# A MAC Protocol for Mobile Ad Hoc Networks Using Directional Antennas

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*Abstract-* **We propose a medium access control (MAC) protocol for an ad hoc network of mobile wireless terminals that are equipped with multiple directional antennas. Use of directional antennas in ad hoc networks can largely reduce the radio interference, thereby improving the packet throughput. However, the main problem of using directional antennas in such networks is due to the dynamic nature of the network caused by frequent node movements. This gives rise to problems such as locating and tracking during random channel access. The MAC protocol presented in this paper proposes a solution to these problems without the help of additional hardware. Results obtained from detailed computer simulations demonstrate the performance improvement obtained with the proposed scheme.**

## 1 INTRODUCTION

A mobile ad hoc network is a wireless network without fixed base stations or any wireline backbone infrastructure. The nodes use peer-to-peer packet transmissions and multihop routes to communicate with one another. The networks topology is continuously changing due to frequent node movements and hence dynamic routing protocols are required to establish and maintain the routes. In literature, terms such as multihop wireless networks and packet radio networks are used to describe such networks. Such networks are very useful in military and other tactical applications such as law enforcement, emergency rescue or exploration missions, where cellular infrastructure is unavailable or unreliable. There is considerable interest in using ad hoc networks in commercial applications as well where there is a need for ubiquitous communication services without the presence of a fixed infrastructure.

The medium access control (MAC) protocol performs the challenging task of resolving contention amongst nodes while sharing the common wireless channel for transmitting packets. Traditional random channel access protocols that are used in wired networks, such as carrier sense multiple access (CSMA) [10], are not very effective here. This is due to the fact that propagation path losses in the wireless medium cause the same signal to be heard differently at different points in the network introducing problems such as the hidden terminal and the exposed terminal problems [14]. To address these problems, the IEEE 802.11 standard suggests a variation of CSMA, known as the carrier sense multiple access with collision avoidance (CSMA/CA), along with an option for channel reservation using an exchange of control packets to ensure a high probability of success for trans-

mitting data packets [4]. Many other MAC protocols such as DBTMA [3], FAMA [5], CARMA [6], etc. have also been suggested addressing the problems of wireles access in ad hoc networks. However, since the wireless spectrum is scarce, there is a lot of interest in seeking newer MAC protocols to improve the bandwidth utilization and throughput. In this paper, we present a MAC protocol that improves the throughput in mobile ad hoc networks by using directional antennas in the mobile nodes.

Typically, MAC protocols for ad hoc networks assume omnidirectional antennas (antennas with a 360 degree pattern), as the nodes are mobile and may need to communicate with neighbors located in any direction. But if a mobile node used a directional antenna for unicast packet transmissions, it could largely reduce the unwanted interference to nodes lying outside its directional pattern. Similarly, a node that is receiving a packet can eliminate the interfering signals from directions other than the signal source by using a directional antenna. Such benefits are utilized in cellular wireless networks, for instance, where the base-stations may use $120^{o]}$ beam-width directional antennas to reduce the interference to mobiles located in another co-channel cell, thereby improving the frequency reuse and the overall system capacity. However, the use of directional antennas on mobile terminals introduce the complex issue of finding the desired direction for transmission or reception using a directional antenna. This issue is particularly critical in an ad hoc network which has no centralized control and the mobile terminals may have limitations of size and the complexity/cost of communication hardware. Despite these difficulties, the idea of using directional antennas in packet radio networks has been explored by several researchers in this area. Zander [16] studied the performance improvement that can be achieved by using electronically steerable adaptive antennas in a slotted ALOHA multihop packet radio network. Horneffer and Plassman [7] explored the use of a modified monopulse tracking algorithm to locate mobile stations in a broadband wireless cellular network. They proposed a dynamic slot assignment MAC to be applied with adaptive directed antennas to improve the performance of the network. MAC protocols using directional antennas in multihop packet radio networks have been proposed in [15, 8]. These protocols use a set of tones transmitted on separate channels to identify and locate transmitting nodes. More recently, MAC protocols using directional antennas in ad hoc networks have been presented in [11]. There, the mobile nodes were assumed to know the physical locations of them-

selves and their neighbors, which may be obtained by using additional hardware such as a Global Positioning System (GPS).

We propose a MAC protocol that uses directional antennas in an ad hoc network where the mobile nodes do not have nay location information. The protocol presented in this paper uses an RTS/CTS exchange similar to that in 802.11 for enabling the source and destination nodes to identify each other's directions. The nodes transmit as well as receive data packets using directional antennas, thereby reducing the level of interference to other nodes as well as to themselves. We perform simulation experiments to evaluate the performance of the proposed protocol. The paper is organized as follows. We present some key features of existing wireless medium access protocols for ad hoc networks, including the 802.11 protocol, in section 2. The description of the node model assumed by us and the details of the proposed MAC protocol using directional antennas are given in section 3. Performance evaluations of the protocol, obtained by using a discrete event MAC simulator, are presented in section 4. We conclude in section 5.

## 2 PRELIMINARIES

A wireless transmitter using a directional antenna transmits the signal equally in all directions. Hence it potentially adds to the level of interference at all nodes in the network. A signal is received correctly at the destination if the ratio of the signal power to the total noise and interference at the receiver is above the receiver sensitivity. The power of a transmitted signal degrades as we move further from its source. A node that senses the signal power to lie above a pre-defined threshold, assumes the channel to be busy and refrains from using it. However, this "listen before transmit" principle, which is very effectively used in CSMA protcols for wired networks, is not very successful in wireless networks. This is due to the fact that the carrier is sensed at the transmitter location which is different from that at the receiver. The hidden-terminal and the exposed terminal problems, illustrated in Fig. 1, are due to this effect, and are the main cause for packet loss in wireless CSMA. In the example shown in Fig. 1(a), for instance, the node **A** senses the channel to be free for transmitting a packet to **B**. However, the channel is busy at **B** due to the transmission from **C**, which is hidden from **A**. Hence the packet from **A** cannot be received correctly by **B** (termed as a "collision"). Fig. 1(b) illustrates a situation where a node (**B**) senses the channel to be busy due to a neighboring transmission (from **C**), and hence goes into a backoff before transmitting its packet to **A**. However, the backoff may be unnecessary if the interference from **C** is not sufficiently high at **A**. This leads to wastage of bandwidth. Both these problems are illustrated assuming omnidirectional antennas, and would be removed by the use of directional antennas.

An effective way of reducing packet loss due to the hidden terminal effect using omnidirectional antennas was suggested in [9]. According to this scheme, before sending the data packet, the source first sends a "request to send" (RTS) control packet to the destination. On receiving the RTS correctly, the destination responds by sending back a "clear to
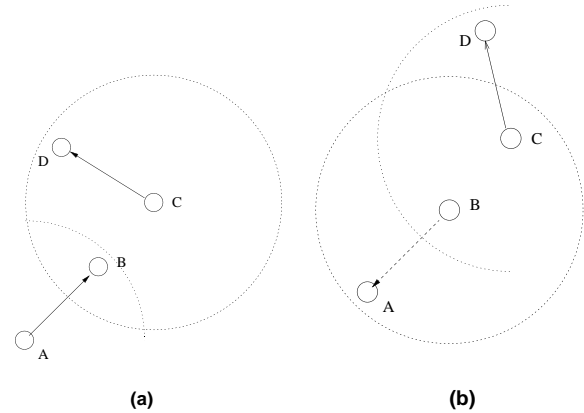


Figure 1: Examples of hidden (a) and exposed (b) terminal problems. The dotted circles indicate the radio transmission ranges.

send" (CTS) control packet to the source and waits to receive the data packet. Other nodes who receive the RTS or CTS packet wait until the ensuing data transmission is over before claiming for the channel. The source then proceeds to transmit the data packet, thereby avoiding any undetected interference from the neighbors of the destination. Thus RTS/CTS exchange performs a "virtual" carrier sensing at the destination from the source. Note that these control packets themselves can suffer losses due to contention in the channel and the hidden terminal effect, but since these packets are short, the scheme benefits from avoiding the loss of the larger data packets.

The RTS/CTS exchange does not solve the exposed terminal problem. It also suffers from other ill, especially under heavy traffic loads and/or highly mobile scenarios [13]. We focus on the importance of reducing the interference as a key factor that can improve the performance of a MAC protocol for ad hoc networks. This motivates the use of directional antennas and the development of appropriate protocols for using them.

## 3 DIRECTIONAL ANTENNAS IN AD HOC NETWORKS

In this section we address the problems and the proposed solution for using directional antennas in the mobile transceivers in an ad hoc network. The node model is described first, followed by a detailed description of the proposed MAC protocol.

### 3.1 Model Description

We assume an ad hoc network of $N$ mobile terminals (nodes) equipped with radio transceivers. All nodes share the same wireless channel. The transmission range of the nodes are limited, decided by the transmission power, antenna gain, receiver sensitivity, channel characteristics, and noise.

The radio transceiver in each mobile node is assumed to be equipped with $M$ directional antennas. Each of the an-
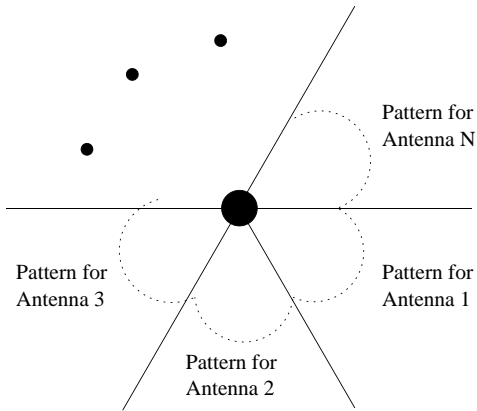
Figure 2: Illustration of deployment of directional antennas in a node. The antennas are numbered starting with the 3 'o clock position.



**Time sequence of packet transmissions**

Figure 3: Illustration of the medium access control protocol using directional antennas. In this figure, $N = 4$ is assumed

tennas has a conical radiation pattern, spanning an angle of $2\pi/M$ radians. The $M$ antennas in each node are fixed with non-overlapping beam directions, so as to collectively span the entire plane (see Figure 2). We use the convention for numbering the antennas from 1 to $N$ as shown in Figure 2, with numbers increasing clockwise starting from the horizontal (3 o' clock) position. It is assumed that all nodes are able to maintain this orientation at all times, irrespective of their movements. This could be implemented with the aid of a direction finding instrument, such as a compass, in each node. The MAC protocol is assumed to be capable of switching any one or all the antennas to *active* or *passive* modes. The radio transceiver uses only the antennas that are active. If a node transmits while all of its antennas are active, the signal is transmitted in all directions, similar to using an omnidirectional antenna. When receiving on all antennas, the receiver uses selection diversity, which implies that it uses the signal from the antenna that is receiving the maximum power of the desired signal. This usually happens with the directional antenna whose conical pattern is directed towards the source of the signal that it is receiving. Though a directional antenna can be designed to have a higher gain than omnidirectional antennas, in this work we assume the antenna gain is the same for all antennas, which does not depend on its angular span. Hence the radio range within the span of an antenna is the same for all values of $M$. We assume complete attenuation of the transmitted signal outside the conical pattern of the directional antennas. Though each node is equipped with multiple directional antennas, there is only one radio transceiver per node, which can transmit and receive only one packet at any given time.

### 3.2  MAC Protocol Using Directional Antennas

The proposed MAC protocol is illustrated in Figure 3. The scheme is similar to the IEEE 802.11 [4] protocol, adapted for use with directional transmission. The key feature that has been added in the adaptation is a mechanism for the transmitting and receiving nodes to determine the directions of
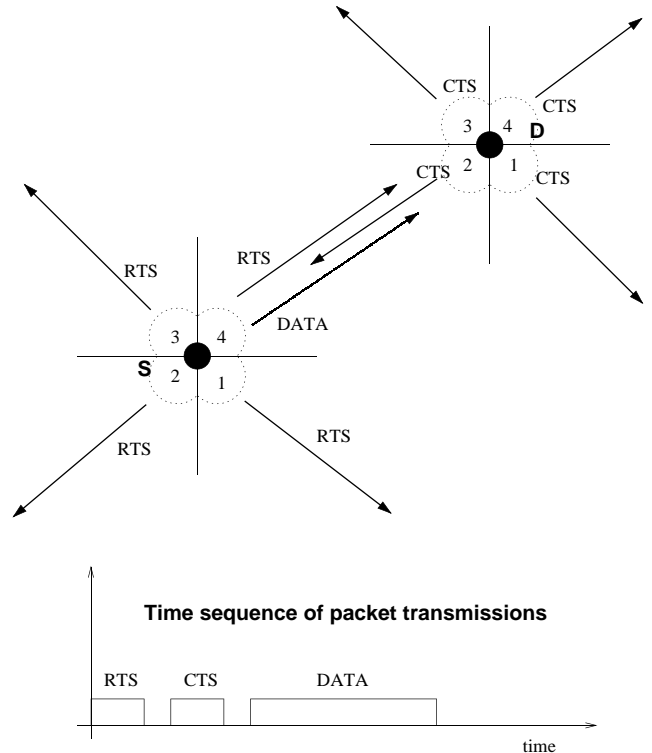
each other. Since the nodes are continuously moving and there is no centralized control, a node is not normally aware of the exact location of its neighbors. The task of finding the sequence of nodes through which to route a packet to the intended destination is performed by the routing protocol. (For descriptions and performances of some existing routing protocols for ad hoc networks, please refer to [1].) Hence, for every data packet that is to be transmitted, the MAC is concerned with only the destination for that hop (one of its neighbors), as specified by the routing layer. However, the MAC must be capable of finding the direction of the destination node before the data packet can be transmitted using a directional antenna. Similarly, as we require the receiver to use a directional antenna as well, the destination node must also know the direction of the source before it can start receiving the transmitted data packet. We propose to perform this task in the following way. We assume that an idle node listens to ongoing transmissions on all its antennas. Any node that wishes to send a data packet to a neighbor, first sends an omnidirectional RTS packet addressed to the destination. For example, in Figure 3, **S** wanting to send a data packet to **D**, first transmits an RTS packet to **D**. This is transmitted on all antennas of **S**, as it does not know the direction of **D** at the start. If **D** was in standby and receives the RTS packet correctly, it responds by transmitting a CTS packet, again on all directions (antennas). However, **D** notes the direction from which it receieved the RTS packet by noting the antenna that received the *maximum power* of the RTS packet (antenna 2

in the figure). Similarly **S** estimates the direction of **D** while receiving the CTS packet, and if the RTS–CTS handshake is performed successfully, proceeds to transmit the data packet on the antenna facing **D** (antenna 4). All the neighbors of **S** and **D** who hear the RTS-CTS dialog, use this information to prevent interfering with the ongoing data transmission.

We now describe the details of the MAC protocol that is executed while transmitting a data packet from a "data source node" (DSN) to a "data destination node" (DDN). Other neighboring nodes who can correctly receive their RTS and CTS packets will be designated as "other listening node"s (OLN). We first describe the "defer and transmit" process that is used in the protocol (similar to IEEE 802.11):

**Defer and transmit:**

1. Each node monitors the medium continuously, whenever it is not transmitting. It detects whether the total received signal strength (TRSS) is above or below its sensing threshold (ST). If the TRSS is below the ST, the node remembers the time at which the TRSS dropped low.

2. At the start of a protocol cycle, i.e., when a packet arrives at the MAC layer for transmission:

    (a) If the TRSS is above ST, the node waits until the TRSS goes below ST. Then it waits for a period called the Long Interframe Space (LongIFS), and it waits further for a random access backoff period before transmitting the packet. It is required that the channel remains IDLE during this period.

    (b) If the TRSS has gone below ST for less than LongIFS, the node waits for the remainder of the LongIFS period and then initiates a backoff delay as in (a).

    (c) If TRSS has been below ST for atleast LongIFS, the node initiates transmission immediately without delay.

3. A backoff delay is canceled immediately if the TRSS goes above ST at any time during the backoff period. When the TRSS again goes below ST, an access retry counter is incremented, and a new LongIFS/backoff period is scheduled if the access retry count has not exceeded the specified limit.

4. If the TRSS stays below ST for the entire backoff period, the node initiates transmission.

The sequence of operations followed in the MAC protocol are as follows:

**Proposed MAC protocol:**

1. DSN: Defer and transmit an RTS packet on all $M$ antennas. Start a CTS time-out counter.

2. OLN: If an RTS packet addressed to another node is correctly received, begin an off-the-air (OTH) period of duration OTH-RTS[1]. During the OTH period, the node

will not transmit any packet. If an OTH period is already in force, extend as necessary.

3. DDN: If an RTS packet, addressed to itself, is correctly received, note the antenna which received the maximum power of the RTS signal, SOURCE-DIR. Wait a Short-IFS period, transmit a CTS packet on all $M$ antennas. Set the antenna SOURCE-DIR to *active* and all others *passive*, and wait for a data packet for a data packet time-out period.

4. OLN: If a CTS packet addressed to another node is correctly received, begin or extend a pre-existing OTH period of duration OTH-CTS[2].

5. DSN: If the CTS packet, addressed to itself, is correctly received within the CTS time-out window, note the antenna which received the maximum power of the RTS signal, DEST-DIR, and go to (7). Else, proceed.

6. DSN: Wait a LongIFS period and initiate a no-CTS backoff delay. At the end of the no-CTS backoff set the access retry counter to zero and begin (1) again.

7. DSN: Wait a ShortIFS period, set the antenna DEST-DIR to *active* and all others to *passive*, and transmit the data packet. Wait for LongIFS after end of transmission and set all antennas to *active*.

8. DDN: If data packet reception has not begun within the data packet time-out window, set all antennas to *active* and resume processing any packet held or queued at this node or resume the standby mode. If data packet reception has started, set all antennas to *active* at the end of reception and resume processing any packet held or queued at this node or resume the standby mode.

9. OLN: At the expiration of the OTH period, initiate the protocol cycle for any packet either held or queued for transmission at this node; or resume standby mode.

## 4 SIMULATION MODEL

To evaluate the performance of the proposed MAC protocol, we use an event driven simulator which contains details of an indoor radio propagation model, multipath fading, and parameterized radio receiver characteristics. The IEEE 802.11 MAC layer specifications, along with the modifications for implementing the directional antenna based MAC protocol as described in the last section, are included in the program. The simulator assumes a network consisting of $n^2$ stationary wireless nodes that are initially placed in a $n \times n$ square grid. The transmitter power, the receiver sensivity for carrier sensing, the minimum signal-to-interference (SIR) required at the reciver to correctly detect a signal, and the grid spacing, are parameters specified by the user. Following the radio propagation model, the path loss is varied according to a piecewise log-log function. This implies that the dB path loss varies linearly for each of a sequence of linear ranges of distances from a transmitter. The slope for the path loss line

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[1] The OTH-RTS is computed based on the total time needed to complete the full protocol cycle of CTS and data packet transmissions

[2] The OTH-CTS is computed based on the total time needed to complete the protocol cycle of data packet transmission

for each linear range decreases with increasing distance from the transmitter. Multpath fading is simulated by generating a seperate random loss component for each packet. This fading loss is independent for every packet and is modeled as a Rayleigh distributed random variable.

We assume that the nodes move randomly within the sqaure area of the network following a mobility model similar to that used in [12, 2]. According to this model, every node moves to a new position in the network after a random interval of time. The new location of a node for every movement is computed based on an user-defined speed of movement, the random time interval elapsed since the last move, and a random direction of movement. For every movement, a new direction is chosen that is different from the last direction of movement of that node by a random value uniformly distributed within $[-10^o, +10^o]$. The time interval between successive movements of a node is modeled as an exponential random variable. All nodes move independently of one another. A node tending to move out of the square network area is "bounced back" so that the total number of nodes is maintained constant in the network area.

Whenever a packet transmission is initiated, the powers of the signal received at all the nodes located within the span of the transmitter's *active* directional antennas are computed. Only those nodes whose *active* antenna(s) are directed towards the source of transmission receive this signal. For every source-destination pair, the power of the signal received by the destination from the source is calculated separately as the *desired* signal strength. The sum of the signal powers received from all other transmissions received at that time constitute the interference for that pair. The radio signal distribution at all nodes are updated at the following epochs: (a) at the commencement or end of transmission of a packet, and (b) after every node movement. If the calculated SIR at the receiver is found to be above the minimum required threshold for the entire packet duration, the packet is assumed to be received correctly. Packet count statistics are reported after the simulation is run for a certain period of time.

## 5  SIMULATION RESULTS

We first evaluate the throughput performance of a 225 node ad hoc network where the nodes are initially assumed to lie on a $15 \times 15$ uniform grid. Some of the important and fixed parameters used for our simulations are shown in Table 1. With these parameters, a transmitter can reach all nodes who are located within the angular span of its *active* antenna upto a maximum distance of 400 m. For evaluating the average throughput in the entire network, we simulate new packet arrivals at every node according to independent but identical Poisson processes. For every new packet that is generated at a node, a destination is chosen at random from the set of its "reachable" neighbors. Since the MAC protocol is concerned with data transmissions between neighboring nodes only, this scenario captures the average hop-wise packet transmission behaviour in an ad hoc network where several independent multihop conversations are taking place. The variation of the total throughput of the network with the total offered load are shown in Fig. 4 for different values of $M$.. For the same
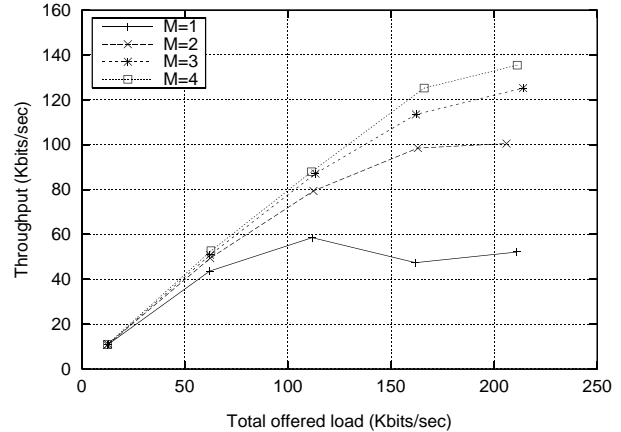


Figure 4: Throughputs of the proposed MAC protocol using different number of antennas for an ad hoc network of 225 nodes which are moving randomly with a speed of 3 m/s.

network and traffic conditions, the throughput is found to increase dramatically with $M$. The peak throughput nearly doubles when $180^o$ directional antennas ($M = 2$) are used in place of the omnidirectional ones. When the number of directional antennas per node are increased beyond 2, the incremental improvement of throughput is less pronounced.

Table 1: Parameter values used in simulations

| Parameter | Values used |
|---|---|
| Grid size | 200 m |
| Transmitter power | 50 dBm |
| Carrier sense threshold (ST) | -70 dBm |
| Noise floor | -90 dBm |
| Minimum SIR | 20 dB |
| Packet size | 1000 bytes |
| Node speed | 10 m/s |
| Total bandwidth | 1 Mb/sec |

We next evaluate the effect of mobility on the proposed protocol, which is not captured in Fig. 4. A concern with this protocol is that the RTS/CTS dialog may not be able to capture the quickly changing directions that occur with faster node movements. This might lead to unsuccessful transmission of the data packet even after a successful RTS/CTS dialog. In Fig. 5, the net throughput of the proposed protocol with different values of $M$ are plotted against the speed of node movements. The same offered load of 200 Kb/s is used for all the simulation runs. The results indicate a small drop in the throughput obtained with directional antennas with increasing values of speed of movement. Using higher values of the speed did not cause any appreciable degradation of throughputs in our simulations. However, we note that the mobility model used in our simulations allow nodes to change positions at discrete intervals of time, which is not correctly resemble the real life situation. Reducing the interval between successive node movements is prohibitive beyond a certain point, due to limitations in available computational power.
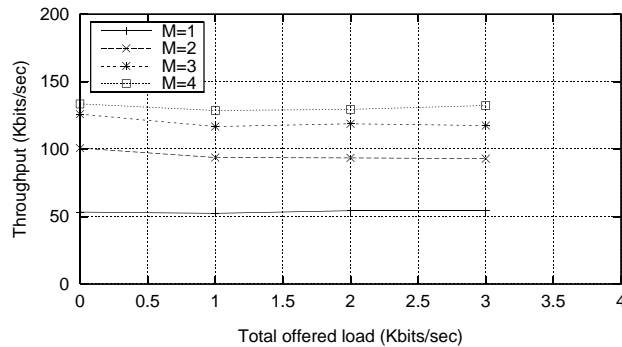
Figure 5: Variation of the net throughput of the 225 node mobile ad hoc network with speed of node movement.

## 6 Conclusion

The MAC protocol presented in this paper proposes a simple yet effective scheme for using directional antennas in ad hoc networks. The protocol uses a variation of the RTS/CTS exchange to let both the source and the destination nodes determine each other's directions. The data packets are sent using directional antennas, which improves the throughput performance in the network. Simulation experiments indicate that by using the proposed protocol with 4 directional antennas per node, the average throughput in the network can be improved upto 2 to 3 times over that obtained by using the CSMA/CA with RTS/CTS exchange protocol with traditional omnidirectional antennas.

We expect the performance of the proposed protocol to degrade with increased node mobility. However, our simulations indicate negligible effects for speeds upto 3 m/s. Results for higher node speeds may be more accurately captured by using an experimental setup.

References

[1] J. Broch, D. A. Maltz, D. B. Johnson, Y-C. Hu, and J. Jetcheva, "A performance comparison of multi-hop wireless ad hoc network routing protocols", *Proc. of ACM MOBICOM'98 Conf.*, October 1998.

[2] R. Castaneda and S.R. Das, "Query localization techniques for on-demand routing protocols in ad hoc networks", *Proc. of ACM MOBICOM'98 Conf.*, pages 186-1941999.

[3] Jing Deng and Zygmunt J. Haas, "Dual busy tone multiple access (DBTMA): A new medium access control for packet radio networks", *Proc. of IEEE ICUPS'98*, October 1998.

[4] IEEE Standards Department, Wireless LAN medium access control (MAC) and physical layer (PHY) specifications, IEEE standard 802.11–1997, 1997.

[5] R. Garces and J. J. Garcia-Luna-Aceves, "Floor acquisition multiple access with collision resolution", *Proc. ACM MOBICOM'96 Conf. Conf.*, pages 10–12, November 1996.

[6] R. Garces and J. J. Garcia-Luna-Aceves, "Collision avoidance and resolution multiple access with transmission queues", *ACM Wireless Networks Journal*, 1998.

[7] M. Horneffer and D. Plassman, "Directed antennas in the mobile broadband system", *Proc. of IEEE INFOCOM'96*, pages 704–712, 1996.

[8] K. W. Hung and T. S. Yum, "The multi-tone multi-access protocol with collision detection for multihop packet radio networks with multiple directional antenna stations", *Proc. of IEEE Int. Conf. Communications*, June 1986.

[9] P. Karn, "MACA: A new channel access method for packet radio", *Proc. of ARRL/CRRL Amateur Radio $9^{th}$ Computer Networking Conf.*, 1990.

[10] L. Kleinrock and F. A. Tobagi, "Packet switching in radio channels: Part–I - carrier sense multiple access modes and their throughput-delay characteristics", *IEEE Transactions in Communications*, COM-23(12):1400–1416, 1975.

[11] Y. B. Ko, V. Shankarkumar, and N. H. Vaidya, "Medium access control protocols using directional antennas in ad hoc networks", *Proc. of IEEE INFOCOM'2000*, Mar. 2000.

[12] Asis Nasipuri, Robert Castaneda, and Samir R. Das, "Performance of multipath routing for on-demand protocols in mobile ad hoc networks" (in press), *ACM/Baltzer Mobile Networks and Applications Journal*.

[13] Asis Nasipuri and Samir R. Das, "Multichannel CSMA with signal power-based channel selection for multihop wireless networks" (to appear), *Proc. IEEE Fall Vehicular Technology Conference*, Sept. 2000.

[14] F. A. Tobagi and L. Kleinrock, "Packet switching in radio channels: Part–II - the hidden terminal problem in carrier sense multiple-access and the busy-tone solution", *IEEE Transactions in Communications*, COM-23(12):1417–1433, 1975.

[15] T.-S. Yum and K.-W. Hung, "Design algorithms for multihop packet radio networks with multiple directional antennas stations", *IEEE Transactions on Communications*, 40(11):1716–1724, 1992.

[16] J. Zander, "Slotted ALOHA multihop packet radio networks with directional antennas", *Electronics Letters*, 26(25), 1990.