On Designing MAC Protocols for Wireless Networks using Directional Antennas

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Abstract

We investigate the possibility of using directional antennas for medium access control in wireless ad hoc networks. Previous research in 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 remain silent. With directional antennas, two pairs of nodes located in each other's vicinity may potentially communicate simultaneously, increasing spatial reuse of the wireless channel. Range extension due to higher gain of directional antennas can also be useful in discovering fewer hop routes. However, new problems arise when using directional beams, that simple modifications to 802.11 may not be able to mitigate. This paper identifies these problems and evaluates the tradeoffs associated to them. We also design a directional MAC protocol (MMAC) that uses multi-hop RTSs to establish links between distant nodes, and then transmits CTS, DATA and ACK over a single hop. While MMAC does not address all the problems identified with directional communication, it is an attempt to exploit the primary benefits of beamforming, in presence of some of these problems. Results show that MMAC can perform better than IEEE 802.11, although we find that the performance is dependent on the topology and flow patterns in the system.

Index Terms

Directional Antennas, Medium Access Control, Wireless Ad Hoc Networks, Deafness

I. 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. The contribution of this paper lies in identifying the fundamental problems with directional medium access control, evaluating their impact on network performance, and in proposing a protocol-design that attempts to maximize the benefits of directional beamforming.

This paper is organized as follows. In Section II, we discuss related work on medium access control using directional antennas, including a brief summary of IEEE 802.11. We describe our antenna model in Section III. The problem under consideration 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, and proposes a simple variation called DMAC-I. 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. We discuss some of the issues with DMAC/MMAC in Section IX and summarize the paper in Section X.

II. RELATED WORK

The use of directional or beamforming antennas has been extensively studied in the context of broadband and cellular networks [2],[1],[34]. Recently, attention has been focused on the possibility of using directional antennas for medium access control in multi-hop networks [4],[9],[13],[19],[25], [14],[24],[31],[32],[35]. In principle, many of the proposed protocols are similar to IEEE 802.11, carefully adapted for use over directional antennas. We present a brief overview of IEEE 802.11, followed by a discussion of the existing protocols for directional medium access control.

A. IEEE 802.11 Distributed Coordinated Function (DCF)

In the IEEE 802.11 MAC protocol [16], an exchange of request to send(RTS)/clear to send(CTS) precedes DATA communication. Both RTS and CTS packets contain the proposed duration of transmission. Nodes located in the vicinity of communicating nodes, which overhear either of these control packets, must themselves defer transmission for the proposed duration. This is called *Virtual Carrier Sensing* and is implemented through a mechanism 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, to overcome the hidden terminal problem [17].

IEEE 802.11 is a CSMA/CA protocol that performs *physical carrier sense* before initiating transmission. Once the channel is sensed as idle for a DIFS (DCF interframe spacing) duration, 802.11 invokes a backoff mechanism for contention resolution. A node S chooses a random *backoff interval* from a range [0, CW], where CW is called the *Contention Window*. CW is initialized to the value of CW_{min}. Node S then decrements the backoff counter once every idle “slot time”. When the backoff counter reaches 0, node S transmits the RTS packet. If the transmission from S collides with some other transmission (collision is detected by the absence of a CTS), S doubles its CW, counts down a newly chosen 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, the node continues counting down from its previous (frozen) value.

B. MAC using Directional Antennas

The design of IEEE 802.11 implicitly assumes an omnidirectional antenna at the physical layer. Although 802.11 may operate correctly when using directional antennas, performance may get affected [15],[30]. Recently, several MAC protocols have been proposed that suitably adapt 802.11 for beamforming antennas [5],[22],[29],[30]. Ko *et al.* [19] have proposed to transmit an RTS directionally, only if the RTS does not collide with other ongoing communications. Kobayashi *et al.* [20] propose a similar mechanism in which NAVs are assigned on a per sector basis. The DNAV mechanism [11] described later in this paper is derived from the above observation. Nasipuri *et al*. [23] proposes to reduce the interference in the wireless channel by communicating directionally. However, their proposals require the transmission of an omnidirectional CTS to inform the receiver's neighborhood about the imminent dialog. This offsets spatial reuse – a key advantage of using directional antennas. In [13], Elbatt *et al.* propose an interesting idea – they use RTS/CTS to inform the neighborhood about the beam indices to be used for the imminent communication. Based on this information, neighbors of the communicating nodes decide which beams may be used for initiating their own RTS packets. Bandyopadhyay *et al*. [3] present another MAC protocol that informs neighborhood nodes about ongoing communications through additional control messages. In addition, the protocol assumes knowledge of network traffic.

Takai *et al*. [33] proposes *Directional Virtual Carrier Sensing* (DVCS) and DNAV mechanisms similar to the notion of DNAV in our Basic DMAC protocol [12], described in section V. We identify several problems affecting this protocol. We also propose a new MAC protocol for directional antennas.

In [25], Ramanathan presents an interesting discussion on several issues arising from directional communication. In this paper we identify several other problems, namely, hidden terminals, deafness, etc. that have not been identified in the past. We discuss how these problems may affect performance of the MAC protocol and explain why they may be hard to alleviate with simple modifications to 802.11. Work reported in this paper has been published in part in [12]. Later, several authors have aimed to address these problems and designed new directional MAC protocols. Korakis *et al.* [21] attempt to address the problems arising from directional antennas, including deafness. To inform neighbors of a communicating node pair, the authors propose to transmit directional RTS/CTS packets on every beam. Transmitting multiple RTS/CTS packets for each transmitted data packet may alleviate the impact of deafness but at the cost of high control overhead. In [10], we addressed the problem of deafness separately, by using sub-band tones to notify the neighbors of a communicating node, of its activity. While this scheme shows encouraging performance, the receiver hardware necessary to implement it, may be relatively complex.

There are some ongoing work in implementing testbeds that utilize directional/beamforming antennas for networking. Ramanathan *et al.* have demonstrated how directional antennas can offer up to factors of ten improvement in throughput [26]. In [8], the authors have designed a prototype and have studied individual aspects of beamforming (deafness, spatial reuse, etc.) from the MAC and routing perspectives. In [6], authors present the challenges faced in implementing a rural network using 802.11 and directional antennas. They discuss how range extension capabilities of directional antennas may be utilized heavily in specific outdoor environments. Several other efforts, also underway in mesh networking communities [7],[18], indicate the rising interest in utilizing directional antennas more effectively for wireless networks.

III. PRELIMINARIES

A. Antenna Model

We have incorporated a steerable antenna model[1] at the radio layer of the Qualnet simulator [16]. The antenna system offers two modes of operation: *Omni* and *Directional* (imagine two passive antennas, attached to a single transceiver). A node resides in the *Omni* mode when it does not know the direction from which a signal might arrive. Once a signal is detected, the antenna begins to receive the signal with an omnidirectional gain, G^o. While the signal is being received, the antenna performs an azimuthal steer and selects the beam on which the impinging signal power is maximum. This beam is then cached at the receiver, and may be used in the near future for communicating back to the transmitter. Of course, while transmitting for the first time, the MAC layer needs to specify the direction in which the antenna must steer its beam. 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.

Observe that when using directional beams for communicating (transmitting or receiving), the main lobe gain in the direction of the beam is G^d. Typically, $G^d \geq G^o$. The Friss Equation

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[1] Although we model a steerable antenna, our discussions on medium access control in this paper, can be generalized to other kind of antennas like switched beam antennas.

represents how transmit and receive gains (G_T and G_R) are related to the transmit and receive powers (P_T and P_R) [27]:

$$P_R = \frac{P_T G_T G_R}{K r^{\alpha}}$$

The term K is a constant that accounts for atmospheric absorption, ohmic losses, etc., r (greater than some r_0) is the distance between the transmitter and the receiver, and α is the path-loss index ($2 \leq \alpha \leq 4$). Note that G_T and G_R are transmit and receive gains along the straight line joining the transmitter and receiver. Observe from the equation that the maximum distance, r, over which two nodes can communicate, increases with increase in transmit and the receive gains. Of course, the increase is not linear and depends on the path-loss index, as evident from reorganizing the above equation as

$$r = \left(\frac{P_T G_T G_R}{K P_R}\right)^{1/\alpha}$$

When compared to omnidirectional antennas, directional antennas will offer range extension capabilities. Put differently, two nodes in omni mode may be out of communication range because the product of their omnidirectional transmit and receive gains, ($G^o \times G^o$), is not large enough. However, if one of the nodes beamforms in the direction of the other, the new product, ($G^d \times G^o$), may be sufficiently large to enable direct communication. Moreover, nodes that beamform towards each other, with gain product ($G^d \times G^d$), may be able to communicate directly with each other over a distance greater than what is possible when only one (or none) of them is beamformed (because $G^d \times G^d \geq G^d \times G^o = G^o \times G^d \geq G^o \times G^o$). As shown later, the benefits of range extension when using directional antennas can be significant, compensating for the losses that arise due to channel access overheads.

Relating to 802.11, a transmitter can transmit the RTS directionally, assuming that it is aware of the direction of its intended receiver. Since the receiver does not know *a priori* who the transmitter might be, it cannot receive the RTS directionally. The receiver receives the RTS omnidirectionally and performs the azimuthal scan in parallel to obtain the best beam for this transmitter. Thereafter, the CTS, Data, and ACK packets can be transmitted and received directionally. However, since we assume that the RTS must be received omnidirectionally, the maximum distance between two communicating neighbors is dictated by the gain product ($G^d \times G^o$).

IV. 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 communication range than omnidirectional antennas. This enables two distant nodes to communicate over a single hop. From the perspective of routing, 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 communication range*. The Basic DMAC protocol described in the next section attempts to improve spatial reuse of the channel. In addition the basic DMAC protocol offers useful insight into the key problems that arise from directionality – problems that we believe would be broadly applicable to directional MAC protocols in general. The MMAC protocol presented in section VII attempts to exploit the higher communication 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. We describe the protocols in the subsequent sections.

V. BASIC DMAC PROTOCOL

We use the term Basic *Directional MAC* or Basic DMAC [12] 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 [12] presented here generalizes the ideas in [19], and it is similar to the DVCS mechanism proposed by Takai *et al.* [33] and a protocol proposed in [2]. 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.

A. 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). While in the *backoff* phase, Basic DMAC requires node S to remain in the directional mode. 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_iS}). Node X_i defers all transmissions directed towards a certain range of directions around D^{X_iS}. 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.

B. 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 [19] [25] [11] [33].

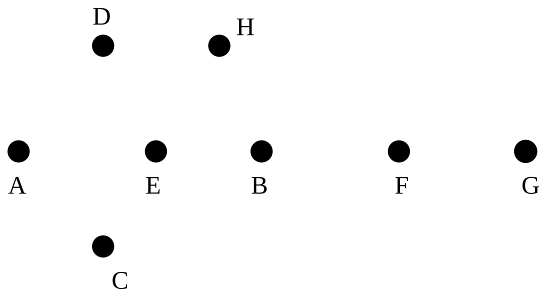


Fig. 1. An example topology scenario

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. The accurate choice of θ depends on the radiation pattern of the antenna in use. If the gain of the mainlobe reduces sharply with increasing angular separation from the mainlobe direction, then the value of θ can be small. This is because lesser interference will be emanating in directions away from the mainlobe direction, allowing for lesser spatial separation between adjacent communications. For our simulations we have assumed θ to be zero, in view of the sharp beam pattern used.

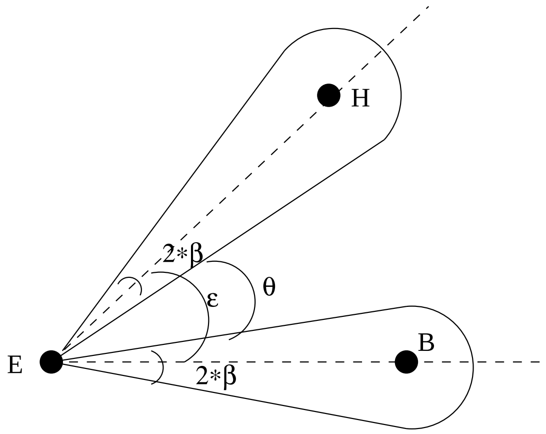


Fig. 2. An example where node E wishes to send a packet to H while it has a DNAV entry for direction D^{EB}. The figure shows a condition where node E can safely transmit to node H, since it would not interfere with node B's communication

VI. 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.

A. 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 [17] 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 (*Omni* mode) 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 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).

While such hidden terminal problems are possible, closer examination revealed that they may not be frequent. Considering the example in Figure 1, node A may not always interfere with packet reception at node F (from B) because node A will almost certainly be further away from F than B. If node F locks on to signals from node B, then interfering at F can be rare - to interfere, A must be far enough from B to not sense B's transmission through B's backlobes, and yet needs to be close enough to F to cause a collision.

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

Assume that in Figure 1, E is transmitting a packet 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 kind of hidden terminal problems can be frequent with directional communications, but 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.

B. Underutilization

When using Basic DMAC, the communication range is bounded by the product of $G^d \times G^o$. This is because an idle receiver receives a directional RTS in the omni mode. However, as discussed earlier, it is possible for nodes to communicate over a longer range if both the transmitter and the receiver could agree to beamform at each other at the same time. In such a case the communication range would be greater – bounded by $G^d \times G^d$ ($G^d \geq G^o$). Basic DMAC fails to exploit this potential of range extension, possible when all nodes are in the network are equipped with directional antennas.

C. Deafness

Another drawback of directional beamforming is *deafness*. We explain deafness using the scenario in Figure 3. Assume that node C and B have packets to send to node A (node A being the common receiver for both the flows). At any given instance, if A is receiving B's packet, C would be unaware of it (when using Basic DMAC) and may transmit a RTS meant for A. Since A would be beamformed in the direction of B, A does not receive the RTS and consequently does not respond with a CTS. Node C, on receiving no response from A, doubles its contention window, chooses a new backoff interval from the new window, and begins counting down. When the countdown reaches zero, C retransmits the RTS. Retransmissions can go on multiple times until A has finished the dialog with B, and has switched back to the omni mode. Unproductive retransmissions from C is an outcome of deafness.

Now consider the case where B has multiple packets to send to A. Once B has finished transmitting the first packet, it immediately prepares to transmit the next packet by choosing a backoff interval from the minimum contention window [0, CW_{min}]. It is likely that node C is still engaged in the backoff phase when B finishes counting down its small backoff value for the second packet. B acquires channel access. This can continue for a long time, causing

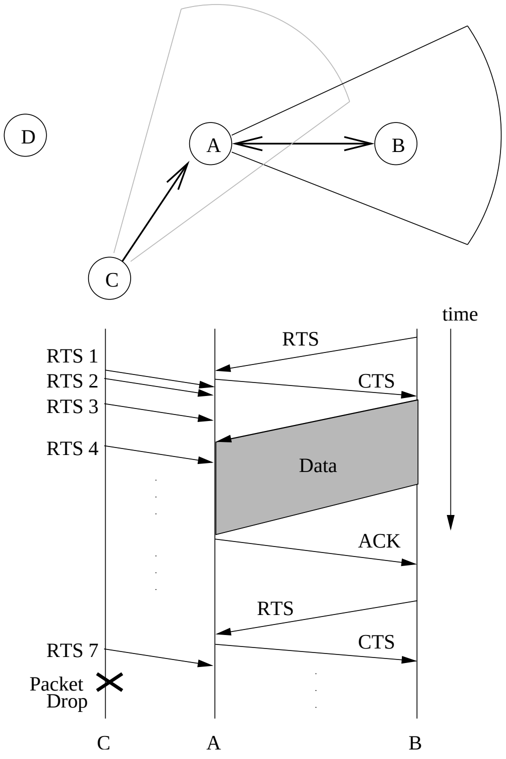


Fig. 3. An example scenario depicting the possibility of deafness

C to drop multiple packets before it gets fortunate enough to steal channel access from B. After this point B encounters repeated deafness, and continues to drop packets whenever it exceeds the retransmission threshold. Multiple packet drops at the source node, without actual congestion or link failure, can adversely affect performance. Higher layer protocols, that use packet drops as indicators of the network condition, may be misled. End-to-end throughput and latency can degrade. Deafness also leads to short-term unfairness between flows that share a common receiver.

Now consider another case in which node C intends to send packets to A, and A intends to originate packets meant for B. In other words, node A is both a receiver and a traffic originator. Also assume that both the originator of the flows (C and A) are always backlogged. Observe that once A has finished transmitting a packet, it beamforms immediately in the direction of B, carrier senses, and begins counting down the backoff interval in the directional mode (as required by Basic DMAC). Clearly, while backlogged, A would almost always remain in the directional mode, forcing C to drop all packets during the interval. Since C continues to remain beamformed towards A while attempting transmission, another node, say D, trying to communicate to C, may also experience prolonged deafness. A "chain" is possible in which none of the nodes communicate successfully – a "deadlock". This is a serious problem, caused when the intended receiver of a node is itself a traffic originator.

D. Variation to Basic DMAC

The possibility of "deadlock" can be pronounced in the case of ad hoc networks because nodes that forward traffic on behalf of other nodes, may also originate data traffic themselves. A simple modification to Basic DMAC can reasonably address this problem. Observe that the problem of deadlock arises primarily because the "deaf" node (node A in our example in Figure 6) always remains beamformed towards its intended receiver. Put differently, node A performs carrier sensing, backoff, transmission, and retransmission, all in the directional mode. This deprives node C the chance to communicate to A. We propose a variation to Basic DMAC in which nodes switch back to the omnidirectional mode while counting down their backoff values. Once the backoff timer expires, a node beamforms towards its intended receiver and initiates transmission. While backing off in the omnidirectional mode, a node senses the carrier busy only if a signal arrives from the direction in which the node intends to transmit. However, if an RTS or CTS arrives from other directions, a node will be capable of receiving them. This mitigates the "deadlock" problem. However, the possibility of *hidden terminal problem due to asymmetry in gain* increases if nodes remain in the omnidirectional mode while backing off, but as discussed earlier, the possibilities can be small. The tradeoff is evaluated in Section 8, where we refer to this variation of Basic DMAC as DMAC-I.

VII. MULTI-HOP RTS MAC PROTOCOL

In this section, we enhance Basic DMAC by proposing Multi-Hop RTS MAC (MMAC). While Basic DMAC was motivated by the possibility of higher spatial reuse, MMAC attempts to exploit the extended communication range of directional antennas, while achieving spatial reuse comparable to the Basic DMAC protocol. Although *deafness* and *hidden terminals* problems still exist in MMAC (we have addressed the problem of deafness separately in [10]), 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 communication range, let us refer to Figure 4. 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.

A. 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 4, 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 4). 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 [28],[26]. 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 [28].

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 4) 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 4, 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 4.

B. 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.

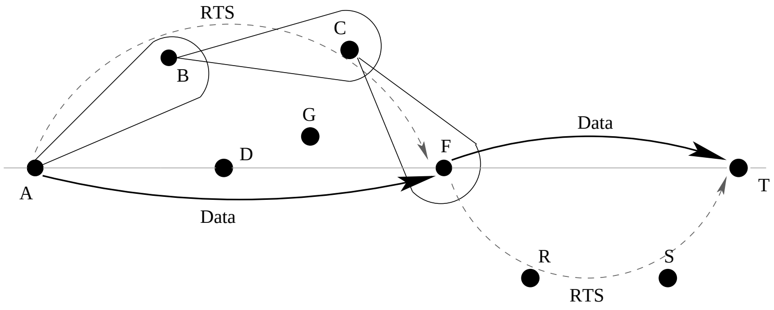


Fig. 4. A scenario showing how the multi-hop RTS is forwarded from node A to node F

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) mod 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) mod 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 assumed constant. This assumption may sometimes turn out to be incorrect. In particular, if a node in the *DO-neighbor route* is busy, or has a DNAV set for the direction of forwarding, it will simply drop 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 forwarding-RTS gets dropped before reaching the destination, or if a node like G, lying outside the DO-range of A initiates a transmission in the direction of A, then A will not receive the CTS. If the CTS does not come back within a CTS-timeout duration, then A cancels its attempt of DD communication, and initiates traditional DO-communication to B (as in DMAC). The CTS-timeout duration 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 estimated 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.

VIII. PERFORMANCE EVALUATION

In this section we evaluate the performance of Basic DMAC, DMAC-I, as well as the Multi-Hop RTS (MMAC) protocol. We compare the protocols to the IEEE 802.11 standard. We discuss 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.

A. 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; nodes placed in a straight line may suffer due to the higher directional interference. Performance also depends on the flow or route configuration in the system; 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 deliberately kept simple.

First, we show the dependence of performance on topology. Figure 5 depicts 6 nodes in two different configurations. Nodes A, B and C in Figure 5 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 (DMAC-I and MMAC behave identically to Basic DMAC in these scenarios) with 802.11, for both configurations. In the rest of the paper, we would refer to Basic DMAC as DMAC, and enhanced DMAC as DMAC-I.

In Table I, for the scenario from Figure 5(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 5(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, except in infrequent cases where communications get scheduled in time in fortunate schedules. For example, if node C transmits an RTS to F while nodes A and B are waiting to initiate communication, then even if A initiates an RTS later, it might not interfere at F. This is because F is already captured in C's communication, and A is too far (in this case) to unlock F from C's signals. Now, if F can complete the CTS to C, before A initiates data communication to D, then the two dialogs may overlap in time. Observe that A would initiate directional transmission to D irrespective of whether C is communicating with F. Thus independent of C-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 comparatively higher throughput, while introducing unfairness. For 802.11, all the three flows share the channel almost equally. However, due to infeasibility of time-overlapping communications, 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.

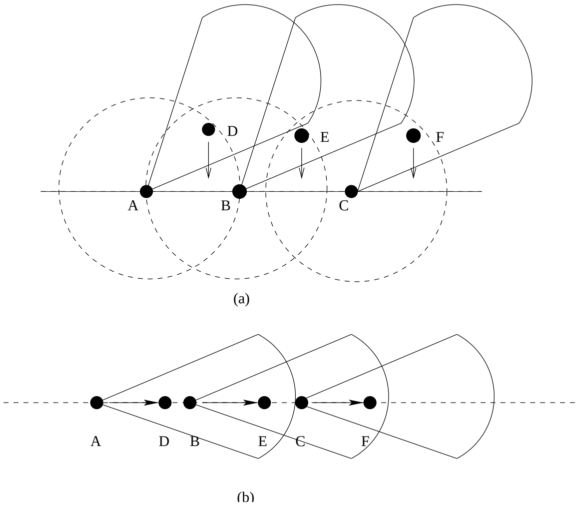


Fig. 5. (a) A scenario allowing high spatial reuse for DMAC. (b) High directional interference degrades performance of DMAC

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

	Per Flow Throughput (Kbps)	
	IEEE 802.11	Basic DMAC
Figure 5(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 5(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 I

COMPARING PER FLOW THROUGHPUT OF DMAC AND 802.11

tions for an example scenario shown in Figure 6. Both nodes A and B wish to send packets to node C. Table II compares Basic DMAC, DMAC-I and 802.11 in terms of total throughput (as a function of the rate of CBR traffic). Results show that DMAC and DMAC-I perform worse than 802.11. This degradation occurs due to deafness, as discussed earlier. Observe that between Basic DMAC and DMAC-I, the performance is comparable. This is because, in the common receiver case, the advantages of omnidirectional carrier sensing in DMAC-I is not reflected. It should be pointed out that 802.11 also suffers the problem of deafness, although less acutely. Consider Figure 6, 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.

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.

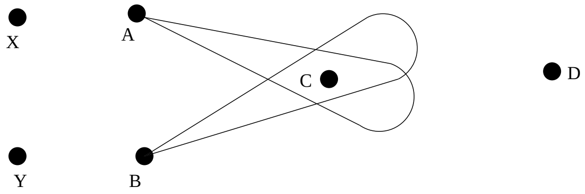


Fig. 6. An example to illustrate deafness

Deafness also occurs in a scenario where a node is both the receiver of a particular flow, as well as the originator of another flow. Figure 7 shows such a scenario. The arrows in the figure depict single hop flows, indicating that nodes B and C are both receivers and originators.

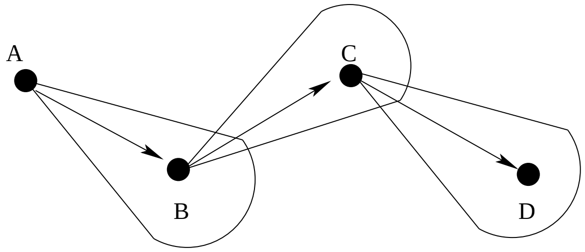
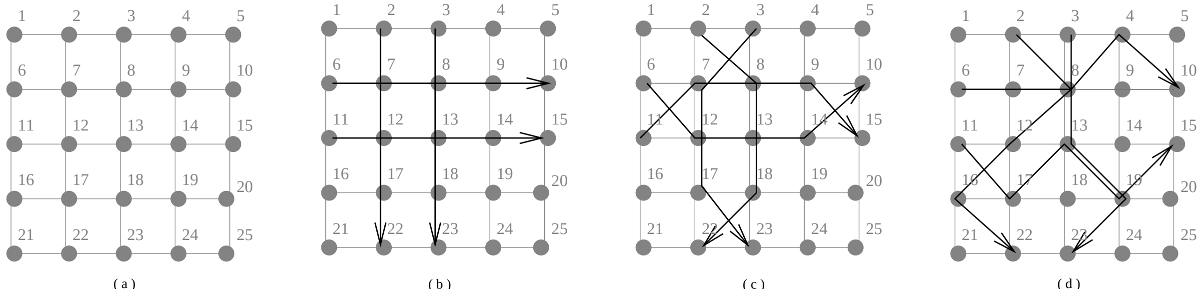


Fig. 7. A scenario in which a node is a receiver and originator.

Table III compares Basic DMAC, DMAC-I and 802.11 in terms of total throughput for the scenario in Figure 7. Clearly, DMAC-I outperforms both 802.11 and Basic DMAC. Between 802.11 and Basic DMAC, we observe that 802.11 performs better. The results can be explained, based on the key observation that the scenario in Figure 7 can lead to “deadlocks” due to deafness. Consider the case of Basic DMAC. Since node B would not be able to communicate to node C, while C has backlogged traffic for D, node B continues to drop packets. Since node B always remains beamformed towards C (trying to establish successful communication), node A attempts repeated retransmissions to B, and drops packets after continued failures. As a result, the performance of the system degrades. Also, this leads to acute unfairness since the flow from C to D can always communicate, depriving both the other flows. While 802.11 does not suffer from such a deadlock scenario[2], it requires node B to remain silent while node C is communicating. In addition, node A does not initiate an RTS to B since it senses the signal from C to D. As a consequence, the problem of backing off unnecessarily does not appear with 802.11, although only one communication can occur at any given time. Also observe that the fairness of 802.11 is higher than DMAC. Once C finishes its communication to D, the probability that A or B accesses the channel is high. This is because when C had won channel contention, A and B had frozen their backoff counters. Once C completes transmission, A and B counts down their remaining backoff duration, which is likely to be smaller than the new backoff value chosen by C. The performance improves further when DMAC-I is used. Observe that using DMAC-I, when C communicates to D, A may communicate to B if A manages to transmit the RTS while B is in the omnidirectional mode. This increases spatial reuse. Moreover, the problem of deadlock does not arise since B often can communicate to C with reasonable frequency – i.e., if C receives an RTS from B while C is in the omnidirectional backoff phase, C replies to B with a CTS, and the dialog between B and C can proceed.



(a) (b) (c) (d)

Fig. 8. (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

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, DMAC-I and MMAC in all cases. However, this

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[2] With 802.11, node B is aware of the transmission between nodes C and D, and therefore refrains from initiating a dialog with C

	Aggregate Throughput(Kbps)		
Traffic (per flow)	802.11	DMAC	DMAC-I
CBR 500 Kbps	880.27	793.48	792.58
CBR 1000 Kbps	1204.76	1026.20	1025.94
CBR 1500 Kbps	1189.18	1019.34	1019.62

TABLE II

EVALUATING THE IMPACT OF “DEAFNESS”

	Aggregate Throughput(Kbps)		
Traffic (per flow)	802.11	DMAC	DMAC-I
CBR 500 Kbps	992.38	912.27	1294.08
CBR 1000 Kbps	1236.60	1139.62	1748.48
CBR 1500 Kbps	1238.48	1165.73	1751.92

TABLE III

EVALUATING THE IMPACT OF “DEADLOCK DUE TO DEAFNESS”

does not bring out the best performance of DMAC, DMAC-I 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 our proposed MAC protocols, using routes that are feasible only with directional antennas.

Figure 8(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 8(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 9 shows the comparative results of 802.11, DMAC and MMAC in terms of aggregate throughput over all flows. In Figure 9, 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. The performance of DMAC-I is comparable to DMAC, even with omnidirectional backoff. This can be expected because the scenario shows that all originators of traffic are at the edge of the network, and do not require to forward traffic on behalf of the others. Consequently, the problem of “deadlock”, as observed earlier, does not occur – the benefits of DMAC-I are therefore not visible. MMAC performs better than both DMAC, DMAC-I 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.

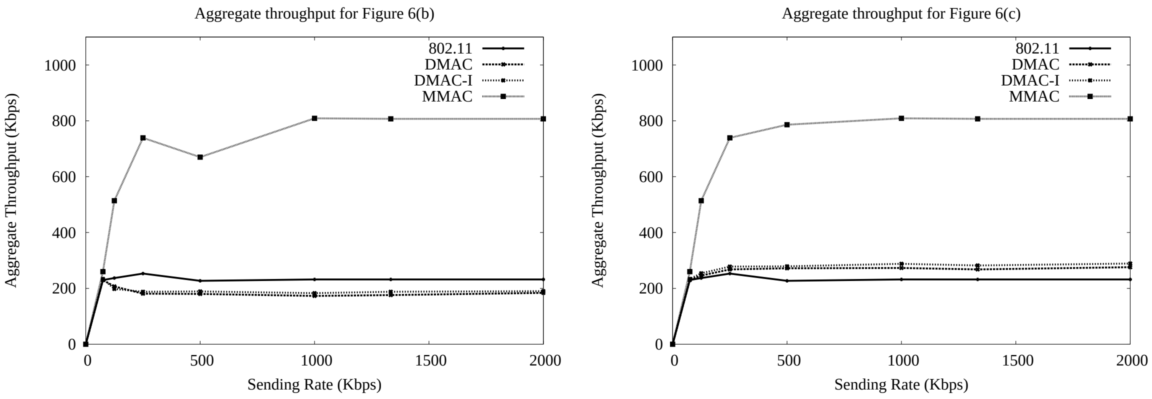

Fig. 9. Aggregate throughput (Kbps) of the network with routes in Figure 8(b) and 8(c)

In the next experiment, we alter the routes. The new routes are less aligned as shown in Figure 8(c). Figure 9 shows the relative performance of 802.11, DMAC, DMAC-I, 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 8(b). The throughput curves saturate beyond a particular data sending rate, because the channel capacity gets fully utilized. The

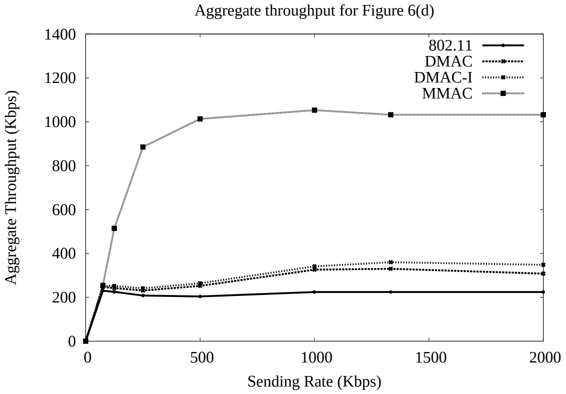

Fig. 10. Aggregate throughput (Kbps) of the network with routes in Figure 8(d)

aggregate throughput is higher for directional protocols, because more links can simultaneously communicate. However, DMAC and DMAC-I are marginally better than 802.11 because deafness (due to common receiver) 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, DMAC-I, and 802.11 remain occupied for the entire span of CTS, DATA and ACK transmission.

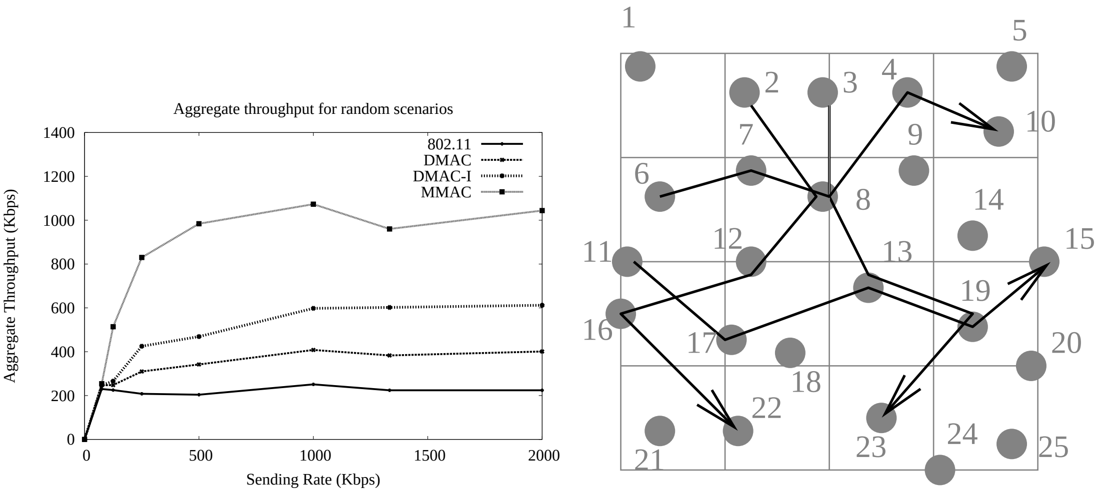

Fig. 11. Average aggregate throughput over multiple simulations using random topologies and routes

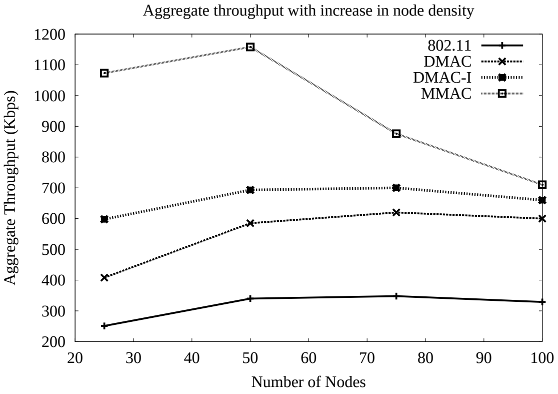

Fig. 12. Variation of throughput with increase in node density.

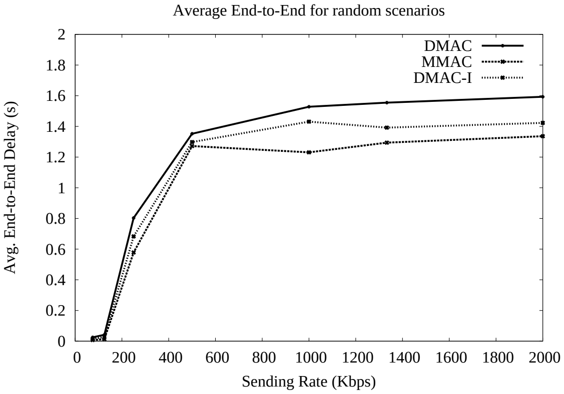

Fig. 13. Average end-to-end delay of DMAC/MMAC over multiple simulations using random topologies and flows

The next comparison of 802.11, DMAC, DMAC-I and MMAC is performed for the scenario shown in Figure 8(d). The chosen routes are characterized by a smaller degree of alignment, allowing higher spatial reuse. Figure 10 shows the results for this experiment. The aggregate throughput achieved by MMAC is much higher than DMAC and DMAC-I, which are, 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. The flows are between the same source-destination pairs (as in Figure 8(d)), except that the nodes are are now randomly distributed in the region. An example topology has been shown in Figure 11. Observe that with randomly located nodes, the degree of link alignment is less, indicating the possibility of higher spatial reuse. 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. While the performance of DMAC is poor (and comparable to 802.11), DMAC-I outperforms both DMAC and 802.11. The improvement of DMAC-I over DMAC can be attributed to the possibility of "deadlocks", occurring whenever the traffic originator needs to forward traffic on behalf of others. Since such cases occur when nodes are randomly placed, the benefits of omnidirectional backing off becomes conspicuous. However, the benefits of higher communication range in MMAC exceeds the benefits of DMAC-I.

We investigated the performance of our protocols with varying node density. With twice the number of nodes, we doubled the number of flows to measure protocol scalability. Figure 12 illustrates the variation of aggregate throughput with higher node density. Clearly, with increase in network traffic, MMAC routes fail more often – multi-hop RTS packets are unable to reach the destination, and MMAC falls back on individual DO routes. Consequently, MMAC degenerates to DMAC-I and the performances become comparable. However, due to the possibility of higher spatial reuse, MMAC, DMAC, and DMAC-I, all continue to outperform 802.11, even at higher node densities.

Having illustrated the comparative performances of IEEE 802.11 and our directional protocols, we now focus on the comparison between DMAC, DMAC-I, and MMAC. As mentioned earlier, to compare the throughput of DMAC, DMAC-I, 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, DMAC-I, and MMAC. To compare the relative performance of DMAC, DMAC-I, 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 that increasing distance between nodes improves throughput of DMAC, DMAC-I, 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 13 shows the average end-to-end delay for DMAC, DMAC-I, and MMAC 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 13, we observe that the delay increases initially with increase in sending rate. On further increasing the sending rate, the end-to-end delay curves saturate. This behavior may be explained as follows. When the network load is low, the contention and queueing 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). DMAC-I performs better than DMAC because omnidirectional backoff in DMAC alleviates the possibility of prolonged deafness, and eliminates the possibility of "deadlocks". However, MMAC outperforms DMAC-I and DMAC since it utilizes the longest possible links between node pairs. While data packets have to travel on each *DO-link* when using DMAC and DMAC-I, 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.

IX. DISCUSSION

Neighbor Discovery: To be able to transmit to a neighbor, the MAC layer needs to determine the direction of beam-steering. We have assumed that higher layers are capable of providing this direction-of-neighbor information. One way to achieve this could be a proactive mechanism whereby nodes periodically transmit omnidirectional "hello" messages at higher power levels. The power level can be adjusted such that even with omnidirectional transmission and omnidirectional reception, the communication range matches the DO or DD range. Nodes that overhear the periodic "hello" messages can record the best beam for receiving these signals. To initiate directional transmissions to a neighbor later, a node can use this (periodically refreshed) recorded beam. Another alternative is where nodes periodically transmit directional "hello" messages in multiple directions on the azimuth plane. Neighbors of the transmitter may receive these "hello" messages omnidirectionally, while determining the best beam to transmit back to this transmitter at a later time. Yet another alternative is where nodes synchronously beamform in specific directions at pre-specified times, and oscillate randomly between beamforming in that direction and the opposite. While nodes require to be clock-synchronized, such a scheme has shown to perform well in [26].

Mobility: We do not consider mobility in this paper. We believe that several applications of ad hoc networks relate to static topologies (e.g., mesh networks, wireless backbones). Our evaluations are more applicable to such scenarios. However, as discussed earlier, we assumed a neighbor-discovery module to provide the MAC layer with beamforming information. Therefore, the sensitivity of DMAC/MMAC to topology changes depends largely on the ability of the neighbor discovery protocols. In conjunction with a directional-antenna aware neighbor discovery module, our ideas may hold even in the face of mobility.

Multipath: In a multipath environment, signals may arrive at the receiver from multiple directions, thereby causing a node to set DNAVs around all these directions. This can potentially reduce the performance gains from spatial reuse. Our simulations do not model multipath environments. We plan to incorporate this in our future work.

X. CONCLUSION

This paper considers the problem of designing medium access control protocols for ad hoc networks using directional antennas. The results show that the performance improvement, in terms of aggregate throughput and end-to-end delay, is possible when using directional antennas. 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, DMAC, and DMAC-I, suggesting that it is beneficial to employ directional communication in shared wireless medium in multi-hop ad hoc networks.

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