

Using Directional Antennas for Medium Access Control in Ad Hoc Networks*

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ABSTRACT

Previous research in wireless ad hoc networks typically assumes the use of omnidirectional antennas at all nodes. With omnidirectional antennas, while two nodes are communicating using a given channel, MAC protocols such as IEEE 802.11 require all other nodes in the vicinity to stay silent. With directional antennas, two pairs of nodes located in each other's vicinity may potentially communicate simultaneously, depending on the directions of transmission. This can increase spatial reuse of the wireless channel. In addition, the higher gain of directional antennas allows a node to communicate with other nodes located far away, implying that messages could be delivered to the destination in fewer hops. In this paper, we propose a MAC protocol that exploits the characteristics of directional antennas. Our design focuses on using multi-hop RTSs to establish links between distant nodes, and then transmit CTS, DATA and ACK over a single hop. Results show that our directional MAC protocol can perform better than IEEE 802.11, although we find that the performance is dependent on the topology configuration and the flow patterns in the system.

Categories and Subject Descriptors

C.2.1 [Network Architecture and Design]: Wireless communication; C.2.2 [Network Protocols]

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General Terms

Algorithms, Design, Performance

Keywords

Directional Antennas, medium access control, ad hoc networks, carrier sensing

1. INTRODUCTION

The problem of utilizing directional antennas to improve the performance of ad hoc networks is non-trivial. Directional antennas can provide higher gain, and reduce interference by directing beamforms towards a desired direction. However, they also pose challenges in the design of medium access control (MAC) protocols. A directional transmission, due to its greater transmission range, may potentially interfere with communications taking place far away. Previous research on MAC protocols using directional antennas has assumed equal transmission range when using directional and omnidirectional beamforms. However, this prevents exploiting the potential of directional antennas, especially the possibility of replacing many small hop communication links with one long, single hop link.

By using directional antennas, a node may also be able to selectively receive signals only from a certain desired direction. This enables the receiver node to avoid interference that comes from unwanted directions, thereby increasing the signal to interference and noise ratio (SINR). However, due to selective reception of signals, a node A might not be aware of some other node, B , attempting to initiate communication with it. Node B , receiving no response from node A would continue to retransmit, wasting channel capacity in unproductive control packet transmission. Thus the question of whether directional antennas improve the performance of an ad hoc network is not straightforward, but requires close examination of issues involved in channel access.

This paper is organized as follows. In Section II, we discuss related work on medium access control using directional antennas. We describe our antenna model and a summary of IEEE 802.11 in Section III. The problem under consider-

ation is discussed in Section IV. In Section V, we describe a basic Directional MAC (DMAC) protocol that is similar to 802.11, but adapted for directional antennas. Section VI identifies several problems with Basic DMAC. In section VII, we propose a multi-hop RTS protocol. We compare the performance of our proposed protocols with IEEE 802.11 in Section VIII. Section IX discusses future work and Section X presents a brief summary.

2. RELATED WORK

Some researchers in the past have addressed the challenges of using directional antennas in an attempt to improve wireless channel utilization [1][3][5][15][16][18][20]. Although substantial work has been done in the context of broadband and cellular networks (e.g. [4][6][19]), literature in the context of directional antennas in ad hoc networks is limited.

Nasipuri *et al.* [9] have addressed the problem of using directional antennas in the design of a MAC protocol. However, they have assumed that the gain of directional antennas is equal to the gain of omnidirectional antennas. In this paper, we evaluate the impact of higher gain of directional antennas. Ko *et al.* [8] also assume that the directional gain equals the omnidirectional gain. They, however, make the simple but useful observation that, when using directional antennas, a node may transmit in directions that do not interfere with ongoing transmissions. The DNAV mechanism [13] described later in this paper is derived from the above observation. Bandyopadhyay *et al.* [2] present another MAC protocol that is somewhat complex. The protocol uses additional messages to inform neighborhood nodes about ongoing communications, which may increase MAC layer control overhead.

Takai *et al.* [17] proposes *Directional Virtual Carrier Sensing* (DVCS) and DNAV mechanisms similar to the notion of DNAV in our Basic DMAC protocol [13], described in section V. We identify several problems affecting this protocol. We also propose a new MAC protocol for directional antennas.

In [11], Ramanathan presents an interesting discussion on several issues arising from directional communication. In this paper we identify several other problems, arising from directional communication that have not been identified in the past.

3. PRELIMINARIES

3.1 Antenna Model

We have incorporated an antenna model at the radio layer of the Qualnet simulator [16]. The assumed antenna system has two separate capabilities, or modes; *Omni* and *Directional*. This may be envisioned as two separate antennas; a omnidirectional and a steerable single beam antenna (the actual implementation may be somewhat different). In the *Directional* mode, the antenna system can point its main lobe towards any specified direction. For simplicity, we approximate the radiation pattern of the side lobes into a sphere with the node at its center. The gain of the side lobes is assumed to be very low.

In principle, both the *Omni* and the *Directional* modes may be used to transmit or receive signals. However, in our protocols, the *Omni* mode is used only to receive signals, while the *Directional* mode may be used for transmission as well as reception.

In *Omni* mode, a node is capable of receiving signals from all directions (360 degrees) with a gain, say, G^o . While idle (i.e. not transmitting or receiving) a node stays in the *Omni* mode when using the proposed protocols.

In *Directional* mode, a node can point its beam towards a specified direction with a gain of G^d ; G^d is typically greater than G^o . The direction in which the main lobe should point for a given transmission is specified to the antenna by the MAC protocol. In general, other beamforming parameters like *transmission power* could also be specified. A tuple comprising all these beamforming parameters is called a *transceiver profile*. Since we do not consider power control and we assume a fixed beamwidth for this paper, our transceiver profiles include only the direction of transmission or reception. Due to higher gain, nodes in *Directional* mode have a greater range in comparison to *Omni* mode. This is true under the assumption that both *Omni* and *Directional* modes operate at identical power levels, which is indeed the case for this paper.

Now, using this antenna model, the maximum possible distance at which two nodes may be able to communicate would depend on the transmitter's and receiver's mode of operation. In other words, a transmitter and receiver can communicate over a larger distance when both are in *Directional* mode, as compared to when they are in *Directional* and *Omni* mode, respectively.

3.2 IEEE 802.11

In the IEEE 802.11 Distributed Coordinated Function (DCF) protocol, an exchange of RTS and CTS precedes DATA communication. Both RTS and CTS packets contain the proposed duration of data transmission. Nodes located in the vicinity of communicating nodes, that overhear either (or both) of these control packets, must themselves defer transmission for this proposed duration. This is called *Virtual Carrier Sensing* and is implemented by using a variable called the *Network Allocation Vector* (NAV). A node updates the value of the NAV with the duration field specified in the RTS or CTS. Thus the area covered by the transmission range of the sender and receiver is reserved for data transfer. We term this region as the *silenced region* in view of the fact that nodes located in this region do not initiate any transmission while communication is in progress. By silencing nodes in the *silenced region*, the RTS/CTS mechanism overcomes the hidden terminal problem [7].

The IEEE 802.11 MAC protocol uses a backoff interval to resolve channel contention. Before initiating transmission, a node S chooses a random *backoff interval* from a range [0, CW], where CW is called the *Contention Window*. Node S then decrements the backoff counter by 1 after every idle "slot time". When the backoff counter reaches 0, node S transmits the packet. If the transmission from S collides

with some other transmission (collision is detected by the absence of a CTS), S doubles its CW, chooses a new backoff interval and attempts retransmission. The *Contention Window* is doubled on each collision until it reaches a maximum threshold, called CW_{max} . While in the backoff stage, if a node senses the channel as busy, it freezes its backoff counter. When the channel is once again idle for a duration called DIFS (DCF interframe spacing), the node continues counting down from its previous (frozen) value.

The carrier sensing mechanism in IEEE 802.11 includes *physical carrier sensing* and *virtual carrier sensing*. 802.11 invokes the backoff procedure only after a channel has been sensed to be idle for DIFS duration. A shorter interframe space, SIFS, is used to separate transmissions belonging to a single dialog (i.e., a node performs physical carrier-senses for SIFS duration before transmitting CTS, Data and ACK frames).

4. PROBLEM FORMULATION

The IEEE 802.11 protocol limits spatial reuse of the wireless channel by silencing all nodes in the neighborhood of the sender and receiver. Using directional antennas, however, it is possible to carry out multiple simultaneous transmissions in the same neighborhood. In Figure 1, simultaneous communication between node pairs A, B and C, D is possible, provided the beamwidth of the directional transmissions is not very large. However, simultaneous communication from E to F , and from A to B is not possible.

Due to higher gain, directional antennas have a greater transmission range than omnidirectional antennas. This enables two distant nodes to communicate over a single hop. From the perspective of routing, this means that routes using directional antennas may contain fewer hops than what may be possible using omnidirectional antennas. In this paper, we do not consider transmit power control, not because it is irrelevant, but because the problem of directional medium access control is by itself rich, even without power control. Future work would address power control as well.

A MAC protocol for directional antennas should attempt to exploit both the benefits of directionality, namely, *spatial reuse* and *higher transmission range*. The Basic DMAC protocol described in the next section attempts to improve spatial reuse of the channel. The MMAC protocol presented in section VII attempts to exploit the higher transmission range of directional antennas by attempting to form longest possible links. This is achieved by propagating an RTS over multiple hops and then transmitting CTS, DATA and ACK directionally over a single hop.

5. BASIC DMAC PROTOCOL

We use the term Basic *Directional MAC* or Basic DMAC [13] to refer to the MAC protocol for directional antennas described in this section. In designing MAC protocols, we assume that an upper layer is aware of the neighbors of a node, and is capable of supplying the transceiver profiles required to communicate to each of these neighbors. The DMAC protocol receives these transceiver profiles from upper layers along with the packet to be transmitted. The

Basic DMAC protocol [13] presented here generalizes the ideas in [8], and it is similar to the DVCS mechanism proposed by Takai *et al.* [17] and a protocol proposed in [1]. Later in this paper we point out the shortcomings of the Basic DMAC protocol and also compare its performance with the “Multi-Hop RTS MAC” protocol proposed in section VII. In principle, “Basic DMAC” is similar to IEEE 802.11, adapted for use over directional antennas.

5.1 Channel Reservation

Channel reservation in Basic DMAC is performed using a RTS/CTS handshake, both being transmitted directionally. An idle node listens to the channel omnidirectionally (i.e., it is in the *Omni mode*). When it receives a signal arriving from a particular direction, it locks on to that signal and receives it. Please note that while a node is in the *Omni mode* and is receiving the signal, it is susceptible to interference from all directions. Only when the node has beamformed in a specific direction, it can avoid the interference from other directions.

In describing the Basic DMAC protocol, we refer to a sender node as node S and the receiver node as node R .

- *RTS Transmission*

The MAC layer at node S receives a packet from its upper layers, along with the transceiver profile T^p to be used for transmission. Having received this, DMAC requests the physical layer to beamform according to the transceiver profile T^p . Let us denote this beamform by B^R , since this beam points in the direction of node R . To detect whether it is safe to transmit using beam B^R , node S now performs physical carrier sensing using B^R . If the channel is sensed idle, DMAC checks its *Directional NAV Table* (or DNAV, explained in the next section) to find out whether it must defer transmitting in the direction of node R . The DNAV table, as explained in the following section, maintains a *virtual carrier sense* status for every *Direction of Arrival* (DoA) in which it has overheard a RTS or CTS packet. Once node S finds that it is safe to transmit using B^R , it enters the *backoff* phase (similar to 802.11). When the backoff counter counts down to zero, DMAC at node S sends down the RTS control packet to the physical layer, meant to be transmitted to node R , using beam B^R .

- *RTS reception and CTS transmission*

A node when idle remains in the *Omni mode*, listening to the channel omnidirectionally. The antenna system is capable of determining the direction of arrival (DoA) of this incoming signal. Let us assume that node R is in the *Omni mode* and is able to receive the RTS from node S with DoA denoted by D^{SR} .

Nodes other than R , say X_i , that also receive the RTS, update their respective DNAV tables with the captured DoAs (note that the DoA captured by node X_i would be D^{SX_i}). This prevents node X_i from transmitting any signal in the reverse direction of D^{SX_i}

(i.e., $D^{X_i^S}$). Node X_i defers all transmissions directed towards a certain range of directions around $D^{X_i^S}$. We discuss the details later in our discussions on DNAV. These nodes also update the DNAV table with the transfer duration specified in the RTS packet.

Having received the RTS from S , node R determines the direction D^{RS} to send the CTS in response. If the DNAV table at R permits transmissions in the direction D^{RS} , then the DMAC at node R requests the physical layer to beamform in this direction. Let this beam be denoted by B^S , since it is directed towards node S . The physical layer at node R senses the physical channel using B^S , for SIFS time slots. If the channel remains free during this interval, the CTS is transmitted using beam B^S . If the carrier is sensed busy during the SIFS period, CTS transmission is canceled (similar to 802.11).

- *CTS Reception and DATA/ACK Exchange*
The sender node S , meanwhile, waits for the CTS using the beam B^R that it had used to send the RTS. If the CTS does not come back within a *CTS-timeout* duration (calculated as in 802.11), then S schedules a retransmission of the RTS. If S receives the CTS, it initiates the transmission of DATA using beam B^R . Node R , on receiving the DATA successfully, transmits an ACK using beam B^S . Nodes other than S and R that receive the CTS, DATA or ACK update their DNAV table with the respective DoAs, and the duration specified in the packet, as elaborated below.

5.2 Directional NAV (DNAV) Table

The Network Allocation Vector (NAV) is a status variable maintained by the IEEE 802.11 MAC for virtual carrier sensing. The value of the NAV is updated from the “duration” field of overheard packets. The value of NAV indicates the duration for which the node must defer transmission to avoid interfering with some other transmission in the vicinity.

Using directional antennas requires that the NAV be directional as well [8] [11] [13] [17]. To put it differently, if a node receives a RTS or a CTS from a certain direction, then it needs to defer only those transmissions that are directed in (and around) that direction. A transmission intended towards some other direction may be initiated. The *Directional NAV Table (DNAV)* is a table that keeps track of the directions (and the corresponding durations) towards which a node must not initiate a transmission. We illustrate this with a simple example with reference to Figure 1. Assume that communication between nodes A and B is in progress, with A transmitting to B . During this interval if node E has a packet to send to F , it must check its DNAV table to check if it is safe to transmit in the direction of F . However, note that node E would have already received a CTS from node B and updated its DNAV table. Thus, on checking the DNAV table, E finds that it is unsafe to transmit in the direction of F . However, if E had a packet to send to D , the DNAV check would indicate that it is safe to transmit. In that case, E can proceed to transmit towards D . At this

point we would like to mention that even if F was a little displaced and the line joining EF did not coincide exactly with the line joining EB , E might still need to defer transmission to F in order to avoid interfering at B . Specifically, in Basic DMAC, node E defers transmission towards F if the angle between EF and EB is less than some threshold, ϵ . We illustrate ϵ with the help of Figure 2. We assume that all nodes transmit with a beamwidth of 2β degrees. Now if node E has overheard a RTS or CTS from node B , it updates the DNAV table with the direction D^{EB} . Now if E wants to send a packet to node H , then it must beamform in the direction of D^{EH} to transmit the RTS. Node E checks whether, the angle between D^{EB} and D^{EH} is greater than a threshold ϵ , where ϵ is as following:

$$\epsilon = 2\beta + \theta$$

where θ is the angular separation of the edges of the two beamforms. If θ is negative then the two beamforms may overlap. For our simulations we have assumed θ to be zero.

6. PROBLEMS WITH BASIC DMAC

In this section we discuss some channel access problems with Basic DMAC that may arise with other directional MAC protocols as well.

- *Hidden terminal problems*
The well-known hidden terminal problem in multi hop wireless networks can be resolved by the exchange of RTS/CTS control packets as in MACA [7] and 802.11. However, the RTS/CTS exchange assumes that these packets are transmitted omnidirectionally. Directional transmission of RTS/CTS introduces two new kinds of hidden terminals, discussed below.

(1) Hidden terminal due to asymmetry in gain:

Consider Figure 1. Assume that all nodes in this figure are currently idle. Nodes in their idle state (*Omnimode*) have a gain of G^o . Now assume that node B transmits a Directional RTS (DRTS) to node F , and F responds with a Directional CTS (DCTS). Assume that node A (still in *omni mode*) is far enough from node F not to hear this DCTS. DATA transmission begins from node B to F , both nodes pointing their transmission and reception beams with a gain G^d . Node A cannot sense this transmission. While this communication is in progress, assume that node A has a packet to send to node E . Node A senses the channel with a directional beam (of gain G^d) pointed towards E and concludes that the channel is idle. Subsequently, it sends a DRTS to node E . However, since node F is receiving DATA with a gain G^d with a beam pointed toward node B (and node A), it is very much possible that the DRTS from A interferes at node F . In other words, sender and receiver nodes with transmit and receive gain of G^d and G^o respectively, may be out of each other’s range, but may be within range if they both transmit and receive with gain G^d (note that G^d is greater than G^o).

(2) Hidden terminal due to unheard RTS/CTS:

Assume that in Figure 1, E is transmitting a packet

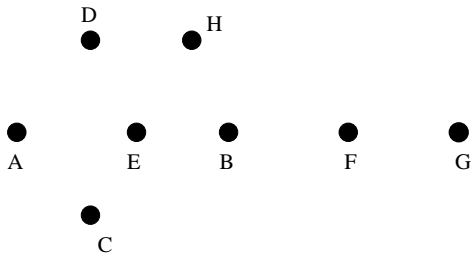


Figure 1: An example scenario

to D . While this transmission is in progress, node B sends a RTS to node F . F responds with a CTS. Although E may be within the transmission range of F , it does not receive the CTS, since it is beamformed in the direction of D . On receiving the CTS from F , B starts transmitting data to F . While communication between B and F is in progress, assume that E finishes transmitting to D and now wants to transmit to F (or any other node in the direction of F). E 's DNAV table indicates that it is free to transmit towards F and on performing physical carrier sense, E finds that the channel is idle. E transmits the RTS and a collision occurs at F (since F 's receiving beam is pointing in the direction of E). Such occasions may not arise in the case of omnidirectional transmissions. With omnidirectional transmissions, node B may be aware of the ongoing transmission from E . This would prevent B from transmitting the RTS while E is engaged in communication. This clearly suggests a potential tradeoff between spatial reuse and collisions when using directional antennas.

- *Shape of Silenced Regions*

Due to the higher gain of directional antennas, the shapes of the *silenced regions* are different for omnidirectional and directional antennas. The impact of the shape of the *silenced regions* on the overall network performance is not straightforward, but it is indirectly dependent on the topology characteristics, traffic patterns and beamwidth of directional transmission.

- *Deafness*

Another drawback of directional beamforming is *deafness*. We explain deafness using the scenario in Figure 1. Assume that both nodes C and D have packets to send to node B . Assume that both nodes C and D choose the route through E to reach B . At a given time, if E is forwarding D 's packet, C would be unaware of it (when using Basic DMAC) and may transmit a RTS meant for E . Since E would be beamformed in the direction of B , E does not receive the RTS and consequently does not respond with a CTS. Node C , on receiving no response from E , retransmits the RTS. This goes on until the RTS-retransmit limit has been reached. This amounts to excessive wastage of network capacity in unproductive control packet transmissions. Also, since C would increase its backoff interval on each attempt, this phenomenon can result in unfairness as well. We refer to this as *deafness* since node E

is “deaf” to the signals from node C while it is beamformed in the direction of B .

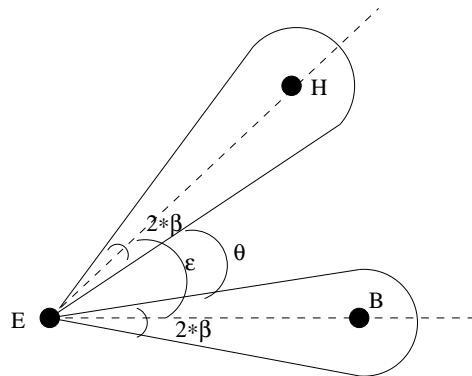


Figure 2: An example where node E wishes to send a packet to H while it has a DNAV entry for direction D^{EB} . The figure shows a condition where node E can safely transmit to node H , since it would not interfere with node B 's communication

7. MULTI-HOP RTS MAC PROTOCOL

In this section, we propose a variation to Basic DMAC, called Multi-Hop RTS MAC (MMAC). While Basic DMAC was motivated by the possibility of higher spatial reuse, MMAC attempts to exploit the extended transmission range of directional antennas, while achieving spatial reuse comparable to the Basic DMAC protocol. Although *deafness* and *hidden terminals* problems still exist in MMAC, better use of directional capabilities in MMAC can compensate for their negative impact, leading to improvement in performance as observed in later sections. To illustrate the benefit of utilizing extended transmission range, let us refer to Figure 3. Assume that all the nodes are idle (i.e., in the *Omni mode*). Also assume that if A transmits directionally, only B , G and D would be able to receive the signal while they are in their *Omni mode*. However, a communication may directly take place between A and F , if both A and F are pointing their beams towards each other. With the protocol below, such direct communication between nodes A and F is possible.

7.1 Protocol Description: Multi-Hop RTS

For describing the multi-hop RTS protocol, we define two kinds of neighbors: *DO-neighbors* and *DD-neighbors*.

- *Direction-Omni (DO) Neighbor*: A node B is a DO-neighbor of a node A if node B can receive a directional transmission from A even if B is in the *Omni mode*.
- *Direction-Direction (DD) Neighbor*: A node B is a DD-neighbor of a node A if node B can receive a directional transmission from A when node B is beamformed in the direction of node A . A DD-neighbor of a node may also be reached using a route through other nodes such that adjacent nodes on the route are DO-neighbors. We call such a route a *DO-neighbor route*. It may

be noted that DD-neighbors are capable of single hop communication, since they can form a direct link between them. Also note that, all *DO-neighbors* are also *DD-neighbors*, but not necessarily vice versa.

In the above notation DO is an abbreviation for “Directional-Omni” and DD is an abbreviation for “Directional-Directional”. Following similar terminology, communication between DO-neighbors may be called DO-communication, and between DD-neighbors, DD-communication. In the scenario depicted in Figure 3, assume that node F is a DD-neighbor of node A and node B is a DO-neighbor of node A . Similarly, node C is a DO-neighbor of node B , and node F is a DO-neighbor of node C . A *DO-neighbor route* from A to F is $A-B-C-F$.

It is important to note that although two DD-neighbors can communicate with each other directly (provided they beamform in each other’s direction), some mechanism is needed to first make them beamform in each other’s direction. This observation motivates the proposed Multi-Hop RTS MAC protocol. The Multi-Hop RTS MAC protocol (MMAC) builds on the Basic DMAC protocol. The MAC layer is supplied with a *DO-neighbor route* to the intended DD-neighbor (F in our example in Figure 3). We assume that a module running above the MAC layer is capable of deciding the suitable *DO-neighbor route* to a DD-neighbor, and can specify the corresponding transceiver profiles to be used. The multi-hop RTS protocol has been designed as part of a larger ad hoc networking system that utilizes directional antennas [12]. Architecture of this system includes several modules such as neighbor discovery, link characterization, proactive routing, and a position information module. Interested readers are referred to [12].

Once the MAC layer has received the packet with the route, the idea is to send a RTS along the DO-neighbor route to the DD-neighbor (destination), and request the destination node (node F , in the example in Figure 3) to point its receiving beam towards the RTS sender (node A) at a specific point of time in the near future. Node F receives the RTS, transmits the CTS in the direction of the RTS sender (node A) and waits for the arrival of the DATA packet. The details of this MMAC protocol are discussed below. For illustration purposes we will refer to Figure 3, where we assume that node A wishes to transmit a packet to node T . This is achieved by having node A transmit the data packet directly to node F , using MMAC. Node F , in turn, delivers the packet to node T using MMAC as well, as shown in Figure 3.

7.2 Channel Reservation

The notion of reserving the channel before communication is retained in this protocol. In fact, the necessity for channel reservation becomes acute in MMAC. Setting up the directional link between A and F involves multiple RTSs (to be forwarded) as well as requires node A to inactively wait for CTS during that time interval. This may be viewed as a substantial investment of network resources that is worthwhile only if the subsequent CTS/DATA/ACK (transmitted using DD-communication) is successful. This motivates conservative channel reservation so that once the directional link has been established, the DATA transmission may be carried out uninterrupted. The mechanism is described below.

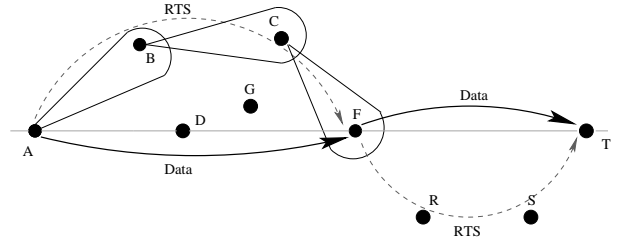


Figure 3: A scenario showing how the multi-hop RTS is forwarded from node A to node F

- *RTS Transmission:*
 1. The MAC layer of node A receives a packet (from an upper layer) containing the DO-neighbor route to the next DD-neighbor, F . The route is specified as $A-B-C-F$. Let T^B and T^F be the transceiver profile of the DO-neighbor and the DD-neighbor. The transceiver profiles for nodes B and F are necessary for directional RTS transmissions as detailed in the subsequent steps. These profiles are assumed to be maintained by a neighbor discovery module in our proposed system.
 2. Upon receiving the packet, MMAC checks for the status of the physical layer. It proceeds to step 3 only when the physical layer is not engaged in transmitting or receiving packets.
 3. MMAC at node A , now requests the physical layer to beamform according to the transceiver profile T^F . Let us denote this beam by B^F , since the beam points in the direction of node F .
 4. The MMAC protocol at node A now performs the same set of operations as described in the RTS transmission procedure of DMAC. These operations include physical carrier sensing, DNAV check and counting down the backoff timer. Once these steps are completed, MMAC at node A sends a RTS to the physical layer to be transmitted using beam B^F (in the direction of the DD-neighbor F). The duration field of this RTS includes the entire duration for multi-hop RTS transmissions and subsequent CTS, DATA and ACK transmissions. This RTS packet has its destination node as node F . It may be noted that this RTS, transmitted using beam B^F , may not reach node F since F in idle state is listening in *Omni* mode. However, the intention of sending this RTS in the direction of node F is not to deliver the RTS to F , but to reserve the channel in the region between node A and F . To put it differently, since a communication between nodes A and F is imminent, nodes like G and D should be informed to avoid interference. When G and D receive this RTS, they set their DNAVs in the direction of A and also in the opposite direction. For illustration, let us consider node D . If D^{AD} denotes the DoA of the RTS at node D , then D sets the DNAV for direction

D^{AD} for the duration specified in the RTS packet. In addition, D sets DNAV for the direction $(D^{AD} + 180) \bmod 360$. The latter is necessary so that D does not initiate a communication in the direction of node F, before F has received the multi-hop RTS. Therefore, the duration for which transmission is deferred along the direction $(D^{AD} + 180) \bmod 360$ is equal to the time required for the multi-hop RTS to reach F from A. This time is calculated by node D as the *Time required for 1 RTS transmission* \times *Number of hops in the multi-hop route* (note that the *Number of hops in the multi-hop route* is also included in the RTS packet, and the *Time required for 1 RTS transmission* is constant as explained in the next step of this protocol).

Destination node F may receive the RTS from A in some instances. For example, this may occur if F happens to be beamformed in the direction of A, when A initiates RTS transmission. If F receives this RTS, it may reply immediately with a CTS, or may optionally switch to the omni mode to be able to receive the imminent multi-hop RTS (discussed in step 5). We use the former option in our simulations. When using this option, node A remains beamformed in the direction of F after transmitting the RTS. If node A receives a CTS from F, it initiates data transmission. If the CTS does not arrive within a suitable timeout interval (similar to Basic DMAC), node A proceeds to step 5.

5. MMAC now constructs a special type of RTS packet that is delivered to the destination over multiple hops (we call it the *forwarding-RTS*). This RTS packet contains the *DO-neighbor route* from node A to F (A-B-C-F in our example) and the duration field indicating the duration of subsequent DATA/ACK transmissions. When all the steps (namely virtual and physical carrier sensing, backing off and waiting for DIFS interval) have been successfully performed, MMAC at node A transmits the *forwarding-RTS* packet to the DO-neighbor specified in the route (B in our example). None of the nodes (either on the DO-neighbor route or otherwise) modify their DNAV tables on receiving or overhearing the *forwarding-RTS* packet.

Nodes which receive the forwarding-RTS packet forward it to their DO-neighbor specified in the *DO-neighbor route*. The forwarding-RTS packet gets highest priority for transmission (forwarding of RTS by the intermediate node does not involve backing off). This implies that the *Time required for 1 RTS transmission* is a constant, known *a priori*. Now, if a node in the *DO-neighbor route* is busy, or has a DNAV set for the direction of forwarding, it simply drops the RTS. The forwarding-RTS packets are not acknowledged on receipt.

6. In the meantime, while the forwarding-RTS packet is being forwarded to node F, node A beamforms in the direction of F and waits in anticipation of the CTS. If the CTS does not come back within a CTS-timeout duration, then A goes back to step 3 and initiates retransmission. The time for which A waits for the CTS

is calculated as the time required for the forwarding RTS packet to reach F (over the specified route) plus the turn-around time for F to send the CTS. Since intermediate nodes do not backoff while forwarding RTS packets, the CTS timeout duration can be calculated accurately.

- *RTS Reception and CTS Transmission:*

On receiving the forwarding-RTS, node F replies with a CTS by pointing its transmitting beam in the direction of A. The transmission of the CTS must be preceded by virtual and physical carrier sensing, and waiting for a SIFS interval of time (as described previously for the Basic DMAC protocol).

- *CTS Reception and DATA/ACK Exchange:*

Node A remains beamformed in the direction of F and would thus receive the CTS directionally. Once the CTS is received, the directional-directional link (DD-link) has been successfully formed and node A proceeds to send the DATA packet using beam B^F . If F receives the DATA packet successfully, it acknowledges node A with an ACK. The ACK is sent using the same beam used for sending the CTS. Nodes that overhear the CTS or DATA packet update their DNAV tables with the duration specified in the packets. The duration field of the CTS includes the time required for completing the subsequent exchange of data and ack packets. This time is obtained from the duration field specified in the RTS packets.

8. PERFORMANCE EVALUATION

In this section we evaluate the performance of Basic DMAC as well as Multi-Hop RTS protocol. We compare both the protocols to the IEEE 802.11 standard. We discuss some results reflecting the pros and cons of directional communication. For our simulations we have used the Qualnet Simulator, version 2.6.1 [16]. The directional gain for the antenna is 10 dB and the beamwidth used is 45 degrees. The approximate transmission range when using IEEE 802.11 is 250 meters. The approximate transmission range of a *DD-link* is 900 meters. We use the *two-ray* propagation model. We do not consider node mobility in our simulation scenarios.

8.1 Simulation Results

Directional communication introduces three new problems; new kinds of hidden terminals, higher directional interference, and deafness (as discussed in Section VI). In this paper we intend to evaluate the net impact of directional antennas. The problems related to using directional antennas are dependent on topology; for instance, nodes placed in a straight line may suffer using directional antennas due to the higher directional interference. Performance also depends on the flow or route configuration in the system; for instance, if routes of two flows share a common link, then *deafness* would be a consequence. To understand these dependencies better, we have identified several simulation scenarios that capture these issues individually. The chosen scenarios are

	Per Flow Throughput (Kbps)	
	IEEE 802.11	Basic DMAC
Figure 4(a)		
A to D	409.05	1106.76
B to E	379.92	628.82
C to F	400.76	968.60
Aggregate	1189.73	2704.18
Figure 4(b)		
A to D	391.54	978.66
B to E	401.48	233.46
C to F	401.79	207.39
Aggregate	1194.81	1419.51

Table 1: Comparing per flow throughput of DMAC and 802.11

deliberately kept simple.

First, we show the dependence of performance on topology. Figure 4 depicts 6 nodes in two different configurations. Nodes A, B and C in Figure 4 are always backlogged with CBR traffic and packets of size 512 bytes. The transmitting beamforms of nodes A, B and C are shown. The destinations are nodes D, E and F, respectively. We compare the performance of Basic DMAC (MMAC behaves identical to Basic DMAC in single hop communication) with 802.11, for both configurations.

In Table I, for the scenario from Figure 4(a), the total throughput of DMAC is more than twice of 802.11. This is because directional communication increases the spatial reuse of the channel. For the scenario in Figure 4(b), DMAC does not offer much benefit. Since the interfering range of directional antennas is larger, using DMAC, only one of the 3 transmissions can occur at any given time. Scenario in Figure 4(b) is also affected by the hidden terminal problem. This happens because A neither receives F’s CTS to C, nor senses C’s DATA towards F (the hidden terminal problem due to *asymmetry in gain*). Observe that A would initiate directional transmission to D irrespective of whether C is communicating with F. Thus even though a collision happens at F, the packet from node A to D is transmitted successfully. This prevents the *contention window* of node A from growing exponentially. As a result of lesser backing off, node A achieves a high throughput compensating partially for the negative impact of higher directional interference. As evident from the individual flow throughputs, nodes B and C get a smaller fraction of the bandwidth while A consumes a much larger fraction. For 802.11, all the three flows share the channel almost equally. However, due to higher collision and backing off, it achieves slightly lesser throughput relative to DMAC.

Random topologies would be characterized by lesser degree of node alignment, allowing higher scope for spatial reuse. Later in this section, we evaluate the performance on random topologies.

Routes taken by the flows also affect the performance of directional antenna protocols. Flows that share a common link cause deafness problems. To illustrate this, we per-

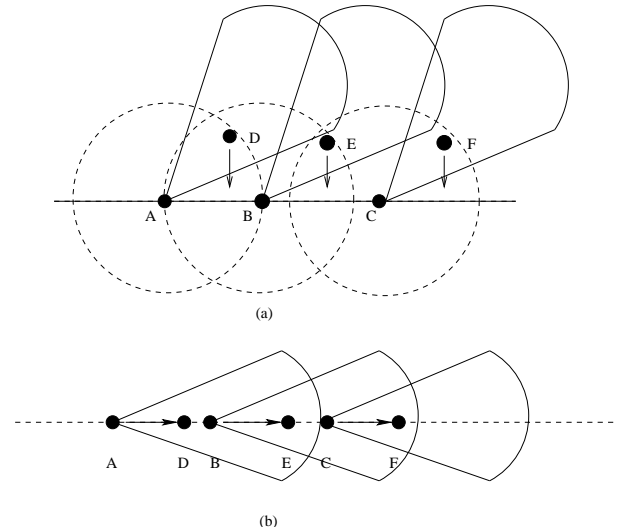


Figure 4: (a) A scenario allowing high spatial reuse for DMAC. (b) High directional interference and the hidden terminal problem degrade performance of DMAC

formed simulations for an example scenario shown in Figure 5. Both nodes A and B wish to send packets to node D, via node C. Table II compares DMAC and 802.11 in terms of total throughput (as a function of the rate of CBR traffic). Results show that DMAC performs worse than 802.11. This degradation occurs due to deafness, as discussed earlier. It should be pointed out that 802.11 also suffers the problem of deafness, although less acutely. Consider Figure 5, but using 802.11 with omnidirectional antennas. Assume now that A is forwarding node X’s packet to C and B is forwarding node Y’s packet to C. Both packets are finally destined to reach D. Using 802.11, when C is transmitting to D, nodes A and B are aware of the communication and defer transmission.

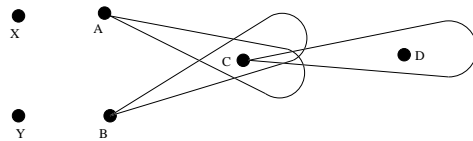


Figure 5: An example to illustrate deafness

However, nodes X and Y may initiate RTSs to A and B respectively, to which they receive no response. X and Y would continue to send RTSs and backoff repeatedly. Thus the problem of deafness occurs two hop away from the communicating link in 802.11 while in DMAC (and MMAC), it occurs in the one-hop region.

Having observed the individual effects of introducing directional communication, we now proceed to evaluate their combined effect on network performance, and compare them with the IEEE 802.11 standard. It is relevant to point out at this time that for the purpose of comparison, we use identical routes for 802.11, DMAC and MMAC in all cases. However,

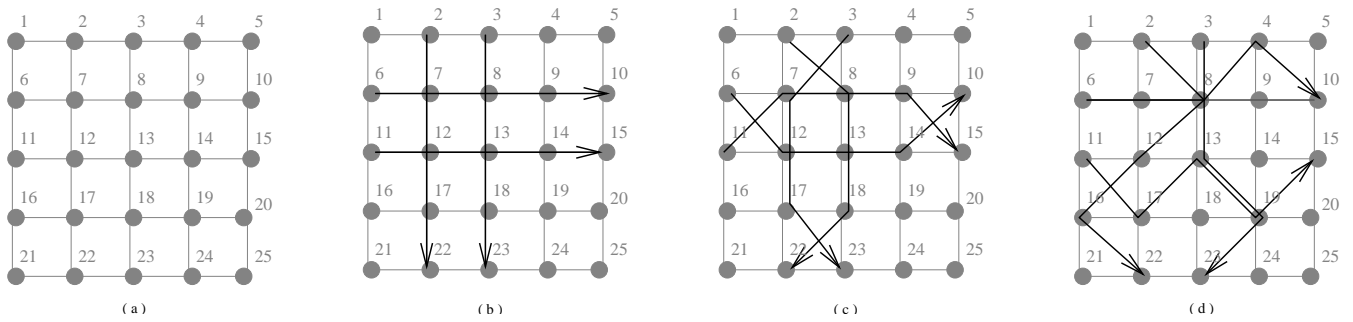


Figure 6: (a) The 5x5 grid topology used for simulations. (b) Flows with aligned routes (c) Less alignment in routes (d) Randomly chosen routes. We compare the performance of DMAC, MMAC and 802.11 for all the above scenarios. The grid distances, although shown to be identical, are varied over multiple simulations

Traffic (per flow)	Aggregate Throughput (Kbps)	
	IEEE 802.11	Basic DMAC
CBR 500 Kbps	403.91	299.47
CBR 1000 Kbps	409.34	290.47
CBR 1500 Kbps	409.38	290.47

Table 2: Evaluating the impact of “deafness”

this does not bring out the best performance of DMAC or MMAC since nodes which can be reached in a single hop using directional antennas, are forced to reach through multiple hops since omnidirectional communication requires so. As discussed later, we have also performed some preliminary experiments comparing DMAC with MMAC, using routes that are feasible only with directional antennas.

Figure 6(a) shows a grid topology of 25 nodes. We systematically introduce flows into this grid and vary the traffic patterns. We begin with 4 multi hop flows as shown in Figure 6(b). The distance between rows and columns in the grid, called grid-distance henceforth, is 150 meters. This ensures that adjacent, as well as diagonal nodes can communicate with each other. Note that nodes 7, 9, 17 and 19 are considered diagonal to node 13. In our simulations, the multi-hop RTS is forwarded over not more than 3 hops and using the same route as shown in the figures. The traffic on each flow is CBR (Constant Bit Rate) and is varied from 75 Kbps to 2000 Kbps with packet size of 512 bytes. Figure 7 shows the comparative results of 802.11, DMAC and MMAC in terms of aggregate throughput over all flows. In Figure 7, DMAC performs worse than 802.11. The poor performance of DMAC may be attributed to the high “alignment” of hops in the chosen routes and to higher interference in directions of ongoing communication. MMAC performs better than both DMAC and 802.11. This is because DATA is transferred over fewer hops using MMAC as opposed to 4 hops using DMAC/802.11. Therefore, the total consumption of the wireless bandwidth is much less, allowing greater number of packets to be transmitted within the same span of time.

In the next experiment, we alter the routes. The new

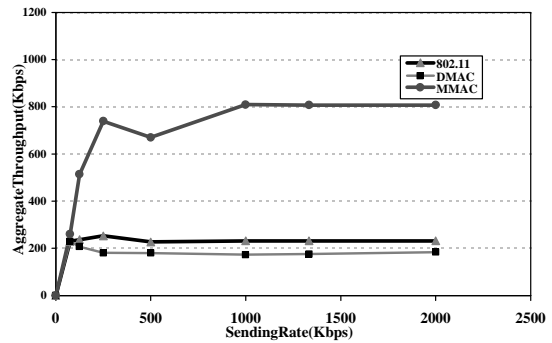


Figure 7: Aggregate throughput (Kbps) of the network with routes in Figure 6(b)

routes are less aligned as shown in Figure 6(c). Figure 8 shows the relative performance of 802.11, DMAC and MMAC. Evident from the graph, directional antenna protocols perform much better than 802.11 because the potential for spatial reuse is greater for this scenario. To put it differently, two node pairs on the route of a given flow can now communicate simultaneously using directional antennas, e.g., node pairs (6, 12) and (13, 14). This is possible because the direction in which the individual node pairs communicate are not same, unlike the scenario in Figure 6(b). The throughput curves saturate beyond a particular data sending rate, because the channel capacity gets fully utilized. The aggregate throughput is higher for directional protocols, because more links can simultaneously communicate. However, DMAC is marginally better than 802.11 because deafness offsets the gains derived from spatial reuse. It is interesting to note that deafness does not affect the performance of MMAC as much, because nodes that forward RTSs in MMAC are engaged in communication for a very small amount of time (and are not silenced during the CTS/DATA/ACK exchange). In comparison, intermediate nodes in DMAC and 802.11 remain occupied for the entire span of CTS, DATA and ACK transmission.

The next comparison of 802.11, DMAC and MMAC is performed for the scenario shown in Figure 6(d). The chosen

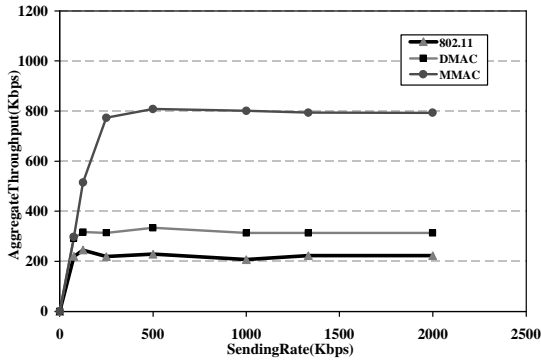


Figure 8: Aggregate throughput (Kbps) of the network with routes in Figure 6(c)

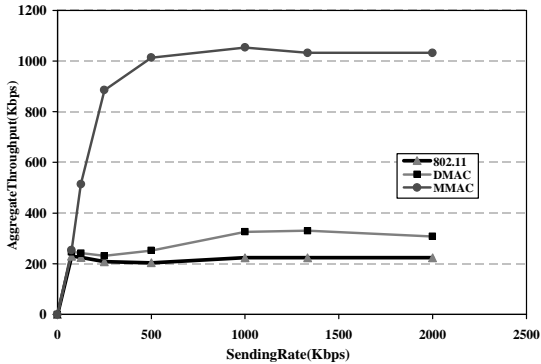


Figure 9: Aggregate throughput (Kbps) of the network with routes in Figure 6(d)

routes are characterized by a smaller degree of alignment, allowing higher spatial reuse. Figure 9 shows the results for this experiment. The aggregate throughput achieved by MMAC is much higher than DMAC, which is, in turn, higher than 802.11. This supports our intuition that “unaligned” routes enhance spatial reuse of the wireless channel, and directional communication would consequently benefit.

We now compare the performance of the three protocols simulated over 25 random topologies and route patterns. One of the 25 random topologies (shown in Figure 10) is obtained by displacing the x and y coordinates of the nodes in the grid by random distances, chosen from an interval of $[-150, 150]$ meters. The flows are same as the four flows used for the scenario in Figure 6(d). Observe that, although the intermediate nodes in the respective routes are identical, the degree of link alignment is less, indicating the possibility of higher spatial reuse. The other random topologies, generated by placing 25 nodes randomly in the bounded region, also exhibit similar characteristics. The simulation results have been averaged over all the scenarios and shown in Figure 11. On an average, random topologies show a significant improvement in performance using MMAC as evident in Figure 11.

Having illustrated the comparative performances of IEEE 802.11 and our directional protocols, we now focus on the

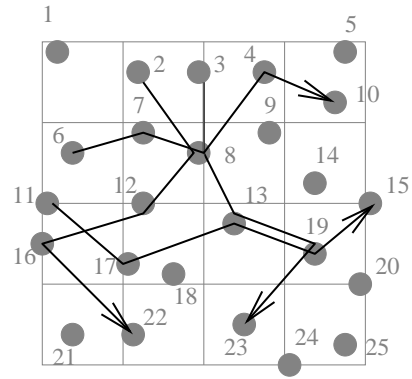


Figure 10: An instance of a random topology with randomly selected routes

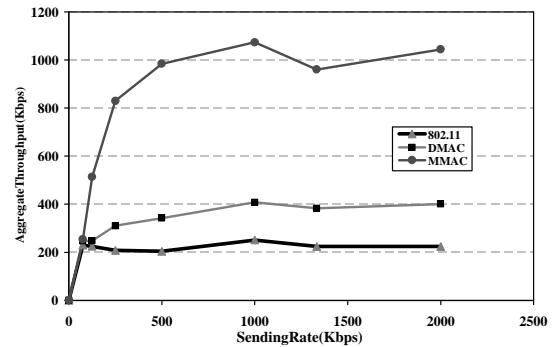


Figure 11: Average aggregate throughput of DMAC/MMAC over multiple simulations using random topologies and routes

comparison between DMAC and MMAC. As mentioned earlier, to compare the throughput of DMAC, MMAC and 802.11, we used identical routes in our previous simulations. However, this is unfair for protocols that use directional antennas because routes suitable for 802.11 may be sub-optimal for DMAC and MMAC. To compare the relative performance of DMAC and MMAC, we design the routes to contain longest possible links that can be formed by each of the protocols. To achieve this, we scaled up distance between nodes in the random topologies by a factor of two. On these random topologies, we use the same set of flows and routes used previously. We observed from simulation results (not documented in this paper), that increasing distance between nodes improves throughput of both DMAC and MMAC, provided the network does not get disconnected. This improvement is an outcome of lesser contention and interference experienced by the communicating nodes in the network.

Figure 12 shows the average end-to-end delay for MMAC and DMAC flows, averaged over 25 scaled topologies mentioned above. The end-to-end delay is the time interval calculated from the instance a packet is handed down by the application layer at the source node, to the instance the packet is received by the application layer at the destination node. In Figure 12, we observe that the delay increases ini-

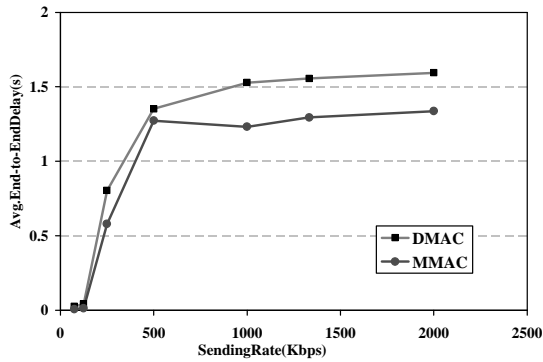


Figure 12: Average end-to-end delay of DMAC/MMAC over multiple simulations using random topologies and flows

tially with increase in sending rate. On further increasing the sending rate, the end-to-end delay curves saturate for DMAC as well as MMAC. This behavior may be explained as follows. When the network load is low, the contention and queuing delay at each intermediate hop is small. As the network load increases, queue sizes grow, increasing in turn, the average end-to-end delay of delivered packets. The curves saturate when the queues get full (the delay is calculated only over packets that are not dropped due to queue overflow). However, MMAC outperforms DMAC since it utilizes the longest possible links between node pairs. While data packets have to travel on each *DO-link* when using DMAC, MMAC requires only RTSs to travel on the *DO-links* and data to be transmitted on the potentially longer *DD-links*. This enables MMAC to use fewer hops in several instances. However, the higher failure probability in transmitting the *multi-hop RTS* packet when using MMAC, increases the latency of packet delivery due to frequent timeouts and retransmissions. This partially offsets the advantage of utilizing *DD-links* when using MMAC. Therefore, the performance of MMAC (in terms of end-to-end delay) is only slightly better in comparison to DMAC.

9. FUTURE WORK

We plan to work on the design of directional MAC protocols that incorporate transmit power control. We also plan to evaluate new protocols that rely less on the upper layers for beamforming information. One such protocol could replace the *omni mode* operation of DMAC and MMAC, by having idle nodes to continuously rotate its receiving beam over 360 degrees. In this case, a node willing to initiate communication transmits a pre-defined “tone” towards the intended neighbor for time T , where T is time required by an idle node to complete one full rotation. When the intended neighbor senses the pre-defined “tone”, it aborts rotating and continues to point its receiving beam towards the DoA of the “tone”, in anticipation of an RTS from the sender. The sender node can then transmit an RTS once it has transmitted the “tone” for T time units, and the receiver replies with a CTS. This effectively establishes a DD-link, with minimal reliance on upper layers. Through information exchanged in the RTS/CTS packets, the required transmit power levels of DATA and ACK packets could be suitably

calculated. This approach has its own disadvantages. We intend to pursue these and other ideas towards the design of more efficient directional MAC protocols. In addition to directional MAC protocols, we are also interested in the impact of directional antennas on the performance of routing [14] and other higher layer protocols.

10. CONCLUSION

This paper considers two medium access control protocols for ad hoc networks using directional antennas. The results show that the performance of the system improves in terms of aggregate throughput and end-to-end delay. We also notice that the performance of the system clearly depends on the topology and flow pattern in the network, more aligned topologies degrading the performance of directional antenna protocols. The multi-hop RTS protocol can outperform 802.11 and DMAC, suggesting that it is beneficial to employ directional communication in shared wireless medium in multi-hop ad hoc networks.

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