Resource Allocation in Wireless Networks Using Directional Antennas

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***Abstract*— With the continued increase of speed and capacities of computing devices and the growing needs of people for mobile computing capabilities, Mobile ad hoc networks (MANETs) have gained a lot of interest from the research community. Quality of service (QoS) provisioning in MANETs is an essential component that is needed to support multimedia and real-time applications. On the other hand, directional antenna technology provides the capability for considerable increase in spatial reuse which is essential in the wireless medium. In this paper, a bandwidth reservation protocol for QoS routing in TDMA-based MANETs using directional antennas is presented. The routing algorithm allows a source node to reserve a path to a particular destination with the needed bandwidth which is represented by the number of slots in the data phase of the TDMA frame. Further optimizations to improve the efficiency and resource utilization of the network are provided.**

Keywords: Mobile ad hoc networks (MANETs), quality of service (QoS), routing, time division multiple access (TDMA), directional antennas.

I. INTRODUCTION

Spatial reuse is a very important factor in wireless networks. In order to communicate with another node in a particular location, an node that is transmitting using an omnidirectional antenna radiates its power equally in all directions. This prevents other nodes located in the area covered by the transmission from using the medium simultaneously. Directional antennas allow a transmitting node to focus its antenna in a particular direction. Similarly, a receiving node can focus its antenna in a particular direction, which leads to increased sensitivity in that direction and significantly reducing multi-path effects and co-channel interference (CCI). This allows directional antennas to accomplish two objectives: (1) Power saving: a smaller amount of power can be used to cover the same desired range. (2) Spacial reuse: since transmission is focused in a particular direction, the surrounding area in the other directions can still be used by other nodes to communicate. (3) Shorter routes (in number of hops): this is due to the longer range achieved by using the same transmission power as omnidirectional antennas. (4) Smaller end-to-end delay: this is due to shorter routes [1][4][14][21][23]. These factors provide a network whose nodes use directional antennas with the ability to reduce unintended interference, and increase network efficiency and communication capacity.

There are different models that are presented in the literature for directional antennas [20]. An antenna array generally provides an increased antenna gain against multi-path fading. A constant signal gain can be maintained in a particular direction and the nulls can be adjusted toward the source of interference to reject CCI. Consequently, the communication capacity, coverage and quality of the wireless system can be considerably increased. Different models for directional antennas exist in the literature. In this paper, the multi-beam adaptive array (MBAA) system is used [1]. It is capable of forming multiple beams for simultaneous transmissions or receptions of different data messages.

Medium Access Protocols (MAC) protocols for directional antenna systems can be classified into two categories: on-demand and scheduled. In the on-demand scheme nodes must exchange short signals to establish a communication session. Usually, the omnidirectional mode is used during this short exchange, which establishes node intentions to communicate and angular positions. Channel access protocols based on slotted ALOHA for directional antennas with single and multiple beam forming capabilities are presented in in [26], and [25] respectively. Data message transmission is done using the omnidirectional mode, and reception is done using the directional mode. Signal detection and beam orientation at the receiver are accomplished through the addition of a special preamble to each data packet. Another scheme is used by Ko [10] and Nasipuri [16], in which the carrier sense multiple access with collision avoidance (CSMA/CA) approach is used. Directional antennas are used to transmit request-to-send (RTS) and receive clear-to-send (CTS) signals while the receiver antenna remains in the omnidirectional mode during this exchange. In [16], communicating pairs are set up using the multi-beam forming ability of directional antennas. Through cashing of the angle of arrival (AoA), Takai

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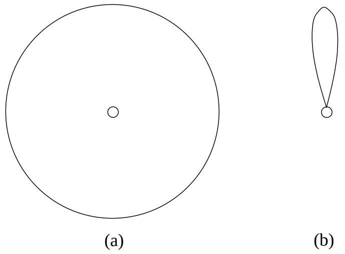


Fig. 1. (a) Transmission pattern of an omnidirectional antenna. (b) Transmission pattern of a directional antenna.

[24] avoided the use of the omnidirectional mode, which is only used when the AoA information is not available.

Scheduled access schemes negotiate a set of timetables that allow node pairs to communicate with each other. Many schemes that use this approach rely on the omnidirectional mode to exchange directional antenna transmission schedules. The computation of such schedules given the complete topology of the network is NP-complete [5][6][22]. Ramanathan [19] presented a heuristic framework, named UxDMA, for time, frequency, or code division multiple access channel assignment. A drawback in this approach is the collection of the complete topology of the network and distribution of the schedules, which limits scalability.

The remainder of the paper is organized as follows. Section 2 provides a discussion of related work. Section 3 presents the assumptions and definitions used in the protocol. Section 4 presents protocol. Section 5 presents simulation results. The paper concludes with the conclusions and future research section.

II. RELATED WORK

Bao et al [1] propose a Receiver-Oriented Multiple Access (ROMA) protocol, for networks using MBAA-antennas in a TDMA environment. ROMA uses the neighbor-aware contention resolution algorithm (NCR) in [2]. Transmission and reception are done using directional antennas. In ROMA, nodes contend for shared resources (transmission slots in this case) and contention resolution is done based on the context number (slot number in this case) and node identifier. Nodes with the highest priorities among their contenders are elected to access the resource, or transmission slot, without conflict. The neighbor protocol in ROMA is used for topology maintenance which includes 2-hop topology information for each node and detection of neighbors. This is accomplished by employing short signals that use the omnidirectional mode of the antenna. ROMA is a distributed algorithm that allows the nodes to calculate their channel access schedules based on their 2-hop topology information. ROMA evenly splits nodes in the network into transmitters and receivers which are paired together to establish communication.

In [7] and [9], Jawhar and Wu present a race-free routing protocol for QoS support in TDMA-based MANETs. The protocol allows a source node to find and reserve a QoS path with a certain required bandwidth (which is translated into number of data slots) to a desired destination node. In this paper, the protocol is extended to allow the path reservation scheme to work in TDMA-based MANETs, where the nodes are equipped with directional MBAA-antennas.

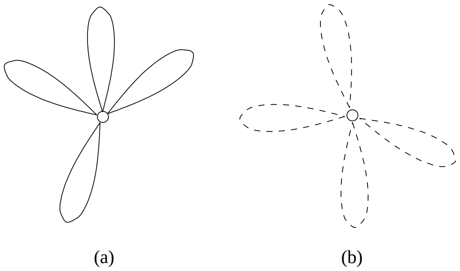


Fig. 2. Transmission pattern of an MBAA antenna system with k=4 beams. Each of the k beams can be oriented in a different desired direction. The figure shows: (a) Beams in transmission mode. (b) Beams in reception mode.

III. DIRECTIONAL ANTENNA SYSTEM ASSUMPTIONS AND DEFINITIONS

In this paper, it is assumed that each node in the network is equipped with an MBAA-antenna system. Each antenna is capable of transmitting or receiving using any one of k beams which can be directed towards the node with which communication is desired. In order for node x to transmit to a node y, node x directs one of its k antennas to transmit in the direction of node y, and node y in turn directs one of its k antennas to receive from the direction of node x.

Radio signals transmitted by omnidirectional antennas propagate equally in all directions. On the other hand, directional antennas install multiple antenna elements so that individual omnidirectional RF radiations from these antenna elements interfere with each other in a constructive or destructive manner. This causes the signal strength to increase in one or multiple directions. The increase of the signal strength in a desired direction and the lack of it in other directions is modelled as a lobe. The angle of the directions, relative to the center of the antenna pattern, where the radiated power drops to one-half the maximum value of the lobe is defined as the antenna beamwidth, denoted by β [1]. With the advancement of silicon and DSP technologies, DSP modules in directional antenna systems can form several antenna patterns in different desired directions (for transmission or reception) simultaneously. Figure 1(a) shows the transmission patterns of an omnidirectional antenna. Figure 1(b) shows the transmission pattern of a directional antenna.

In the MANET environment considered in this paper, each node is equipped with an MBAA antenna that is capable of receiving and transmitting one or more packets simultaneously by pointing the antenna beams toward the nodes with which it is communicating, while annulling all other undesired directions. The antenna system can transmit or receive data at a time but cannot do both simultaneously.

It is assumed that the an MBAA antenna is capable of broadcast that covers a transmission range that is similar to that of the directional mode by adjusting the beam width or by using the omnidirectional mode of the antenna at a lower frequency band. This broadcast capability can be used

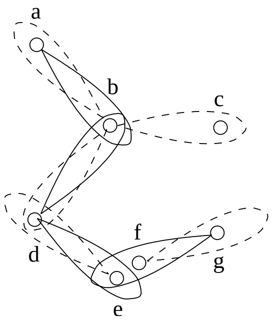


Fig. 3. An example showing nodes communicating using directional antennas.

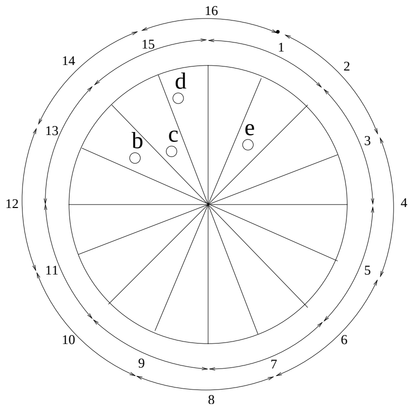


Fig. 4. The horizon as seen by a node. The figure includes 16 segments and 16 angular groups.

for control information communication as well as neighbor-direction findings. Preston [18] presented operation modes for the directional antennas for finding the coarse as well as the precise angular location of a single and multiple sources. In this paper, it is assumed that an MBAA antenna system is capable of detecting the precise angular position of a single source for locating and tracking neighbor nodes. Figure 2 shows a node equipped with an MBAA antenna array with k=4 beams. Each of the k beams is able to be oriented in a different desired direction. Figure 2(a) shows the antenna array in the transmission mode, and Figure 2(b) shows the antenna array in the reception mode.

Two nodes x and y are considered 1-hop neighbors if they are within each other's directional range. In order for a node x to successfully transmit data to one of its 1-hop neighbor nodes, y, x must orient one of its transmitting beams in the direction of y, and y must orient one of its reception beams in the direction of x. Figure 3 shows a group of nodes communicating using MBAA directional antennas. In the figure, node d is transmitting to both b and e simultaneously using two different directional antenna beams. Also, node b is receiving from a and d simultaneously. Node g is transmitting to f. Note that even though node g's transmission to f covers e, e does not have one of its receiving beams oriented towards g, and subsequently will not receive the data being transmitted to f.

Each node x maintains information about the angular location (direction) of each of its 1-hop and 2-hop neighbors [1]. For simplicity, the nodes are assumed to be placed on a flat plane. As illustrated in Figure 4, the horizon of each node is divided into $360°/(\beta/2) = 720°/\beta$ segments, and every two continuous segments define one group. A segment corresponds to the minimum angular separation of two neighbors in order to receive two separate antenna beams without interference. Therefore, there exists $720°/\beta$ groups. Each 1-hop neighbor y of x belongs to two groups that overlap at y. A_x^y denotes the set of angular groups to which belongs the 1-hop neighbor y of x. Two nodes y and z are considered in the same angular direction with respect to a third node x if and only if $A_x^y \cap A_x^z \neq \phi$. As an example, consider the nodes in Figure 4, where the horizon with respect to a node a is shown. According to the definition stated earlier, the set of angular groups for links (a,b), (a,c), (a,d) and (a,e) are $A_a^b = \{13, 14\}, A_a^c = \{14, 15\}$, $A_a^d = \{15, 16\}$, $A_a^e = \{1, 2\}$. Therefore, nodes b and c are considered in the same angular direction with respect to node a because $A_a^b \cap A_a^c = \{14\} \neq \phi$. Similarly, nodes c and d are considered in the same angular direction. However, nodes b and d, for example, are not in the same angular direction, since $A_a^b \cap A_a^d = \phi$.

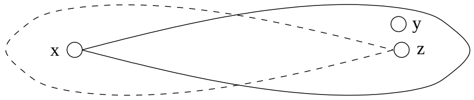


Fig. 5. Illustration of allocation rule 2.

IV. OUR POROTOCOL

The networking environment that is assumed in this paper is TDMA where a single channel is used to communicate between nodes. The TDMA frame is composed of a control phase and a data phase [3][12]. Each node in the network has a designated control time slot, which it uses to transmit its control information. However, the different nodes in the network must compete for the use of the data time slots in the data phase of the frame.

Liao and Tseng [11] show the challenge of transmitting and receiving in a TDMA single channel omnidirectional antenna environment, which is non-trivial. In this section, the slot allocation rules for the TDMA directional antenna environment are presented. The hidden and exposed terminal problems make each node's allocation of slots dependent on its 1-hop and 2-hop neighbor's current use of that slot. This will be explained in a detailed example later in this paper. The model used in this protocol is similar to that used in [7] and [11], but includes modifications to support directional antenna systems. Each node keeps track of the slot status information of its 1-hop and 2-hop neighbors. This is necessary in order to allocate slots in a way that does not violate the slot allocation conditions imposed by the nature of the wireless medium and to take the hidden and exposed terminal problems into consideration. Below are the slot allocation conditions.

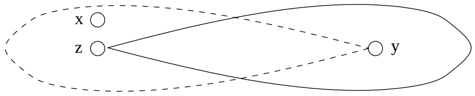


Fig. 6. Illustration of allocation rule 3.

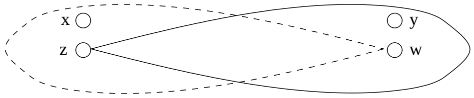


Fig. 7. Illustration of allocation rule 4.

A. Slot allocation conditions for directional antennas

A time slot t is considered free to be allocated to send data from a node x to a node y if the following conditions are true:

1) Slot t is not scheduled to receive in node x or scheduled to send in node y, by any of the antennas of either node (i.e. antennas of x must not be scheduled to receive and antennas of y must not be scheduled to transmit, in slot t).
2) Slot t is not scheduled for receiving in any node z, that is a 1-hop neighbor of x, from node x where y and z are not in the same angular direction with respect to x (i.e. $A_x^y \cap A_x^z \neq \phi$).
3) Slot t is not scheduled for receiving in node y from any node z, that is a 1-hop neighbor of x, where x and z are in the same angular direction with respect to y (i.e. $A_y^x \cap A_y^z \neq \phi$).
4) Slot t is not scheduled for communication (receiving or transmitting) between two nodes z and w, that are 1-hop neighbors of x, where w and y are in the same angular direction with respect to z (i.e. $A_z^w \cap A_z^y \neq \phi$), and x and z are in the same angular direction with respect to w (i.e. $A_w^x \cap A_w^z \neq \phi$).

In Figure 5, which illustrates allocation rule 2, node x cannot transmit to node y using slot t, because it is already using slot t to transmit to node z, which is in the same angular direction as node y. In Figure 6, which illustrates allocation rule 3, node x cannot allocate slot t for sending to node y because slot t is already scheduled for sending from node z, that is a 1-hop neighbor of x, and $A_y^x \cap A_y^z \neq \phi$. In Figure 7, which illustrates allocation rule 4, slot t cannot be allocated to send from x to y because it is already scheduled for communication between two nodes z and w, that are 1-hop neighbors of x, where $A_z^x \cap A_z^w \neq \phi$ and $A_x^y \cap A_x^z \neq \phi$.

B. The data structures

The proposed protocol is on-demand, source based and similar to DSR [17]. Its on-demand nature increases its efficiency, since control overhead traffic is only needed when data communication between nodes is desired.

Each node maintains and updates three tables, ST, RT and H. Considering a network with n nodes, and s data slots in the TDMA frame, in a node x, the tables are denoted by ST_x, RT_x and H_x. The tables contain the following information:

- $ST_x[1..n, 1..s]$: This is the send table which contains slot status information for the 1-hop and 2-hop neighbors. For a neighbor i and slot j, $ST_x[i,\ j]$, is a structure which has two fields: (1) *The state field*: It can have one of the following values representing three different states: 0 - for free, 1 - for allocated to send, 2 - for reserved to send. (2) *The angular groups field*: It contains k sets of angular groups (one for each antenna). The entry $A[a]_i^j$ denotes the set of angular groups to which the ath sending antenna is pointed. $A[a]_i^j = \phi$ is used to indicate that the ath antenna for neighbor i is not used during slot j.
- $RT_x[1..n, 1..s]$: This is the receive table which contains slot status information for the 1-hop and 2-hop neighbors. For a neighbor i and slot j, $RT_x[i,\ j]$, is a structure which has two fields: (1) *The state field*: It can have one of the following values representing three different states: 0 - for free, 1 - for allocated to receive, 2 - for reserved to receive. (2) *The angular groups field*: It contains k sets of angular groups. The entry $A[a]_i^j$ denotes the set of angular groups to which the ath receiving antenna is pointed. Also here, $A[a]_i^j = \phi$ is used to indicate that the ath antenna for neighbor i is not used during slot j.
- $H_x[1..n, 1..n]$: This table contains information about node x's 1-hop and 2-hop neighborhood. Each entry $Hx[i, j]$ is a structure, which has two fields: (1) *The neighbor field*: It contains a 1 if node i, which is 1-hop neighbor of node x, has node j as a neighbor, and contains a 0 otherwise. (2)*The angular group field*: A_i^j, which contains the set of angular groups to which node j belongs.

It is important to note at this point that in the following definitions and algorithms, the word “slot” implies a “slot in a particular direction using the associated antenna”. For example, each of the slot timers defined later in this paper is associated with a particular slot/antenna pair.

C. The QoS path reservation algorithm

When a node S wants to send data to a node D, with a bandwidth requirement of b slots, it initiates the QoS path discovery process. Node S determines if enough slots are available to send from itself to at least one of its 1-hop neighbors. If that is the case, it broadcasts a $QREQ$(S, D, id, b, x, $PATH$, NH) to all of its neighbors. The message contains the following fields:

- S, D and id: IDs of the source, destination and the session. The (S, D, id) triple is therefore unique for every QREQ message and is used to prevent looping.
- b: Number of slots required.
- x: The node ID of the host forwarding this message.
- $PATH$: A list of the form ((h_1, l_1), (h_2, l_2), ..., (h_k, l_k)). It contains the accumulated list of hosts and time slots, which have been allocated by this QREQ message so far. h_i is the ith host in the path, and l_i is the list of slots used by h_i to send to h_{i+1}. Each of the elements of l_i contains the slot number that would be used, along with the corresponding the set of angular groups, A_i^{i+1}, which

represents the direction in which the sending antenna of host i must be pointed, during that slot, to send data to host $i+1$.

- NH: A list of the form (($h_1^{'}$, $l_1^{'}$), ($h_2^{'}$, $l_2^{'}$), ..., ($h_k^{'}$, $l_k^{'}$)). It contains the next hop information. If node x is forwarding this QREQ message, then NH contains a list of the next hop host candidates. The couple ($h_i^{'}$, $l_i^{'}$) is the ID of the host, which can be a next hop in the path, along with a list of the slots, which can be used to send data from x to $h_i^{'}$. $l_i^{'}$ is a list of the slots to be used to send from host i to host $i+1$ along with the angular group for each slot. $l_i^{'}$ has the same format as l_i in PATH.
- $Max\_QREQ\_node\_wait\_time$, $Max\_QREQ\ \_tot\_wait\_\ time$, and $Max\_QREQ\_\ QREP\_\ tot\ \_wait\_time$: These are QREQ message wait timing constraints, which are specified by the application. Each timer will be discussed in more detail in a later section.

When an intermediate node receives the QREQ message, it composes the NH list, which includes its neighbors with which it has a link that contains at least b free slots in the corresponding direction. The message is then forwarded to these neighbors. If the QREQ message reaches the destination node D, then this means that a QoS path from S to D was discovered, and there were at least b free slots available to send data from each node to each subsequent node along this path. These slots are now marked as $allocated$ in the ST and RT tables of the corresponding nodes. Subsequently, node D unicasts a reply message, $QREP(S, D, id, b, PATH, NH)$, to node S. This message is propagated along the nodes indicated in $PATH$. As the QREP message travels back to the source node, all of the intermediate nodes along the allocated path must confirm the reservation of the corresponding allocated slots (i.e. change their status from $allocated$ to $reserved$). The timing and propagation of the QREQ and QREP messages are controlled by timers, a queueing process, and synchronous and asynchronous slot status broadcasts, which is discussed in detail later in the paper.

D. A detailed example of slot allocation at an intermediate node

Figure 8 and the corresponding table in Figure 9 provide an example of the slot allocation considerations at an intermediate node b. In the example, node b receives a QREQ message from node a and is determining to which of its 1-hop neighbors it can extend the QREQ message. The example illustrates the considerations for slots 1 and 2 of the TDMA frame. The portion of the allocation table for slots 1 and 2 at node b is shown in Figure 9. In this example, slot 1 is reserved to send from node a to node b and node p. Slot 1 is also reserved to send from node d to node q, and from node d to node b, simultaneously, for different QoS paths. These reservations of the same slot to send from the same node to multiple nodes, for different QoS paths, is not possible in an omnidirectional antenna system. This demonstrates the significant spacial reuse that can be achieved in the directional antenna environment. According to rule 1 of the slot allocation conditions, slot 1 cannot be allocated by node b to send to any of its neighbors on any of its antennas because this slot is already scheduled to receive by node b (from nodes a and d).

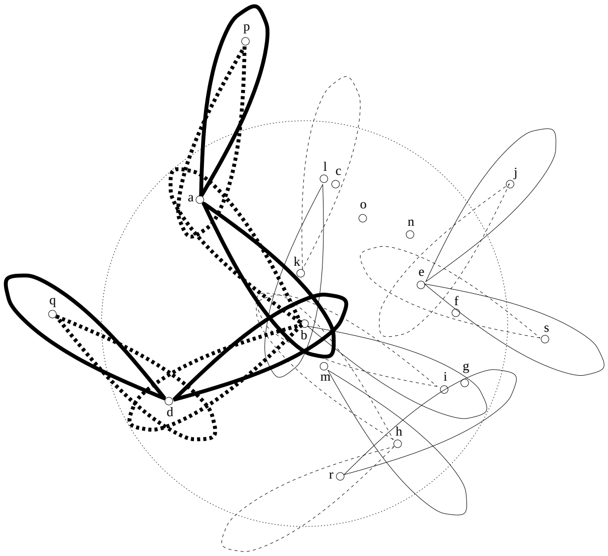


Fig. 8. A detailed example showing the allocation of slots 1 and 2 at node b. Bold cones show transmissions/receptions in slot 1 and plain cones show transmissions/receptions in slot 2. The circle indicates the directional range of node b.

Node	a		b		c		d		e		f		g		h		i	
Slot	S1	S2	S1	S2	S1	S2	S1	S2	S1	S2	S1	S2	S1	S2	S1	S2	S2	S2
S/R	S		R	S			S			S	S					R		R
A1	{4,5}		{12,13}	{5,6}			{1,2}			{1,16}	{1,16}					{13,14}		{8,9}
A2	{1,16}		{8,9}				{12,13}			{4,5}						{8,9}		

Node	k		l		m		n		o		p		q		r		s	
Slot	S1	S2	S1	S2	S1	S2	S1	S2	S1	S2	S1	S2	S1	S2	S1	S2	S1	S2
S/R		S		R		S						R	R			S		R
A1		{1,2}		{9,10}		{5,6}						{8,9}	{4,5}			{1,2}		{12,13}
A2																		

Fig. 9. The allocation table, which corresponds to the detailed example showing the allocation of slots 1 and 2 at node b.

Let's consider the possibility of allocating slot 2 to send from node b to each of its neighbors. According to rule 1, slot 2 cannot be allocated to send from b to i because it is already scheduled to send for another QoS path. Also, according to the same rule, slot 2 cannot be scheduled to send from node b to e because slot 2 is already scheduled to send by node e. Namely, it is scheduled to send from node e to nodes j and s for different QoS paths which is another illustration of the spacial reuse that is afforded to directional antenna systems.

According to rule 2 of the slot allocation conditions, node b cannot allocate slot 2 to send to node g because slot 2 is already scheduled to send from node b to node i, where $A_b^i \cap A_b^g \neq \phi$ (i.e. node i is in the same angular direction as node g with respect to node b). Also, according to rule 3, slot 2 cannot be allocated by node b to send to node h. This is because this slot is already scheduled to receive in node h from node m,

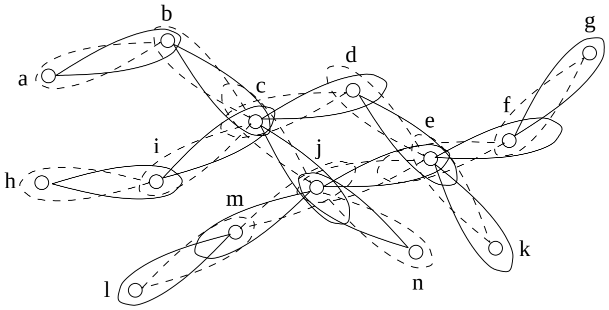


Fig. 10. An example showing three QoS paths: $abcdefg$, $hicjek$, and $njml$.

where $A_h^m \cap A_h^b \neq \phi$. Note that slot 2 is also scheduled by node h to receive from r on a different antenna without preventing the use of the same slot to send from node m to node h.

According to rule 4, slot 2 cannot be scheduled to to send from node b to c because it is already scheduled to send from l to k, where ($A_k^l \cap A_k^c \neq \phi$) and ($A_l^b \cap A_l^k \neq \phi$). According to the same rule, and because of the same reason, slot 2 cannot be scheduled to send from b to k or from b to l.

As a result, node b is able to allocate slot 2 to send to nodes f, n, and o.

E. An example of multiple QoS paths passing through common nodes

Figure 10 shows an example with three different reserved QoS paths: $abcdefg$ (path 1), $hicjek$ (path 2), and $njml$ (path 3). The three paths share several common nodes. Namely, nodes c and e are common between paths 1 and 2, and node j is common between paths 2 and 3. Due to the use of directional antenna systems, these common nodes are able to receive different data belonging to different paths from multiple directions in the same data slot without interference. Similarly they can transmit to different nodes belonging to different paths in different directions in the same data slot as well. This scenario is not possible in the omnidirectional antenna environment, and illustrates the potential increase of network throughput in MANETs using directional antennas.

F. Wait timers

We define the following timers, which control the allowable delay of the propagation of the QREQ and QREP messages through the system. These timers can be initialized to a tunable value which can vary according to the requirements of the application being used. It is also possible to disable some of these timers, which are specified below, if the application does not have such delay requirements.

TTL_allocated_slot_time. This is a soft state timer which times out the $allocated$ state of a slot to $free$ status if no reservation of this slot is done within this time. A large value for this timer corresponds to a conservative strategy. In that case, there is a lower probability of occurance of the racing conditions in slot allocation between multiple paths [9]. However, this comes at a price of lower slot utilization which can reduce throughput. An optimal value for this timer must be determined by simulation and according to the needs of the application involved.

Explicit deallocation message from the destination. In addition to the above soft allocation timer strategy, further performance improvement can be achieved by having an explicit deallocation message issued as a flood from the destination upon successful path acquisition. Nodes that are not a part of the acquired path can immediately deallocate slots that were allocated in the path discovery phase.

TTL_reserved_slot_time. When a slot is reserved (i.e. its allocation is confirmed and it is in $reserved$ status) for a particular QoS path, it must be used for actual data transmission within a certain time-out period which we define as the $TTL\_reserved\_slot\_time$. If at any time a slot is not used for data transmission for more than this time, it is returned to free status. This is done in the following manner. The associated timer is refreshed each time the slot is used for data transmission. The timer is constantly counted down. If this timer reaches zero at any time then the slot is returned back to $free$ status. This timing is also useful for a situation where the QREP message used to confirm slot reservation is successful in propagating from the destination through some nodes but then is not forwarded to the source. In this case, the nodes which already confirmed the reservation of their slots will still be able to return these slots back to free status after this time-out period.

Max_QREQ_node_wait_time. The QREQ can wait at an intermediate node for a maximum amount of time $Max\_QREQ\_node\_wait\_time$. This is a parameter that is set to a tunable value according to the application and network requirements and characteristics. A reasonable value can be equal to $2 * RTT$.

Max_QREQ_tot_wait_time. Another related delay type is the QREQ total wait time. This is the maximum allowable cumulative wait delay for the QREQ as it propagates through the network.

Max_QREQ_QREP_tot_wait_time. A third timer can be defined as $Max\_QREQ\_QREP\_tot\_wait\_time$. This is the total time for path acquisition ($QREQ\ propagation$ + $QREP\ propagation$).

G. Status broadcasting and updating

There are two types of node status broadcasts: synchronous (periodic) and asynchronous.

Synchronous periodic status updates. In order to maintain local connectivity and slot status information, each node broadcasts its slot allocation status (the ST and RT table information updates) to its 1-hop and 2-hop neighbors (i.e. with a 2-hop TTL). This broadcast is done periodically (synchronously) according to a predetermined periodic slot status update frequency. We define this as $periodic\_status\_update\_time$.

Asynchronous status updates. The status update is done asynchronously as the status of slots is changed from free to allocated, or from allocated to reserved. Note that the status updates are done with a 2-hop TTL flood to the 1-hop and 2-hop neighbors.

H. The main algorithm at an intermediate node

The protocol uses three states per slot to avoid any race conditions when multiple routes that pass through common nodes are being reserved at the same time. The possible race conditions and their remedies, which are similar for omnidirectional and directional antenna environments, are described in detail in [7].

When a node y receives a broadcasting message $QREQ(S, D, id, b, x, PATH,\ NH)$ initiated by a neighboring host x, it checks to determine whether it has received this same source routed request (uniquely identified by (S, D, id)) previously. If not, y performs the following steps. If y is not a host listed in NH then it exits this procedure. Otherwise, it calculates the values of the variables $ANUyz$, and Fyz, which are defined in the following manner:

- $ANUyz$: The number of slots that are allocated-not-usable for sending data from y to z. A slot is called ANU (allocated-not-usable) if there exists totally allocated reservations at y or its neighbors, which do not allow slot t to be used from y to send to z. This is due to pure allocations (not confirmed reservations) at y and/or its neighbors.
- Fyz: The number of slots that are free at a node y to send to a node z respectively.

Therefore, at node y, it is necessary to determine a separate set of $ANUyz$, and Fyz for each neighbor z of y. When a node y receives a QREQ message from a node x, it uses Algorithm 1 which is shown below to forward the message, or to insert it in the $QREQ\_pending\_queue$, or to drop it.

Algorithm 1 works in the following manner. When a QREQ message arrives at a node y from a node x, it does the following. The algorithm first updates the ST and RT tables with the information in PATH. Then, it calculates $ANUyz$, and Fyz from ST and RT tables.

Afterwards, the algorithm initializes the next hop list NH_temp to empty, and then attempts to build it by adding to this list each 1-hop neighbor z of y which has b slots free to send from y to z. The algorithm uses the select_slot function which allocates slots using the slot allocation rules and the information in the updated ST and RT tables and returns a list of these slots. There are three possible conditions that can take place.

If at least one neighbor z of y has b slots free to send from y to z, this is called $condition1$, then the NH_temp list will not remain empty and the node y will broadcast (i.e. forward) the QREQ message after incorporating the node x and the list li' (i.e. the list of slots used to send from x to y) PATH (using $PATH\_temp = PATH \mid (x, li')$). Here, | means concatenation.

Otherwise, if the NH_temp list is empty after checking all of the neighbors, then that means that there are no neighbors z of y which have b slots free to send from y to z according to the slot selection conditions. At this point, the algorithm tries to determine if there is any ”hope”, i.e., if there is at least one 1-hop neighbor z of y which has the condition $(Fyz + ANUyz) \geq b$. This would be $condition2$. In this case, the algorithm checks if the maximum time left for the required allocated slots to become free (or reserved) does not exceed the maximum total wait time left for this QREQ message ($Max\_QREQ\_tot\_wait\_time$), then this QREQ message is placed in the $QREQ\_pending\_queue$. This queue will be discussed in more detail later in this paper. If on the other hand, no 1-hop neighbor z of y has a condition of $(Fyz + ANUyz) \geq b$ then there is ”no hope” at the current time. Therefore, the QREQ message is dropped.

Algorithm 1 The main algorithm at an intermediate node

```
When a node $y$ receives a QREQ message
  Update the $ST$ and $RT$ tables with the information in PATH
  $NH\_temp = \phi$
  for each 1-hop neighbor node $z$ of $y$ do
    $ANUyz = calcA(z, ST, RT)$
    $Fyz = calcF(z, ST, RT)$
    if $Fyz \geq b$ then
      $L = select\_slot(y, z, b, ST, RT)$
      if $L \neq empty$ then
        $NH\_temp = NH\_temp(z, L) \mid (z, L)$
      else
        Error: cannot have $Fyz \geq b$ and $L = empty$
      end if
    end if
  end for
  if $NH\_temp \neq \phi$ then
    Let ($h_i^{'}$, $l_i^{'}$) be the entry in NH such that $h_i^{'}$=y
    let $PATH\_temp = PATH \mid (x, l_i^{'})$
    broadcast $QREQ(S, D, id, b, x, PATH\_temp, NH\_temp)$
    message
  else
    for each 1-hop neighbor node $z$ of $y$ do
      if $(Fyz + ANUyz) \geq b$ then
        let $t_{mas} = maximum\ time\ left\ for\ required\ allocated\ slots\ to\ become\ free\ (or\ reserved)$
        if $max\_QREQ\_tot\_wait\_time \geq t_{mas}$ then
          insert QREQ message in $QREQ\_pending\_queue$
          exit this procedure
        end if
      end if
    end for
  end if
```

I. The QREQ_pending_queue

The QREQ’s that are waiting for slots to become free are placed in a $QREQ\_pending\_queue$. While waiting for the status of the different slots in the table to change, some slots will be freed and others will be confirmed. Every time a change in slot status is done (due to timer expiration, or confirming a reservation), the queue is scanned.

Scanning the $QREQ\_pending\_queue$. Every time the queue is scanned, all QREQ messages, which have any of their corresponding wait timers expired, are deleted from the queue. For each QREQ in the queue, the new values for Fyz, $ANUyz$, and $NUyz$ are calculated, and it is determined under which conditions the new QREQ status falls. There are three possibilities: (1) $Fyz \geq b$: Forward the pending QREQ using Algorithm 2, and delete the QREQ from the queue. (2) $(Fyz + ANUyz) \geq b$: Leave the corresponding QREQ in the queue. (3) $(Fyz + ANUyz) < b$: Delete the corresponding QREQ from the $QREQ\_pending\_queue$.

Algorithm 2 Forwarding the QREQ message from the $QREQ\_pending\_queue$

```
$NH\_temp = \phi$
for every 1-hop neighbor $z$ of $y$ do
  $L = select\_slot(y, z, b, ST, RT)$
  if $L \neq \phi$ then
    $NH\_temp = NH\_temp \mid (z, L)$
  end if
end for
if $NH\_temp \neq \phi$ then
  let $(h_i^{'}, l_i^{'})$ be the entry in NH such that $h_i^{'}$=y
  let $PATH\_temp = PATH \mid (x, l_i^{'})$
  broadcast $QREQ(S, D, id, b,$y$, PATH\_temp, NH\_temp)$
  delete QREQ message from the $QREQ\_pending\_queue$
end if
```

TABLE I

PARAMETERS FOR THE DIRECTIONAL ANTENNA PROTOCOL SIMULATION

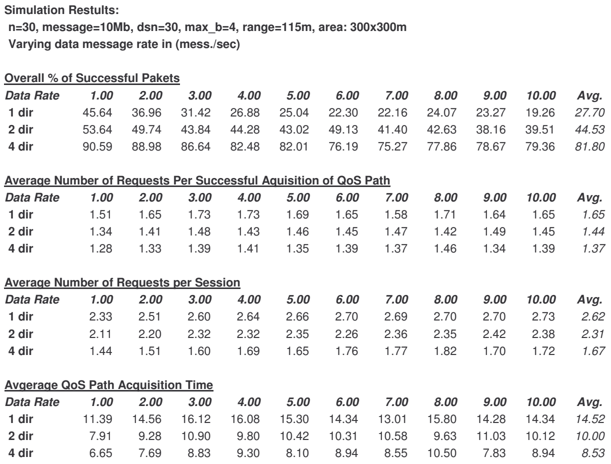
Parameter	**Value**
Network Area	$300 \times 300\ m^2$
Number of Nodes	30
Transmission Range	115 m
Bandwidth	2 Mb/s
Data Packet Size	512 bytes
Number of Data Slots	30
Number of Sessions	20
Average Message Length	100 MB
MAX_SLOT_RES_TIME	10980 ms
MAX_SLOT_ALLOC_TIME	1350 ms
MAX_B	4 slots

V. PERFORMANCE ANALYSIS

In order to verify, and analyze the performance of the presented protocol, simulation experiments were conducted.

A. Simulation

Basically the simulator starts by generating an area with certain dimensions and randomly places a predetermined number of nodes in the area. The nodes have a certain transmission range. From the placement of the nodes and their range a graph is generated. Then the simulator generates a number of data messages with a certain length for each message (different distributions can be used). Each message has a random source and destination pair. The arrival times of the messages is according to a Poisson process with a certain mean inter-arrival time. When the data message is processed by the source, it generates a QREQ message to discover a QoS path to the corresponding destination. The QREQ message is propagated through the nodes according to the proposed algorithm. Each node has a routing table as well as all of the tables needed for the algorithm (ST, RT, H, routing table, all of the required slot data structures, etc.). When the source receives the QREP message, it starts data transmission. The simulations are done for three different cases: (1) 1 antenna representing the omnidirectional antenna case (dir = 1, angle of coverage = $360°$), (2) 2 antennas (dir = 2, angle of coverage = $180°$ per antenna). (3) 4 directional antennas (dir = 4, angle of coverage = $90°$ per antenna).



Simulation Restults:
n=30, message=10Mb, dsn=30, max_b=4, range=115m, area: 300x300m
Varying data message rate in (mess./sec)

Overall % of Successful Pakets

Data Rate	***1.00***	***2.00***	***3.00***	***4.00***	***5.00***	***6.00***	***7.00***	***8.00***	***9.00***	***10.00***	***Avg.***
1 dir	45.64	36.96	31.42	26.88	25.04	22.30	22.16	24.07	23.27	19.26	*27.70*
2 dir	53.64	49.74	43.84	44.28	43.02	49.13	41.40	42.63	38.16	39.51	*44.53*
4 dir	90.59	88.98	86.64	82.48	82.01	76.19	75.27	77.86	78.67	79.36	*81.80*

Average Number of Requests Per Successful Aquisition of QoS Path

Data Rate	***1.00***	***2.00***	***3.00***	***4.00***	***5.00***	***6.00***	***7.00***	***8.00***	***9.00***	***10.00***	***Avg.***
1 dir	1.51	1.65	1.73	1.73	1.69	1.65	1.58	1.71	1.64	1.65	*1.65*
2 dir	1.34	1.41	1.48	1.43	1.46	1.45	1.47	1.42	1.49	1.45	*1.44*
4 dir	1.28	1.33	1.39	1.41	1.35	1.39	1.37	1.46	1.34	1.39	*1.37*

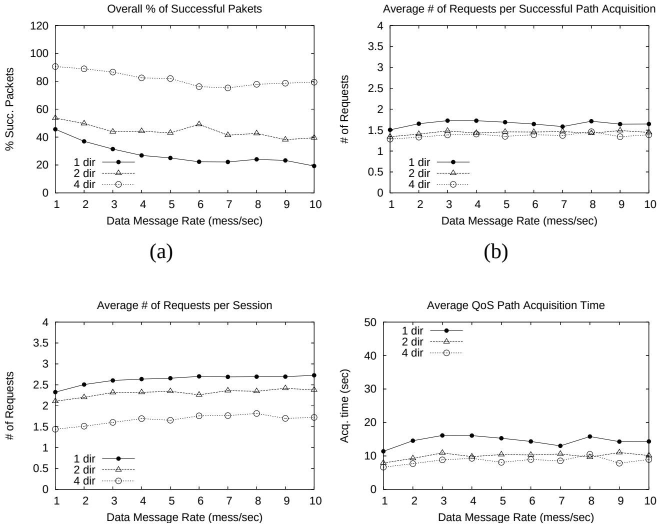
Average Number of Requests per Session

Data Rate	***1.00***	***2.00***	***3.00***	***4.00***	***5.00***	***6.00***	***7.00***	***8.00***	***9.00***	***10.00***	***Avg.***
1 dir	2.33	2.51	2.60	2.64	2.66	2.70	2.69	2.70	2.70	2.73	*2.62*
2 dir	2.11	2.20	2.32	2.32	2.35	2.26	2.36	2.35	2.42	2.38	*2.31*
4 dir	1.44	1.51	1.60	1.69	1.65	1.76	1.77	1.82	1.70	1.72	*1.67*

Avgerage QoS Path Acquisition Time

Data Rate	***1.00***	***2.00***	***3.00***	***4.00***	***5.00***	***6.00***	***7.00***	***8.00***	***9.00***	***10.00***	***Avg.***
1 dir	11.39	14.56	16.12	16.08	15.30	14.34	13.01	15.80	14.28	14.34	*14.52*
2 dir	7.91	9.28	10.90	9.80	10.42	10.31	10.58	9.63	11.03	10.12	*10.00*
4 dir	6.65	7.69	8.83	9.30	8.10	8.94	8.55	10.50	7.83	8.94	*8.53*

Fig. 11. Simulation results table. Data message length: 10MB



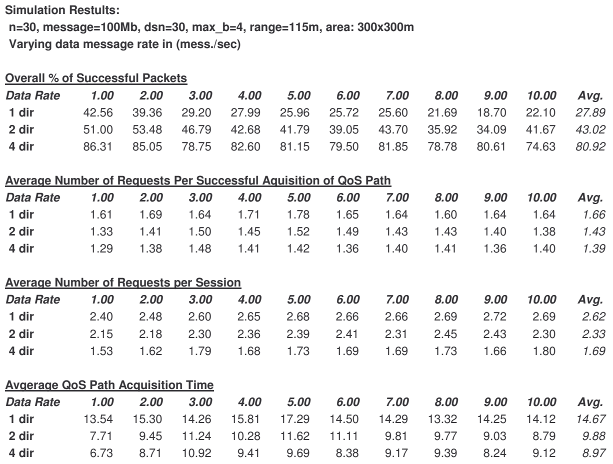
(a) (b)

(c) (d)

Fig. 12. Simulation results. Data message length: 10MB

B. Simulation parameters

A set of simulation experiments were performed. Table I shows a sample of the simulation parameters used in the experiments. The results for two sets of experiments are shown. Figures 11, and 12 contain the results for the first set of experiments, and figures 13, and 14 contain the results for the second set of experiments. The number of nodes (n) is 30 in an area of 300x300 m^2. The total number of data slots in the frame (dsn) is 30. The number of slots required for each session is a random number with a uniform distribution and a range from 1 to 4 slots (1 to max_b). The range of each node was 115 m. The session (or data message) arrival is a Poisson process with a mean which was varied from 1 to 10 messages/sec. The message length is randomly selected according to a uniform distribution with a range from 0 to 10 Mbytes for the first set of experiments, and from 0 to 100



Simulation Restults:
n=30, message=100Mb, dsn=30, max_b=4, range=115m, area: 300x300m
Varying data message rate in (mess./sec)

Overall % of Successful Packets

Data Rate	*1.00*	*2.00*	*3.00*	*4.00*	*5.00*	*6.00*	*7.00*	*8.00*	*9.00*	*10.00*	*Avg.*
1 dir	42.56	39.36	29.20	27.99	25.96	25.72	25.60	21.69	18.70	22.10	*27.89*
2 dir	51.00	53.48	46.79	42.68	41.79	39.05	43.70	35.92	34.09	41.67	*43.02*
4 dir	86.31	85.05	78.75	82.60	81.15	79.50	81.85	78.78	80.61	74.63	*80.92*

Average Number of Requests Per Successful Aquisition of QoS Path

Data Rate	*1.00*	*2.00*	*3.00*	*4.00*	*5.00*	*6.00*	*7.00*	*8.00*	*9.00*	*10.00*	*Avg.*
1 dir	1.61	1.69	1.64	1.71	1.78	1.65	1.64	1.60	1.64	1.64	*1.66*
2 dir	1.33	1.41	1.50	1.45	1.52	1.49	1.43	1.43	1.40	1.38	*1.43*
4 dir	1.29	1.38	1.48	1.41	1.42	1.36	1.40	1.41	1.36	1.40	*1.39*

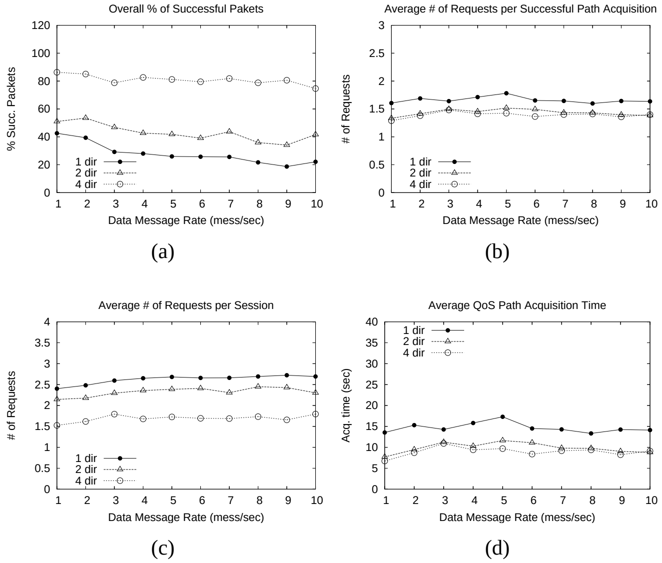
Average Number of Requests per Session

Data Rate	*1.00*	*2.00*	*3.00*	*4.00*	*5.00*	*6.00*	*7.00*	*8.00*	*9.00*	*10.00*	*Avg.*
1 dir	2.40	2.48	2.60	2.65	2.68	2.66	2.66	2.69	2.72	2.69	*2.62*
2 dir	2.15	2.18	2.30	2.36	2.39	2.41	2.31	2.45	2.43	2.30	*2.33*
4 dir	1.53	1.62	1.79	1.68	1.73	1.69	1.69	1.73	1.66	1.80	*1.69*

Avgerage QoS Path Acquisition Time

Data Rate	*1.00*	*2.00*	*3.00*	*4.00*	*5.00*	*6.00*	*7.00*	*8.00*	*9.00*	*10.00*	*Avg.*
1 dir	13.54	15.30	14.26	15.81	17.29	14.50	14.29	13.32	14.25	14.12	*14.67*
2 dir	7.71	9.45	11.24	10.28	11.62	11.11	9.81	9.77	9.03	8.79	*9.88*
4 dir	6.73	8.71	10.92	9.41	9.69	8.38	9.17	9.39	8.24	9.12	*8.97*

Fig. 13. Simulation results table. Data message length: 100MB



(a) (b)

(c) (d)

Fig. 14. Simulation results. Data message length: 100MB

Mbytes for the second set of experiments.

C. Simulation results and analysis

Several performance measures were computed as the traffic rate (messages/second) is varied. The measured parameters are the overall percentage of packets received successfully, the average number of requests per successful acquisition of QoS path, the average number of requests per session, and the average QoS path acquisition time.

In both sets of experiments, it can be observed that the average overall percentage of successfully received packets drops as the traffic rate is increased. Also, as expected by the theoretical analysis, this percentage is consistently the smallest in the omnidirectional case (dir = 1). For example, in the first set of experiments presented in the table in Figure 11, the overall percentage of successfully received packets ranges from 45.64 for a mean traffic rate of 1 messages/sec down to 27.70 for a mean traffic rate of 10 messages/sec. This percentage is higher with the two-antenna case and ranges from 53.69 down to 44.53. The highest percentage is obtained in the four-antenna case which ranges from 90.59 down to 81.80. Also, as expected by the theory, the simulation shows that the average number of requests per successful acquisition of a QoS path, the total number of requests per session (i.e. including sessions that were not able to acquire a path), and the average QoS path acquisition time are consistently higher for the omnidirectional case, followed by the two-antenna and the four-antenna cases. This is due to the fact that it is increasingly easier for the network to acquire a QoS path as the number of antennas increases. The second set of experiments, which were done for a longer data message length of 100 Mbytes, shows a decrease in the overall percentage of successfully received packets due to the increase in total traffic. The overall percentage of successfully received packets, and path acquisition time measurements follow the same trends as the first set of experiments showing a considerable advantage with the increase in number of antennas. This confirms the same analysis and reached conclusions.

These simulation results clearly demonstrate the increased efficiency and performance of the network as the number of directional antennas increases. As was indicated earlier, this increased performance is due to the considerable increase in spatial reuse and the ability for each node to simultaneously send or receive data in different directions. This functionally increases the effective number data slots by a multiple of the number of antennas (or directions) used. This effect significantly improves performance. As the data shows, the increase in performance, or speed-up factor, when the number of antenna is increased by a factor of 2 (i.e. doubled from 1 to 2, and then from 2 to 4) is significant (speed up factor > 1). As expected, however, it still below a the theoretical speed-up factor of 2. For the first set of experiments for example, the data shows that that ratio of the overall average percentage (average for all data traffic rates) of successful packets of the two-antenna case to the one-antenna case is 1.61, which is $>$ 1 and $<$ 2. The ratio for the four-antenna case to the two-antenna case is 1.84, which is also $>$ 1 and $<$ 2, and the ratio for the four-antenna case to the one-antenna case is 2.95 which is $<$ 4. This is to be expected from the theory of parallel and distributed systems because the actual speed-up factor is always below the ratio of the number of parallel units, or antennas, in this case.

D. Additional directional antenna tradeoffs and future research

It is worthy of noting at this point, that in highly mobile MANETs, more overhead would be needed to discover, exchange and maintain topology information between nodes. In the directional antenna environment, this overhead would be higher than that of the omnidirectional case. However, the gain realized due to the significant increase in spatial reuse, power savings, reduced path hop count, reduced end-to-end delay, and higher throughput offset this increase. The effects of mobility on this protocol as well as optimization techniques employed to reduce this overhead is a rich area of future research in this field, and is currently being investigated. Additionally, this protocol is a heuristic approach to a directional antenna version of the scheduling problem in the TDMA environment, which has been proven to be NP-complete [6][8][13][15]. Theoretical bounds and comparison with optimal path assignment is another possible area of future research.

VI. CONCLUSIONS

In this paper, a protocol for TDMA-based bandwidth reservation for QoS routing in MANETs using directional antennas was presented. The protocol takes advantage of the significant increase in spacial reuse provided by the directional antenna environment, which drastically increases the efficiency of communication in MANETs. This is due to the reduction in signal interference, and the amount of power necessary to establish and maintain communication sessions. Additionally, this protocol provides for a relatively smaller hop count for QoS paths due to the extended range of directional antennas using the same total transmission power compared to the omnidirectional case. In turn this results in reduced end-to-end delay. The simulation results clearly show a significant gain in performance with an increase in the number of successfully received packets, as well as a decrease in the QoS path acquisition time. However, as expected, this gain in performance is still below the theoretical speed-up factor. In the future, we intend to improve this protocol through the employment of additional optimization techniques. In addition, we intend to preform more simulations in order to further study, analyze and improve the performance of the protocol under different network environments including different mobility rates, and traffic conditions.

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