figure 2. In parts (a) and (b), we set $M = 64$ and vary the packet generation rate (λ). Part (a) of the figure depicts the network throughput. It is shown that DMAP achieves up to 200% increase over the throughput of the IEEE 802.11b scheme. This increase is attributed to the increase in the number of simultaneous transmissions. Furthermore, DMAP saturates at about twice the load at which the 802.11b scheme saturates. In addition to the 802.11b scheme, we simulated another MAC protocol for directional antennas, called BASIC, which uses DVCS, employs separate channels for data and control packets, sends both the RTS and the CTS directionally, but does not use power control and power scaling of the DCTS. Comparison with BASIC would establish the virtues of power scaling of the DCTS. The value of Γ is chosen so as to maximize the throughput. This is done by running the simulations for different values of Γ and choosing a value that maximizes the throughput. As can be seen, BASIC protocol does not achieve a significant increase in throughput over the 802.11b scheme due to the channel access problems explained in Section III. Part (b) of Figure 2 depicts the energy consumption versus λ. Energy consumption is the total energy used to *successfully transmit* a packet. It includes the energy of the control packets and the lost energy in retransmitting data and control packets in case of collisions. For almost all cases, DMAP consumes less than 19% of the energy required under the 802.11b scheme. This significant power saving is attributed to the gain of directional antennas and to power control. Note that in both protocols, the required energy increases with the load. The reason for this is that as λ increases, the probability of collisions also increases, and hence, more energy has to be spent on retransmissions.

The performance under clustered topologies is depicted in Figure 3. Part (a) of the figure depicts the network throughput versus λ when $p = 0.5$ for clustered topologies. According to the 802.11b scheme, only one transmission can proceed at a time, since all nodes are within the carrier-sense range of each other. However, according to DMAP, two to three transmissions can proceed simultaneously, resulting in a significant improvement in network throughput. Part (b) of Figure 3 depicts the energy consumption versus λ. For almost all cases, DMAP requires less than 13% of the energy required under the 802.11b scheme.

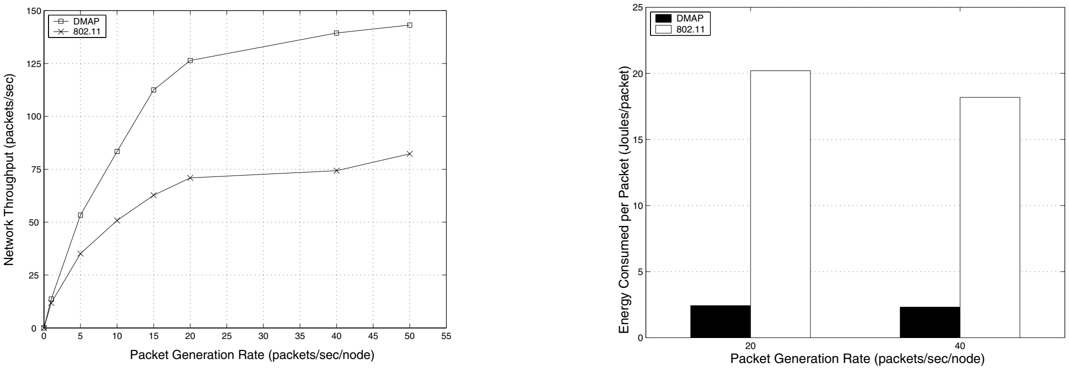
VII. CONCLUSIONS AND FUTURE WORK

In this paper, we proposed a power controlled MAC protocol for wireless ad hoc networks. This protocol, called DMAP, resolves the channel access problems that afflict other MAC protocols for directional antennas by segregating control and data channels. Moreover, the protocol uses CTS power scaling to prevent collisions due to asymmetric gains in omnidirectional and



(a) (b)

Fig. 2. Performance of the DMAP, BASIC, and the 802.11b protocols (random grid topologies).



(a) (b)

Fig. 3. Performance of the DMAP and 802.11b protocols as a function of λ (clustered topologies, $p = 0.5$).

directional modes. For energy efficiency, the protocol employs power control, where the power used by a transmitter is just enough to overcome interference at the receiver. We compared the performance of our protocol with the IEEE 802.11b scheme and the BASIC protocol for directional antennas. Our simulations showed that DMAP could improve the network throughput by 200% over IEEE 802.11b and 165% over the BASIC protocol. At the same time, DMAP achieves 82% reduction in energy consumed over IEEE 802.11b to successfully deliver a packet from the source to the destination

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