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MAC protocols using directional antennas in IEEE 802.11 based ad hoc networks

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Summary

Using directional antennas can be beneficial for wireless ad hoc networks consisting of a collection of wireless hosts. The most important benefit includes a reduction of the radio interference. Thus, it can significantly increase the spatial reuse, thereby improving the network throughput. To best utilize directional antennas, a suitable Medium Access Control (MAC) protocol must be designed. Current MAC protocols, such as the IEEE 802.11 standard, do not benefit when using directional antennas, because these protocols have been designed for omnidirectional antennas. In this paper, we present modified MAC protocols suitable for 802.11 based ad hoc networks using directional antennas. Our comprehensive simulation results demonstrate the performance improvement obtained with the proposed protocols. Copyright © 2007 John Wiley & Sons, Ltd.

KEY WORDS: ad hoc networks; medium access control protocol; directional antennas

1. Introduction

Starting from the days of the packet radio networks (PRNet) [1] in the 1970s, the multi-hop ad hoc network has received great amount of research attention. A wireless ad hoc network is a fully distributed multi-hop networks that can be established by a number of wireless nodes [2]. In ad hoc networks, neither predefined network infrastructure nor centralized administration is required. Networks here can be formed dynamically by participating nodes that may be mobile, static, or quasi-static (i.e., movable, but stationary most of the time). The ease of deployment without the existing infrastructure makes ad hoc networks an attractive choice for situations such as military operations [3], disaster recovery [4], wireless mesh networks [5], wireless sensor networks [6], and so forth. With the advance of IEEE 802.11 technology and the wide availability of mobile wireless devices, civilians can also form an instantaneous ad hoc network in conferences or in class rooms.

This work is motivated by the observation that nodes in ad hoc networks are typically assumed to be equipped with *omnidirectional antennas*. However,

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with the rapid advance of antenna technology in recent years [7,8], it also becomes possible to use *directional antennas* [9] or *smart antennas* [10,11] to improve the capacity of ad hoc networks [12]. Using directional antennas may offer several interesting advantages for ad hoc networks. For instance, routing performance can be improved by using a directional antenna [13,14].

To best utilize directional antennas, a suitable Medium Access Control (MAC) protocol must be used. Previous MAC protocols, such as the IEEE 802.11 standard [15], do not benefit when using directional antennas with changeable beam patterns, because these protocols have been designed to exploit omnidirectional antennas or directional antenna with a single fixed pattern. In recent years, there has been a significant amount of research that can take advantage of the use of directional antennas in multi-hop ad hoc networks. These previously published works mostly assume some ideal antenna propagation patterns with directional antennas. In this paper, we also present the two novel MAC protocols suitable for ad hoc networks based on directional antennas, but with more realistic antenna propagation patterns.

2. Related Works

Recently, research on improving spatial reuse of the channel in wireless ad hoc networks has led to the investigation of the applicability of directional antennas at mobile nodes. As a consequence, various research issues, including MAC, routing [16], transmission scheduling [17], location discovery [18], and topology control [19], have been emerged to best utilize the benefit of using directional antennas. Especially, starting from our previous works [20], a number of researchers have devoted for work on MAC protocols in ad hoc networks with directional antennas. Reference [21] proposed a variation of RTS/CTS frame exchanging mechanism of IEEE 802.11. Unlike our proposed scheme to be described later, both RTS and CTS frames are sent omnidirectionally so that the transmitter and receiver can locate each other and send the following DATA and ACK frames directionally.

Another protocol for MAC in directional antenna based ad hoc networks, named Multi-hop MAC (MMAC) protocol has been proposed [22]. In this protocol, it is argued that if any two nodes are pointing to each other with their antennas, then their transmission ranges can be extended. When the sender initiate the transmission, a communication may not directly take place between sender and receiver, if receiver is not pointing its beam toward the sender. To establish the link between this sender and receiver, MMAC use multi-hop RTS frames which delivered along with specific route path to receiver. By receiving this multihop RTS, receiver make its antenna beamform in senders direction. Accordingly, two nodes exchange CTS, DATA, and ACK frames over a single hop. However, utilizing extended transmission range may cause some problems such as the increase of instances of hidden terminal and the deafness problems. In order to solve these problems, Reference [23] has proposed a new MAC protocol, based on circular directional RTS (DRTS) that scans the area around the transmitter and informs its neighbors for the intended communication. The neighbors then decide for their transmission differentiation so that any possibility of collision can be prohibited. Although this scheme may remedy the hidden terminal problem, it may result in significant increase of time delay and communication cost due to a circular transmission of RTS frames.

In a different way, there is a busy tone-based solution for utilizing directional antennas in the IEEE 802.11 based MAC protocol [24–26]. These approaches are mostly based on the idea of using sub-band tones to notify the neighbors of a communicating node, of its activity. Although these approaches may result in better performance, it needs to have some additional hardware to generate busy-tone terminal and may be relatively complicated to implement.

3. Preliminaries

3.1. Network and Antenna Models

We assume that all hosts in a region share a wireless channel and communicate on that channel. Each host is assumed to be equipped with multiple directional antennas or single electronically steerable parasitic array antenna system [27]. A directional antenna can transmit over predefined beam pattern with a small angle (e.g., 60 degrees), and the beams are fixed with non-overlapping in its direction. By doing so, several directional antennas may be used together to cover the entire directions. Each beam includes one main lobe with a conical radiation pattern and side lobes, each having a low gain. The antenna radiation pattern of side lobes can be quite complex

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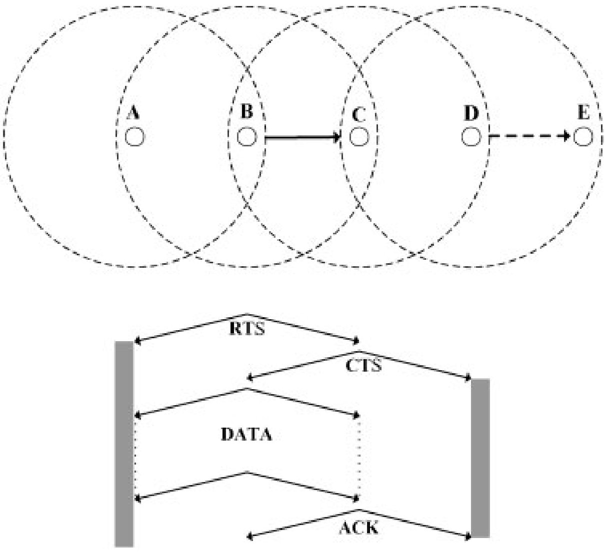

Fig. 1. MAC protocol with omnidirectional RTS/CTS.

in real systems. In order to simplify them into a three dimensional system, in our simulation model, these side lobes are approximated into a single sphere, with the node at its center as modeled in Reference [28]. We assume that transmissions by two different nodes will interfere at some node X, even if different directional antennas at node X receive these two transmissions[‡]. We also assume that simultaneous transmissions by the same nodes to different directions are not allowed.

Each host has a fixed transmission range and two hosts are said to be neighbors if they can communicate with each other over a wireless link. Initially, we assume that each node knows its neighbors' location as well as its own location. The physical location information may be obtained using device like global positioning system (GPS). Based on the location of the receiver, the sender may select an appropriate directional antenna to send frames to the receiver.

Most of the current MAC protocols, such as IEEE 802.11 MAC standard [15], use a handshake mechanism implemented by exchanging small control frames named *Request-to-Send* (RTS) and *Clear-to-Send* (CTS). The successful exchange of these two control frames reserves the channel for transmission of the, potentially longer, data frame and a short acknowledgement (ACK) frame.

[‡] This assumption is somewhat pessimistic, and removing this assumption will improve the performance of the proposed protocols.

3.2. Handshake Mechanism in IEEE 802.11 MAC Protocol

Figure 1[§] illustrates the IEEE 802.11 MAC protocol [15] for omnidirectional antennas that uses RTS and CTS control frames. In this protocol, any node that wishes to transmit data must send a RTS frame before it can start data transmission. For example, in Figure 1, node B broadcasts a RTS frame for its intended receiver, node C. If node C receives the RTS successfully, it replies with a CTS frame so that node B can start transmitting a data frame upon receiving the CTS. When node C successfully receives the data frame, it immediately sends an ACK to node B (the ACK has a priority over any other transmission by any node in the vicinity of nodes B and C). Note that both RTS and CTS frames contain the proposed duration of data transmission. Since nodes are assumed to transmit using omnidirectional antennas, all nodes within the radio range of nodes B and C will hear one or both of those control frames (nodes A and D in Figure 1)—these nodes must wait for the duration of data transmission before they can transmit themselves. This characteristic of RTS/CTS mechanism overcomes the hidden terminal problems in wireless LAN environments. However, it is easy to see that this mechanism can waste a large portion of the network capacity by reserving the wireless medium over a large area. For instance, even though node D has data frames for node E while B and C are communicating with each other, node D has to defer the transmission to E until the transmission from node B to C is completed.

4. Directional MAC (D-MAC) Schemes

The proposed Directional MAC (D-MAC) schemes are similar to IEEE 802.11 in many ways. The D-MAC schemes also send an ACK immediately after the DATA, as in IEEE 802.11—however, in D-MAC schemes, the ACKs are sent using a directional antenna, instead of an omnidirectional antenna. In IEEE 802.11, if a node X is aware of an on-going transmission

[§] The circle centered at each node shows its transmission range. In the lower half of the figure, time progresses from top to bottom. The figure shows messages sent by various nodes. Gray bars below the nodes A and D indicate that these node are not allowed to transmit in the duration covered by the bars (to avoid interference with transfer from B to C).

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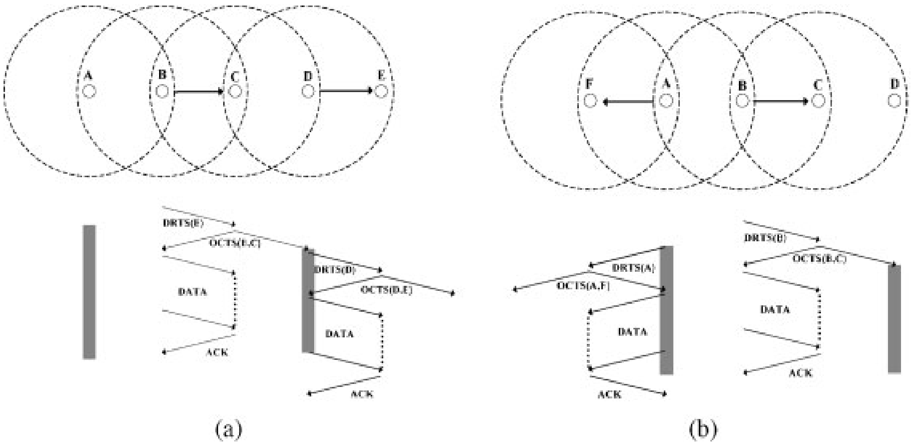

Fig. 2. Examples of using a directional MAC scheme 1.

between some other two nodes (due to the receipt of RTS or CTS from those nodes), node X will not participate in a transfer itself—that is, X will not send a RTS, or send reply to a RTS from another node, while the transfer between other two nodes is in progress. The D-MAC protocols apply a similar logic, but on a per-antenna basis. In brief, if antenna T at node X has received a RTS or CTS related to an on-going transfer between two other nodes, then node X will not transmit anything using antenna T until that other transfer is completed. Antenna T would be said to be ‘blocked’ for the duration of that transfer—the duration of the transfer is included in each RTS and CTS frames (as in IEEE 802.11), therefore, each node can determine when a blocked antenna should become unblocked.

The key point to note about is that, when using directional antennas, while one directional antenna at some node may be blocked (as defined above), other directional antennas at the same node may not be blocked, allowing transmission using the unblocked antennas. This property results in performance improvement when using directional antennas.

Omnidirectional transmission of a frame in D-MAC schemes requires the use of all the directional antennas. Therefore, an omnidirectional transmission can be performed if and only if none of the directional antennas are blocked.

4.1. Scheme 1: Using DRTS Frame

D-MAC scheme 1 utilizes a directional antenna for sending the RTS frames in a particular direction, whereas CTS frames are transmitted in all directions. Figure 2[‖] shows how wireless bandwidth efficiency of the IEEE 802.11 MAC protocol can be improved by using a D-MAC protocol. In Figure 2(a), assume that node B has a data frame for node C, and also assume that no other data transfers are in progress (so none of the antennas are blocked). In this case, node B sends a DRTS frame including the physical location information of B, in the direction of node C. Thus, node A does not receive the DRTS from node B even though node A also exists within B’s transmission range. If node C receives the DRTS frame from B successfully, it then returns an omnidirectional CTS (OCTS) reply. Two location information are included in the OCTS frame: location of the node sending OCTS (e.g., node C’s location in Figure 2(a)) and location of the sender of the corresponding DRTS (e.g., node B in Figure 2(a)). After the successful exchange of DRTS and OCTS frames, a data frame is sent by node B using a directional antenna. When node C receives the data frame, it immediately sends an ACK to node B using a directional antenna as well.

Now, during the proposed length of transmission between nodes B and C, assume that node D, which is a neighbor of node C, has data to transmit to node E. Note that the directional antenna of node D that points towards node C is blocked, since node D would have received on this directional antenna the OCTS sent by node C to node B. However, the blocked antenna is different from the directional antenna that points towards node E. Therefore, node D can send a

[‖] This figure uses notation similar to Figure 1. Letter in parentheses, such as DRTS(B) or OCTS(B,C) denote the physical location information included in the message. The white gray box below node D denotes that node D may transmit to node E in the corresponding duration, unlike when using omnidirectional antennas.

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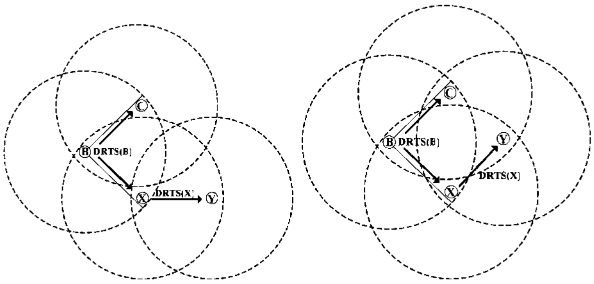

(a) (b)

Fig. 3. A different way to react when node receives DRTS.

DRTS frame towards node E. Essentially, if node D knows that its data transmission to node E would not interfere with the other on-going data transfer from B to C, D sends a DRTS control frame to E. As a result, our modified MAC protocol for directional antennas can improve performance by allowing simultaneous transmissions that are disallowed when using only omnidirectional antennas.

Similarly, in Figure 2(b), node A is allowed to transmit to node F while transmission between B and C is taking place. This is possible because node A does not receive the DRTS from node B, so node A is not blocked from transmitting the DRTS to node F. Note that, with standard omnidirectional RTS/CTS mechanisms, node A in Figure 2(b) must defer transmission to node F until the transmission from B to C finishes, causing performance degradation.

Let us now consider some other node X in Figure 2(b) whose location is covered by the directional antenna of B pointing towards node C. Clearly, node X will also receive the DRTS from B when node B sends the DRTS frame to node C, as shown in Figure 3. Therefore, the directional antenna at node X that points towards node B will be blocked for the duration of transfer from B to C. With this scenario, in scheme 1, node X is still allowed to initiate its data transmission to some other node Y as long as the directional antenna at node X that points towards Y is not blocked by the receipt for DRTS from node B (or, by the receipt of DRTS or OCTS from some other node).

When a node Y gets a DRTS frame from node X, Y may or may not send an OCTS to X, depending on the status of its directional antennas. Since an OCTS frame transmission requires the use of all directional antennas, an OCTS cannot be sent if any of the directional antennas are blocked. Therefore, node Y transmits an OCTS in reply to the DRTS from node X if and only if none of its directional antennas are blocked. Thus, in Figure 3(a), node Y may send an OCTS to node X, however in Figure 3(b), node Y may not send the

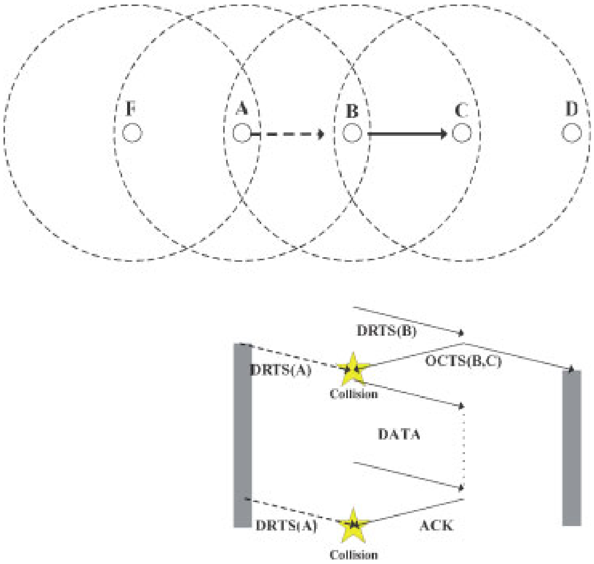

Fig. 4. A possible scenario of collisions with DRTS frame.

OCTS. Since, in case of Figure 3(b), node Y would have received an OCTS from node C blocking its directional antenna for the duration of transfer from B to C.

4.2. Scheme 2: Using both DRTS and ORTS

In our first D-MAC protocol to improve network performance, a DRTS frame is transmitted in the direction of the intended receiver prior to the transmission of the actual data frames. Using DRTS only, instead of omnidirectional RTS (ORTS), may increase the probability of control packet collisions in some cases. We consider one such scenario in Figure 4. In Figure 4, assume that node B has initiated a frame transfer to node C. Node A is unaware of this transfer because node B's DRTS to node C has not been received by node A. Now, node A wants to send a data frame to node B, while B's transfer to node C is still in progress. Transmission of a DRTS by node A to node B may interfere with the reception of OCTS or ACK control frames sent by node C to node B[¶]. Note that node A does not defer its attempt to communicate with node B because A has not received node B's DRTS frame directed to node C. This situation cannot occur in the current omnidirectional RTS/CTS exchange mechanisms. Since the size of control frames is typically

[¶] Recall that we make the pessimistic assumption that signals received on different directional antennas at a given node can interfere. If this assumption is not true, then scheme 2 is not needed, and performance of scheme 1 would be better than the one reported here. However, when the receiver hardware is constrained, our pessimistic assumption may also be true.

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much smaller than the data frames, the probability of collisions described above is not very high, although it is higher than that in case of IEEE 802.11 MAC.

To reduce the probability of collisions between control frames, we propose another variation of the D-MAC scheme. In this new scheme (we name it D-MAC scheme 2), there are two types of RTS frames: DRTS and ORTS. In scheme 2, when a node, say node X, wishes to initiate a data transfer, it may send ORTS or DRTS as per two rules: (a) if none of the directional antennas at node X are blocked, then node X will send an ORTS. (b) otherwise, node X will send a DRTS provided that the desired directional antenna is not blocked. If the desired antenna is blocked, node X will defer until that antenna becomes unblocked.

For example, in Figure 4, assume that when node B wants to send a frame to node C, none of the antennas at B are blocked. In this case, node B will broadcast an ORTS frame (as per rule (a) above). Since this frame will be received by node A, its directional antenna pointing towards B will be blocked for the duration of the transfer from B to C. Now consider two cases:

- If node A wants to send data to node B, it will wait for the duration of transfer from B to C (until the corresponding directional antenna becomes unblocked, as per rule (b) above).
- If node A wants to send data to node F, node A will send a DRTS to node F, provided that the directional antenna pointing towards node F is not blocked (as per rule (b) above).

The combination of DRTS and ORTS frames in scheme 2 can reduce the cases of collisions between control frames (although it does not perfectly eliminate the possibility). Apart from the two rules mentioned above which determine if a node will send ORTS or DRTS, our D-MAC scheme 2 is identical to scheme 1.

5. Performance Evaluation

To evaluate our protocols, we performed simulations using the Qualnet simulator, version 3.6 which is known to provide more actual physical layer models of directional antenna [29]**. The Qualnet is a discrete-event network simulator, which enables it to accurately simulate multihop wireless ad hoc networks. In QuaNet, directional antenna models are implemented to support simulation of state-of-the-art antenna technologies and their impact on higher layer protocol performance. QualNet comes with two types of directional antenna models: switched beam and steerable beam antennas [11]. A switched beam antenna model uses multiple predefined radiation patterns, whereas a steerable beam antenna model steers each radiation pattern over azimuth and elevation towards the signal of interest to maximize the antenna gain. Both directional antenna models use pre-computed radiation pattern files that define the antenna gain for a specific angle on the azimuth and the elevation planes. We have adopted the switched beam antenna model. Each directional antenna has a main lobe with the beamwidth of 60 degrees with 6 elements. We assume that the transmission range for both omnidirctional and directional antennas are approximately the same by modifying the parameter value of receive sensitivity and receive sensitivity.

** Note that simulation in our previous work [20] have been done in NS2 [30] with much simpler directional antenna model.

5.1. Simulation Model

We consider the 5×5 mesh topology illustrated in Figure 5(a). The nodes form 5 rows and 5 columns, with two adjacent rows and two adjacent columns being separated by 200 m. We briefly evaluate the case of 3×3 and 6×6 mesh topologies at the end of the next subsection. Transmission range and carrier sensing range of each node is 250 and 550 m, respectively, and the wireless link bandwidth is 2 Mbps (DQPSK). TCP Reno is used for the transport layer over the IEEE 802.11 MAC layer. The traffic model used in our simulation is FTP with infinite backlog at each source node. The TCP packet size is 1460 bytes and the maximum advertised window is 8 packets. Each simulation is performed for a duration of 900 seconds. Each performance measurement reported below is averaged over 20 executions. Table I summarizes the parameters used in our simulation.

5.2. Simulation Result

The performance metric used to evaluate the protocol is TCP throughput. The unit for all throughput measurements reported here is Kilobits per second (Kbps).

In our simulations, we experimented with TCP connections that traverse different number of hops. Note that throughput of a TCP connection decreases quite rapidly when the number of wireless hops is increased from 1 to 4. For future reference, the throughput of a single TCP connection using the IEEE 802.11, as a function of the number of hops, is as

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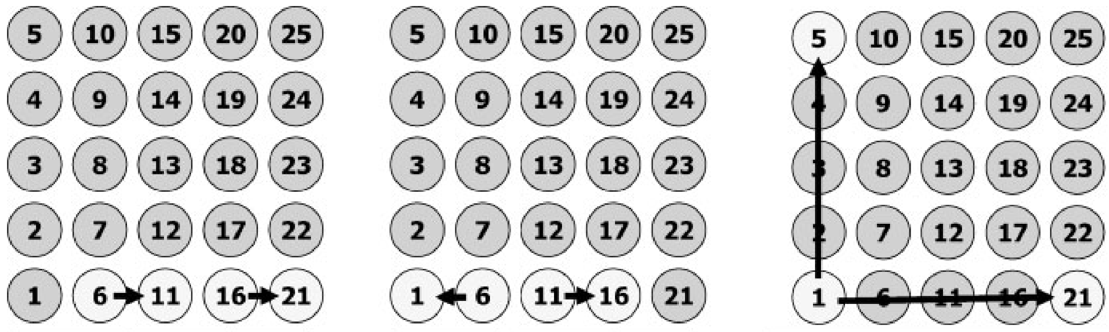

Connections	IEEE 802.11	D-MAC1
6→11	703.931	1106.33
16→21	607.826	1092.326
Total (Kbps)	**1311.757**	**2197.659**

(a) Scenario I: Two single-hop TCP connections in the same direction.

Connections	IEEE 802.11	D-MAC1
6→1	648.298	1236.266
11→16	603.752	1219.168
Total (Kbps)	**1252.05**	**2455.884**

(b) Scenario II: Two single-hop TCP connections in the opposite direction.

Connections	IEEE 802.11	D-MAC1	D-MAC2
1→21	197.065	276.992	236.371
1→5	193.699	273.353	227.105
Total (Kbps)	**390.764**	**550.345**	**463.476**

(c) Scenario III: Two four-hop TCP connections in the different direction.

Fig. 5. Simulation scenarios I–III.

follows: one hop 1258.7 Kbps, two hops 664.4 Kbps, three hops 438.1 Kbps, and four hops 313.0 Kbps.

(1) *Scenario I*: As seen in Figure 5(a), the first scenario considered in our evaluation consists of two single-hop TCP connections: one connection from node 6 to node 11 and the other from node 16 to node 21. The total throughput of D-MAC scheme 1 is higher than the IEEE 802.11 MAC protocol. This is because, with D-MAC scheme 1, simultaneous transmission on the two TCP connections are allowed by using DRTS packet. On the other hand, when using the IEEE 802.11 protocol, the two connections cannot transmit frames at the same time.

Note that the aggregate throughput of the two connections above using IEEE 802.11 is comparable to that of a single TCP connection using IEEE 802.11—essentially, in this case, when the two connections are opened, they share the bandwidth that would have been otherwise available to a single connection.

(2) *Scenario II*: The second scenario considered here also consists of two single-hop TCP connections: one connection from node 6 to node 1 and the other from node 11 to node 16 (see Figure 5(b)). The total throughput using the IEEE 802.11 protocol in scenario II is slightly lower than scenario I. However, the performance of the D-MAC scheme 1 is better than in scenario I. This is because, in scenario II, there is a smaller probability of control packet collision when using our D-MAC scheme 1, as compared to in scenario I. For instance in scenario I, imagine that node 6 transmits a DRTS frame to node 11 while node 16 has already started a packet transfer to node 21. Because node 11 would not have received node 16s DRTS frame, it may send an OCTS frame in reply to the DRTS from node 6. This OCTS frame can interfere with the reception of ACK from node 21 to node 16, causing degradation of the performance. Despite this possibility of collision of OCTS and ACK control frames, simulation results also shows that aggregate throughput with D-MAC scheme 1 is better than the IEEE 802.11—the reason is that the performance benefit of being able to perform multiple transfer in vicinity of each other (which may be disallowed in IEEE 802.11), outweighs the potential performance loss due to collision of control frames. In scenario II, such collisions cannot occur since the direction of data transfer is different from scenario I. therefore, observe that scheme 1 yields throughput twice that

Table I. Simulation parameters.

Type	Parameter name	Value
General	Simulation time (sec.)	900
	Dimension (m^2)	1500 × 1500
	Transmission range (m)	250
Wireless settings	Channel frequency (GHz)	2.4
	Path-loss model	Two-ray ground
	Transmission power (dBm)	15.0
	Receive sensitivity (dBm)	−87.0
	Receive threshold (dBm)	=74.0
	Antenna model	Switched beam
	Directional antenna gain (dBm)	15.5
	Bandwidth (Mbps)	2
Network protocol	Routing protocol	DSR
	TCP variant	Reno
	Maximum segment size	1460
Application	Traffic model	FTP

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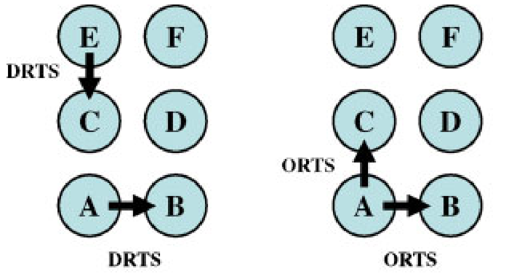
of IEEE 802.11. Scenario II represents the best case for the use of directional antennas.

(3) *Scenario III*: Now we consider scenario III, in which two TCP connections are established. Thus, as in Figure 5(c), one connection traverses a row in the 5 × 5 mesh from node 1 to node 21, and another connection traverses a column from node 1 to node 5. Both paths consist of four hops. Table in the Figure 5(c) presents the throughput measurements. In this case, all three MAC schemes are quite fair. From the performance point of view, D-MAC schemes 1 and 2 both achieve significant improvement over IEEE 802.11, with scheme 1 achieving the larger throughput than scheme 2 (not always, as seen later in scenario IV).

Due to its design philosophy, D-MAC scheme 2 can reduce the probability of collision of control frames. This fact usually contributes to an increase in aggregate throughput. However, ORTS frames in scheme 2 also reduce the possibilities for simultaneous transmission by neighboring nodes (below we present an example to illustrate this). Thus, the network performance improvement by scheme 2 (compared to scheme 1) depends on whether the benefit of reducing control frame collision outweighs the decrease in throughput resulting from reduced possibilities for simultaneous frame transmissions. Thus, there exists a trade-off between probability of collisions of control frames and disallowed simultaneous transmissions, when D-MAC schemes 1 and 2 are compared.

To illustrate the above issue, consider the network consisting of 6 nodes in Figure 6. Assume that 2 TCP connections are established—one from node E to C and another from A to B. In Figure 6(a), when D-MAC scheme 1 is used, node E can transmit to node C, while node A is transmitting to node B. However, with D-MAC scheme 2, this may not always be possible—when node E sends an DRTS to node C, node C will not send OCTS to E, if it has heard an ORTS for an ongoing transfer from node A (see Figure 6(b)). Due to scenarios similar to the above, we believe that, D-MAC scheme 1 allows more simultaneous transmissions when the number of connections are increased both horizontally and vertically, compared to D-MAC scheme 2. This results in larger aggregate throughput for D-MAC scheme 1.



(a) Simultaneous transmission with D-MAC scheme 1.

(b) No simultaneous transmission with D-MAC scheme 2.

Fig. 6. Difference between D-MAC schemes 1 and 2.

Table II. Aggregate TCP throughput.

Topology	IEEE 802.11	D-MAC1	D-MAC2
3 × 3 (6 connections)	657.9847	950.6609	988.7809
5 × 5 (10 connections)	613.680	968.010	930.591

To verify this intuition, we now consider simulations with increasing the number of crossing TCP connections traversing the rows and columns. We measure the aggregate throughput for 6 TCP connections in 3 × 3 mesh topology (one connections along each row and column) and for 10 TCP connections in 5 × 5 topologies (again, one connection along each row and column), to compare with the results for the 10 connections in 5 × 5 topology[††]—Table II presents the aggregate throughput achieved by the TCP connections using the three MAC schemes. Observe that D-MAC scheme 2 has the largest throughput in the case of 3 × 3 topology, whereas D-MAC scheme 1 has the largest throughput with 5 × 5 topology. In summary, we conclude that the effects of concurrent transmission is inversely proportional to the complexity of TCP connection 'topology.'

(4) *Scenario IV*: In the Figure 7, scenario IV consists of 5 TCP connections, each connection traverses one row of the 5 × 5 mesh. For all three schemes, the 'border' connections from node 1 to 5 show much higher throughput than other interior connections (connections from node 2, 3, and 4). This is because the border connections share wireless medium with only one other connection, whereas the interior connections share the medium with two other connections. Similar to the case of two connections in scenario III, both D-MAC schemes have better total throughput than IEEE 802.11

[††] In case of 5 × 5, more detailed simulation result will be shown at the simulation results with scenario V.

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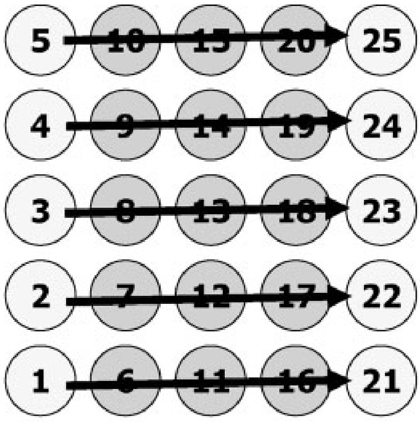


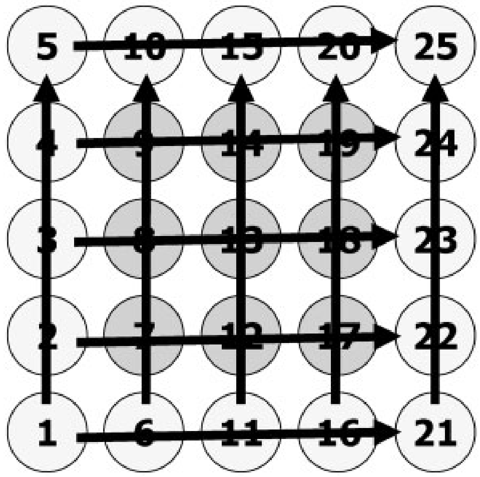
Connections	IEEE 802.11	D-MAC1	D-MAC2
1→21	167.071	161.787	188.444
2→22	100.037	130.045	108.899
3→23	24.153	138.044	170.864
4→24	85.271	118.486	105.611
5→25	200.987	190.400	206.906
Total (Kbps)	**577.519**	**747.762**	**780.724**

Fig. 7. Scenario IV: Five simultaneous connections.

However, in this scenario, D-MAC scheme 2 achieves the largest throughput. We believe, this is because the scheme 2s advantage of reducing control frame collisions becomes dominant in this topology. Another interesting observation is that the D-MAC schemes are somewhat fairer (particularly, to connection from node 3 to node 23) than IEEE 802.11 in this scenario.

(5) *Scenario V*: Next, in scenario V, we increase the number of TCP connections to 10, with 5 connections traversing the 5 rows, and 5 connections traversing the 5 columns. (See Figure 8. Each of these connections traverses four hops.)

In this case, although both D-MAC schemes achieve significantly better throughput than IEEE 802.11, D-MAC scheme 1 performs better than scheme 2. This again means that D-MAC scheme 2 has lower throughput (compared with scheme 1) as the disallowed simultaneous transmissions caused by cross connections increase.



Connections	IEEE 802.11	D-MAC1	D-MAC2
1→21	84.397	151.92	123.371
2→22	25.074	60.457	56.602
3→23	11.835	67.292	54.869
4→24	36.704	67.539	59.494
5→25	149.001	139.74	149.36
1→5	87.554	159.245	136.432
6→10	23.148	60.860	49.715
11→15	11.423	77.372	68.285
16→20	36.098	64.22	60.852
21→25	148.486	139.359	167.61
Total (Kbps)	**618.680**	**968.010**	**930.591**

Fig. 8. Scenario V: Ten TCP connections.

6. Additional Discussions

6.1. Optimized Scheme: Introducing DWTS

We showed above that using DRTS frames can potentially improve performance of wireless ad hoc networks. Let us consider another scenario for using

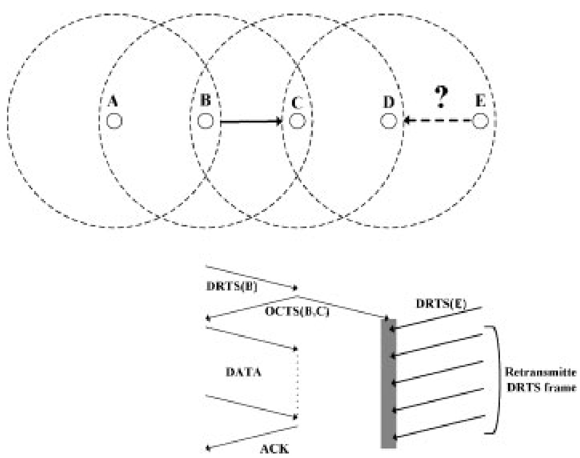


Fig. 9. Useless retransmission of RTS frames.

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DRTS frames. In Figure 9, nodes B and C communicate with each other for some duration of time, similar to Figure 2(a). However, unlike Figure 2(a), where node E has data frames for node D during that period of time, now node E wishes to transmit to node D. When using the first D-MAC mechanism, node E sends a DRTS in the direction of node D and expects an OCTS frame to be returned from D. Node D may know the fact that node C is receiving data frames from node B so its OCTS reply for node E can disturb node C's data reception from node B. Therefore, D will be silent despite a DRTS from node E until the proposed transmission between B and C is done. This can cause unnecessary retransmission of DRTS from E to D (see Figure 9). This situation would happen in the current IEEE 802.11 protocol as well.

One solution to prevent this situation is to introduce a short control frame, directional Wait-To-Send (DWTS). DWTS messages can be used for preventing useless retransmission of RTS frames by telling how much time to wait before retrying the RTS frames. Thus, a DWTS frame contains a duration field that indicates the period a node must wait for transmission. When a node receives a DRTS frame from its neighbor while it is aware of another on-going transmission, it replies with a DWTS frame to the neighbor that sent the DRTS frame.

Figure 10 illustrates this mechanism. In the figure, a DRTS frame from nodes E to D follows an OCTS frame from node C. Upon receiving the DRTS, node D returns a DWTS frame back to node E because D can not reply with an OCTS frame for node E at this time.

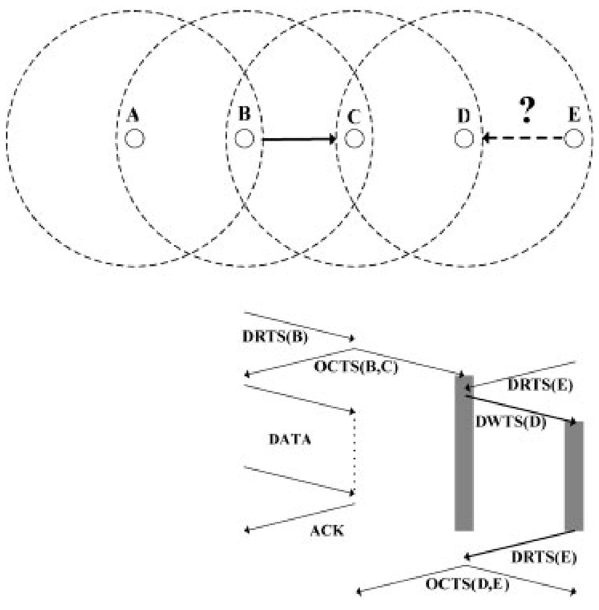

Fig. 10. Example of using DWTS frames.

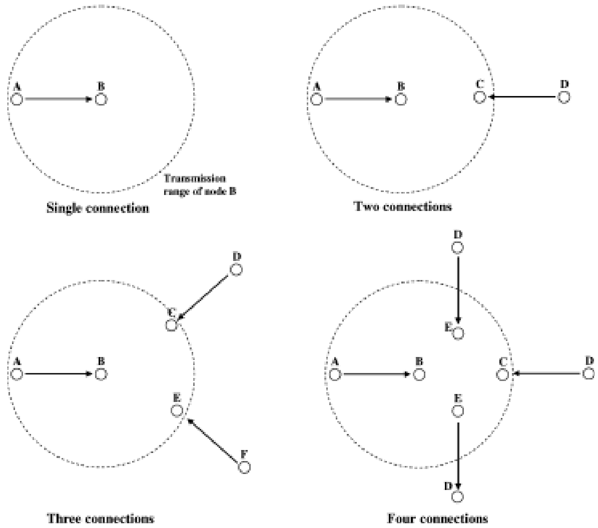

Fig. 11. Four topologies by varying the number of connections.

Using DWTS frames can avoid useless retransmission of DRTS frame by node E until the time specified in the duration field of DWTS frame has elapsed. When E sends the next DRTS (after waiting appropriate duration), node D replies with an OCTS. The main idea of using DWTS frame is to let node E know about how much to wait before retrying the DRTS frame.

In order to study the combining DWTS optimization scheme to D-MAC protocol, we once again developed an evaluation environment. First of all, we try to generate the scenarios that may require the use of DWTS frames, as shown in Figure 11. In the figure, the first case of single connection between the two nodes A and B is simply used for a reference. By putting another adjacent connection, in case of two connections, at least one sender (node A or D) may get DWTS frame from its expected receiver (node C or D). Thus, by increasing the number of adjacent connections, the frequency of

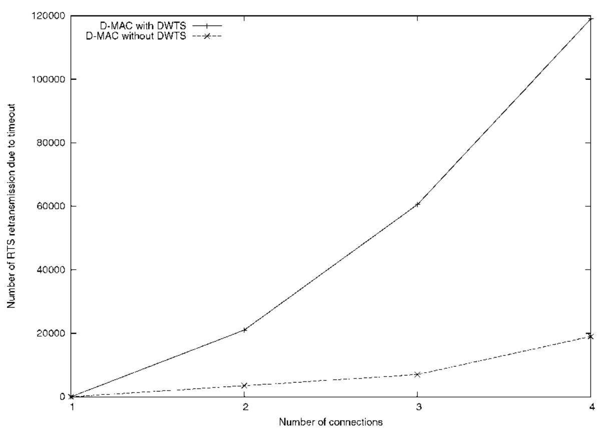

Fig. 12. Result for number of unnecessary RTS retransmission by varying the number of adjacent connection(s).

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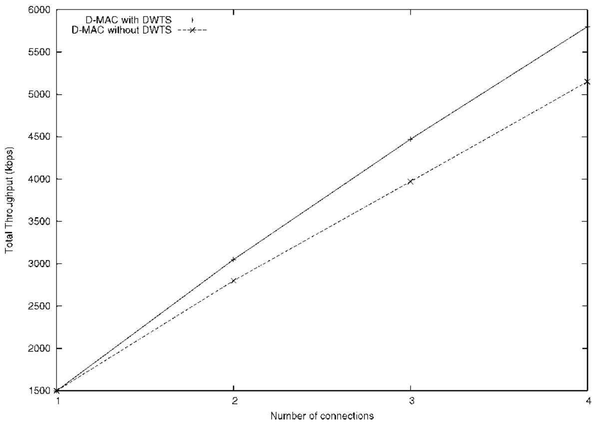

Fig. 13. Result for total throughput of D-MAC with DWTS by varying the number of adjacent connection(s).

using DWTS is increased. These topologies are simple, but it is sufficient to show the effect of unnecessary retransmission of RTS in D-MAC protocol. Other simulation parameters are the same as previous experiments.

The simulation results are shown in Figures 12 and 13. For these figures, a dotted line represents original D-MAC (without DWTS), and a solid line represents optimized D-MAC (with DWTS). Especially, in this scenario, we measure the total number of retransmitted RTS frames. Figure 12, as the number of adjacent connections are increased, the total number of retransmitted RTS begins to increase for both case. However, optimized D-MAC provides a lower rate of increase than D-MAC without DWTS. This is because, with DWTS, D-MAC prevents useless retransmission of RTS frames by telling how much time to wait before retrying the RTS frames. These factors contribute to increase in throughput of D-MAC. As you see in the Figure 13, the total throughput of optimized D-MAC scheme is always lager than that of original D-MAC.

6.2. Conflict-Free ACK

In the current IEEE 802.11 MAC protocol standard, immediate link layer acknowledgements[‡‡] are employed to determine if the data frame was successfully received. Thus, RTS-CTS-DATA-ACK exchange mechanism is used to enhance reliability of data transmission. Note that, in our proposed D-MAC schemes, returning the ACK frame immediately after the DATA is also assumed.

In 802.11, ACK frame collisions are minimized since the transmission range of both a transmitter and a receiver is reserved. However, in our D-MAC schemes, there is no guarantee of collision-free ACK frame reception even though scheme 2 reduces the probability of frame collisions by using ORTS frames. To remedy this problem of no ACK collision guarantee, we present some approaches below.

(1) *Use Two Channels*: To guarantee no conflicts of ACK frames, the single common channel may be split into two separate channels: one for DATA and ACK frame transmission, and the other for RTS and CTS frame transmission. MAC-level acknowledgement requires the receiving node of data frames to respond with an ACK immediately, without exchanging RTS/CTS control frames. This implies that ACK frames are generated by the MAC layer and they are sent on the data channel which has been used for the corresponding DATA reception. Since ACK frames are transmitted on a different channel than other control frames (RTS/CTS), conflict-free transmission for the ACK can be guaranteed.
(2) *Exchange Another RTS/CTS for ACK frames*: Another possible solution is to perform RTS/CTS exchange for the ACK itself. A single common channel is assumed here. The basic idea is that an ACK frame is considered as another data frame requiring a successful RTS/CTS exchange. Unlike immediate MAC-level acknowledgement mechanisms described above, ACK frames are generated by an upper layer such as logical link control (LLC). To send the ACK successfully, another successful exchange of RTS and CTS frames is required. Of course, this additional RTS/CTS exchange mechanism would decrease bandwidth efficiency due to overhead. Thus, there exists a trade-off between reliability of data transmission and the control frame overhead.

6.3. Location Information

The assumption in the above discussion is that a node knows its own location and neighbors' location accurately—this information is necessary to determine which directional antenna to use either to send DRTS or DATA. When the nodes are mobile, it is hard to know the precise location of a node at all times. A mobile node may inform its location to its neighbor periodically using beacons. Also, the location information could be included in other messages (such

[‡‡] Here, an ACK is treated as a control frame sent by a MAC layer. Therefore, no RTS is sent for the ACK.

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as RTS and CTS). However, due to node mobility, the location information can become stale. Since we suggest using directional antennas for DRTS and/or DATA, it is useful to consider how the protocol should be modified when location information is not known accurately.

When a node X wishes to send data to node Y, it may send DRTS or ORTS, using our protocols. Of course, for sending ORTS, node X need not know Y's location. However, to send DRTS, X needs to know the location. If X does not have any location information for Y, then the DRTS may be replaced by ORTS, without loss of correctness. On the other hand, if node X does know, potentially out-dated, location of node Y, then X can transmit the DRTS in the appropriate direction. A reply to the first DRTS may not be received, due to various reasons, such as transmission errors or because the out-dated location information resulted in the use of a directional antenna that does not cover the current location of node Y. To deal with causes such as errors, node X may retransmit the DRTS after a suitable back-off interval. However, to recover from out-dated location information, an ORTS must be transmitted. Thus, in general, node X may retransmit the DRTS up to a specified threshold, and then default to using an ORTS. It is important to note that using an ORTS instead of a DRTS does not affect correctness of the MAC protocol.

When sending the data as well, node X uses a directional antenna. Since an RTS/CTS exchange precedes data transmission, and since location information of node Y can be included in the CTS message, node X has accurate location information. Node X can use this information to choose the appropriate directional antennas. There is always a (small) probability that node Y moves out of scope of the chosen directional antenna during the data transfer. This may result in the loss of the data frame, and may be handled similar to a loss due to transmission errors.

7. Conclusion

The current MAC protocols using omnidirectional RTS and CTS can waste wireless bandwidth by reserving the wireless medium over a large area. To improve bandwidth efficiency of the previous MAC protocols, we propose a new approach, named D-MAC, utilizing the directional transmission capability of a directional antenna. We considered several possible cases and proposed two different schemes: D-MAC scheme 1 for using only DRTS frames, and D-MAC scheme 2 for using both DRTS and ORTS frames. We also proposed an optimization using DWTS frames to prevent unnecessary retransmissions of RTS frames. By simulation studies, we compared our D-MAC mechanisms to the IEEE 802.11 protocol. In summary, our D-MAC protocols can improve performance by allowing simultaneous transmissions that are not allowed in the current MAC protocols.

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References

1. Tornow JD. The DARPA packet radio networks protocols. *Proceeding of IEEE* 1987; **75**(1).
2. Corson S, Macker J. Moible Ad Hoc Networking (MANET): Routing protocol performance issues and evaluation considerations (Internet draft). Mobile Ad-Hoc Networks (MANET) Working Group, IETF, October 1998.
3. Cisco Systems. Mobile ad hoc networks for military. Cisco White Paper, GDSG-APAC-MANET.
4. Zussman G, Segall A. Energy efficient routing in ad hoc disator recovery networks. *Proceedings of the IEEE INFOCOM 2003*, March 2003.
5. Akylidiz IF, Wang X. Wireless mesh networks: a survey. *Computer Networks* 2005; **47**(4): 445–487.
6. Akylidiz IF, Su W, Sankarasubramaniam Y, Cayirdci E. Wireless sensor netowrks: a survey. *Computer Networks* 2002; **38**: 392–442.
7. Merritt R. Startup bolts smart antennas to exisiting WiFi chip sets. Online Resource for CommsDesign Engineer, December 2003.
8. Patrick Mannion. Atheros his home with WLAN chip set. CMP EE TIMES, July 2004.
9. Horneffer M, Plassmann D. Directional Antennas in the Mobile Broadband Systems. *Proceedings of IEEE INFOCOM'96*, 1996; 704–712.
10. Okamoto GT. *Smart Antennas Systems and Wireless LANs*. Kluwer Academic Publishers: Boston, USA, 1998.
11. Lehne PH, Pettersen M. An overview of smart antenna technology for mobile communications systems. *IEEE Communication Surveys* 1999; **2**(4): 2–13.
12. Geier J. Antennas: The Key to Maximizing RF Converage. WiFi Planet Tutorials, May 24, 2002.
13. Ko Y-B, Vaidya N-H. Location-aided routing (LAR) in mobile ad hoc networks. *ACM/Baltzer Wireless Networks (WINET) Journal* 2000; **6**: 4–6.
14. Choudhury RR, Vaidya NH. Impact of directional antennas on ad hoc networks. *IFIP PWC'03*, September 2003.

DOI: 10.1002/wcm

15. IEEE P802.11. Wireless LAN medium access control (MAC) and physical layer (PHY) specifications, 1999.
16. Saha AK, Johnson DB. Routing improvement using directional antennas in mobile ad hoc networks. Rice University Technical Report, TR03-420, July 2003.
17. Lal D, Joshi T, Agrawal DP. Localized transmission scheduling for spatial multiplexing using smart antennas in wireless ad hoc networks. *Proceedings of the 13th IEEE Workshop on Local and Metropolitan Area Networks*, April 2004.
18. Nasipuri A, Li K. A directionality based location discovery scheme for wireless sensor network. *Proceedings of ACM WSNA 2002*, September 2002.
19. Yi S, Pei Y, Kalyanaraman S. On the capacity improvement of ad hoc wireless networks using directional antennas. *Proceedings of the 4th ACM International Symposium on Mobile Ad Hoc Networking and Computing*, June 2003.
20. Ko Y-B, Shankarkumar V, Vaidya NH. Medium access control protocols using directional antennas in ad hoc networks. *Proceedings of the IEEE INFOCOM*, March 2000.
21. Nasipuri A, Ye S, You J. A MAC protocol for mobile ad hoc networks using directional antennas. *Proceedings of the IEEE Wireless Communications and Networking Conference (WCNC)*, September 2000.
22. Choudhury RR, Yang X, Ramanathan R, Vaidya NH. On designing MAC protocols for wirelss networks using directional antennas. *IEEE Transaction on Mobile Computing* 2006; **5**(5): 477–491.
23. Korakis T, Jakllari G, Tassiulas L. A MAC protocol for full exploitation of directional antennas in ad hoc wireless networks. *Proceedings of the 4th ACM International Symposium on Mobile Ad Hoc Networking and Computing*, June 2003.
24. Huang Z, Shen C-C, Srisathapornphat C, Jaikaeo C. A busy-tone based directional MAC protocol for ad hoc networks. *Proceedings of the IEEE Milcom*, 2002.
25. Choudhury RR, Vaidya NH. Deafness: a MAC problem in ad hoc networks when using directional antennas. *Proceedings of the 12th IEEE ICNP*, 2004.
26. Singh H, Singh S. Tone based MAC protocol for use with adaptive array antennas. *Proceedings of the IEEE Wireless Communications and Networking Conference*, March 2004.
27. Aono T, Hashiguchi M, Takizawa K, Higuchi K, Mori H, Ohira T. Basic experiments for binary reactance diversity of a planar 3-Elements ESPAR antenna. *IEICE Technical Report*, RCS2003-44, June 2003; 1–6.
28. Ramanathan R. On the performance of beamforming antennas in ad hoc networks. *Proceedings of the ACM Mobihoc*, October 2001.
29. QualNet Simulator, http://wwww.scalable-netowrk.com
30. VINT Group. UCB/LBNL/VINT network simulator ns (version 2).

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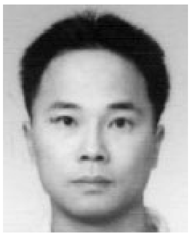

Jong-Mu Choi received the B.S. and M.S. degrees in Computer Science from the Ajou University, Suwon, Korea, in 2002 and 2004, respectively. He is presently a Software Engineer with the division of mobile communication at the Samsung Electronics. Prior to joining Samsung, he worked as research scholar at University of Illinois at Urbana-Champaign. He also spent an year at MIP Telecom, where he worked in the areas of VoIP (Voice over IP) systems. From 2003, he serves as a Lecturer of Samsung Advanced Technology Training Institute where he has taught professional embedded Linux programming, IEEE 802.11, and IP-Based Multimedia Subsystem. His current research efforts are related to IP-based Multi-media system over UMTS networks and Fixed Mobile Convergence Networks.

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