Routing Improvement using Directional Antennas in Mobile Ad Hoc Networks

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***Abstract*— In this paper, we present the initial design and evaluation of two techniques for routing improvement using directional antennas in mobile ad hoc networks. First, we use directional antennas to bridge permanent network partitions by adaptively transmitting selected packets over a longer distance, still transmitting most packets shorter distance. Second, in a network without permanent partitions, we use directional antennas to repair routes in use, when an intermediate node moves out of wireless transmission range along the route; by using the capability of a directional antenna to transmit packets over a longer distance, we bridge the route breakage caused by the intermediate node's movement, thus reducing packet delivery latency. Through simulations, we demonstrate the effectiveness of our design in the context of the Dynamic Source Routing protocol (DSR).**

I. Introduction

A mobile ad hoc network is a group of mobile wireless nodes that dynamically forms a network without the aid of any existing network infrastructure. Nodes cooperate to forward packets for each other so that a node can communicate with another node not in its direct transmission range. Among other issues, the creation of network partitions due to the change in relative distance between nodes is of primary concern in a mobile environment. The only way to bridge permanent partitions in a wireless network is to increase the transmission range, which directly translates to super-linear increase in transmission power.

Unlike an omnidirectional antenna, a directional antenna can transmit directionally and hence cause less interference to receivers that are not in the direction of transmission. This property of a directional antenna has the potential to increase the effective throughput of the network. However, in this paper, we do not attempt to address this issue. Rather, for a given transmission power, a directional antenna can transmit over a longer distance in a particular direction as compared to an omnidirectional antenna. This is because a directional antenna uses most of its power in the direction of transmission, whereas an omnidirectional antenna uses the power to transmit equally in all directions. In this paper, we suggest use of this property to achieve routing improvement in a mobile ad hoc network. Instead of designing a new protocol, we chose to augment existing and established protocols so that the deployment of directional antennas can be facilitated.

Most of the effort toward using directional antennas in mobile ad hoc networks has been targeted at increasing network throughput. Nasipuri et al [7] designed an on-demand routing protocol for use with directional antennas for reducing the number of routing packets transmitted during *Route Discovery*. Wieselthier et al [11] considered connection oriented *multicast* traffic and quantitatively analyzed the benefits obtained in saving power by using directional antennas. Spyropoulos and Raghavendra [10] presented an energy efficient routing and scheduling algorithm in which they minimize the total time for all possible transmitter-receiver pairs to communicate with each other. Ramanathan and Hain [9] used directional antennas coupled with adjusting the transmission power to control the topology of multihop wireless networks.

Our work is complementary to this existing work. Unlike in previous work, in this paper we target *routing improvement* in mobile ad hoc networks. Specifically, we bridge network partitions in the presence of permanent partitions, *and* even in the absence of permanent partitions, we improve packet delivery latency by decreasing route breakages. We have based our design and evaluation on the Dynamic Source Routing protocol (DSR) [3, 4], an on-demand routing protocol for mobile ad hoc networks. DSR is based on *source routing*, in which the originator of a packet decides the entire sequence of hops through which the packet is to be forwarded to the final destination. Due to lack of space, we omit the details of the DSR protocol [3, 4] here.

The rest of the paper is organized as follows. Section II summarizes the model for directional antennas used in this paper. In Section III, we present and evaluate our design to bridge network partitions. In Section IV, we present and evaluate our design to repair broken routes using directional antennas. We conclude in Section V.

II. Directional Antenna Model

Detailed analyses of directional antennas has been presented by Ramanathan [8] and by Liberti and Rappaport [5]. Since the concepts are fundamental to justifying our design decisions, we briefly revisit them here.

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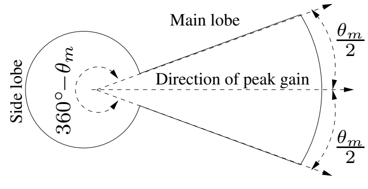

Figure 1. Approximate hypothetical 2D directional antenna pattern

An ideal directional antenna transmits and receives more energy in one direction, called the *primary direction* of the antenna. The *gain* of a directional antenna [5] in a particular direction $\vec{d} = (\theta, \phi)$ is given by $G(\vec{d}) = \eta \frac{U(\vec{d})}{U_{\text{avg}}}$, where $U(\vec{d})$ is the power density in direction $\vec{d}$, U_{avg} is the average power density over all directions, and η is the efficiency of the antenna and accounts for energy losses.

The maximum gain taken over all directions is called the *peak* gain of the antenna. An *antenna pattern* is the specification of the different gain values in each direction in space. A directional antenna pattern has a *main lobe* of peak gain and several *side lobes* of lesser gain. For purposes of analysis, all side lobes are collectively approximated by a single side lobe, as shown in Figure 1.

The *beamwidth* of a directional antenna (θ_m in Figure 1) is the angle subtended by the two directions on either side of the direction of peak gain that are 3 dB lower in gain, as shown in Figure 1. For simplicity, we do not model the 3 dB loss in gain on either side of the primary direction but consider the entire main lobe to have the peak gain.

III. BRIDGING NETWORK PARTITIONS

A. Protocol Modifications

The mobility of nodes in a mobile ad hoc network might lead to network partitioning, as illustrated in Figure 2, in which node *E* has moved out of normal omnidirectional wireless transmission range of node *D*. This figure also illustrates how we adaptively use the ability of a directional antenna to transmit over longer distances to bridge such partitions when needed (as compared to the transmission range of an omnidirectional antenna using equal transmission power). To achieve these goals, we modify DSR [3, 4] while still maintaining the basic operation of its Route Discovery and Route Maintenance mechanisms. Although we present our design in the context of DSR, it can be easily applied to other on-demand routing protocols.

The basic idea behind our design is to use the capability of a directional antenna to transmit over longer distances, but to adaptively use this capability *only* when necessary for *selected* packets.

1) Data Structure Modifications: We add two flags to the source route header in a DSR packet: the *trigger partition bridging* flag and the *long hop* flag. The protocol handles ROUTE REQUESTs differently if the *trigger partition bridging* flag is set. The *long hop* flag is set in packets sent directionally with a greater transmission power than normal in order to transmit over a distance greater than the normal omnidirectional transmission range.

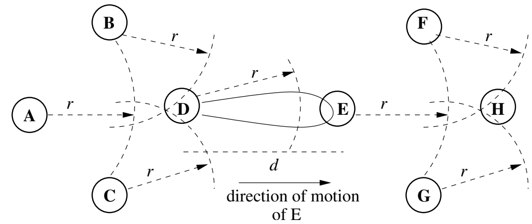

Figure 2. Example of bridging a network partition: node *D* transmits directionally to reach node *E* (*r* is the omnidirectional transmission range, and *d* is the directional transmission range)

In addition to maintaining information required by DSR, each node also maintains a *Passive Acknowledgment Table* recording information about ROUTE REQUESTs it has received in which the *trigger partition bridging* flag is set. Each entry in some node's Passive Acknowledgement Table contains the following fields: (1) *Target address* is the address of the node to which a source route is sought; (2) *When inserted* is the time at which this entry was inserted in the table, used to decide whether or not to initiate partition bridging; (3) *A list of angular ranges* around this node in which this node should search for the target address, where an angular range is specified by a direction and equal angular widths on each side (clockwise and counterclockwise) of that direction; and (4) *A list of* ROUTE REQUEST *packets* having different source addresses but each targeted for the same target address. Space for entries in the table is maintained in a Least Recently Used (LRU) fashion; entries also expire and are automatically deleted after a timeout.

2) Modifications to Route Discovery: The hop between two nodes is called a *long hop* if the greater transmission range possible with directional transmission (compared to the normal omnidirectional transmission range) is necessary to reach between the nodes; otherwise, we consider the hop to be a *normal* hop. In our protocol, it is the responsibility of the MAC layer at the transmitting node at any hop to use a different transmission power and beamwidth for a long hop versus for a normal hop.

A source node that has a packet to send to a destination node checks its own Route Cache for a source route to that destination. If present, the source node uses that source route for sending the data packet to the destination node. Otherwise (no source route is present in the Route Cache), the source node initiates Route Discovery as follows:

- If the source node does not have any pending ROUTE REQUESTs (i.e., awaiting response from the network) for the destination node, then the source node sends a ROUTE REQUEST packet omnidirectionally (as in normal DSR) with the *trigger partition bridging* flag cleared. The flag is cleared so that an intermediate node treats the packet as in normal DSR.
- However, if the source node has already sent a ROUTE REQUEST for that destination and that ROUTE REQUEST has timed out, then the source node sends a new ROUTE REQUEST for the same destination with the *trigger partition bridging* flag set.

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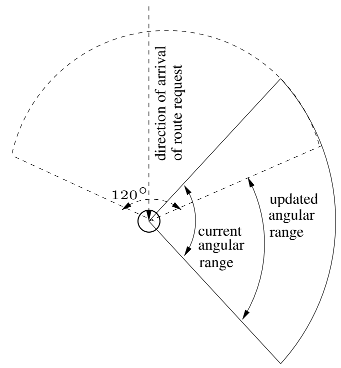

Figure 3. Updating the angular range on arrival of a ROUTE REQUEST

A node receiving a ROUTE REQUEST packet behaves as follows.

If the receiving node's Passive Acknowledgment Table does *not* contain an entry for the target of the ROUTE REQUEST, it does the following:

- If the *trigger partition bridging* flag in the ROUTE REQUEST is not set, then the node locally broadcasts the ROUTE REQUEST packet.
- If, however, the *trigger partition bridging* flag is set, the node forwards the ROUTE REQUEST omnidirectionally and enters the target address of the ROUTE REQUEST in its Passive Acknowledgement Table; the node also records the present time in the *When inserted* field and adds a copy of the ROUTE REQUEST to the list of ROUTE REQUEST packets present for this new entry. Additionally, the node initializes the list of angular ranges for this entry to all directions within 240° of the direction opposite to the direction of arrival of the ROUTE REQUEST.

Otherwise (this node's Passive Acknowledgement Table *does* contain an entry for the target of the ROUTE REQUEST), this node adds the ROUTE REQUEST packet to the list of ROUTE REQUEST packets for that entry, since this node might need to reply with a ROUTE REPLY to the source of the received ROUTE REQUEST. In addition, the node checks the *When inserted* field in the entry as follows:

- If the difference between the current time and the *When inserted* field is not greater than a threshold, the list of directions for the entry is updated to leave out the overlap between the list of angular ranges currently present and 60° on each side of the direction of arrival of the ROUTE REQUEST, as shown in Figure 3.
- However, if the difference between the present time and the *When inserted* field is greater than a threshold, it means that this node has transmitted one or more ROUTE REQUESTs for this Route Discovery with the *long hop* flag set, and hence no further action is taken by this node.

If the difference between the present time and the *When inserted* field in an entry in the Passive Acknowledgment Table expires, then the node (the owner of the Passive Acknowledgment Table) checks the list of angular ranges in that entry. For each angular range in the list, the node sends one or more ROUTE REQUESTs with the *long hop* flag set. Each of these packets are sent considering the next hop to be a long hop. More than one ROUTE REQUEST may be necessary if the angular range is wider than the beamwidth of the ROUTE REQUEST packets. These ROUTE REQUESTs are sent with a higher transmit power so as to transmit each over a longer distance.

When a node receives a ROUTE REQUEST targeted to itself, it sends a ROUTE REPLY back to the source of the ROUTE REQUEST, as in normal DSR. An intermediate node receiving a ROUTE REPLY does the following:

- The node checks its Passive Acknowledgment Table for all ROUTE REQUEST packets with a target of the originator of the ROUTE REPLY, and creates a new ROUTE REPLY packet for each listed ROUTE REQUEST. Each of these ROUTE REPLY packets has the reply route as the concatenation of the route from the originator of the ROUTE REQUEST to the intermediate node and the route from the intermediate node to the intended target of the ROUTE REQUEST, leaving out loops if any. Additionally, the intermediate node deletes from its Passive Acknowledgement Table the entry corresponding to the source of the ROUTE REPLY.
- However, if there is no entry for the source of the ROUTE REPLY in the Passive Acknowledgment Table, then the intermediate node forwards the packet as in normal DSR.

3) Modifications to Route Maintenance: The basic operation of Route Maintenance remains the same as in the base DSR protocol, with the following changes.

If an intermediate node, forwarding a packet for a source, finds the next hop to be a long hop, then the MAC layer at that node is responsible for transmitting the packet accordingly.

If the next hop is *not* a long hop, then this node processes the packet as follows:

- This node transmits the packet directionally (or omnidirectionally if this node does not have an estimate of the direction of the next hop).
- If the transmitted packet is not acknowledged (DSR Route Maintenance), then this node retransmits the packet in the estimated direction of the next hop (if such an estimate is available) and considering the next hop to be a long hop. If the intermediate node receives an acknowledgement, the intermediate node records the next hop to be a long hop. If, however, the intermediate node still does not receive an acknowledgement after limited retransmissions, it returns a Route Error to the original sender of the packet.
- If the forwarding node does not have an estimated direction for the next hop, then the forwarding node returns a ROUTE ERROR after a limited number of omnidirectional retransmission attempts.

If there is no acknowledgment to a packet sent over a long hop, then after a limited number of retransmissions, the intermediate node assumes that the next-hop destination is unreachable and sends to the source of the packet a ROUTE ERROR indicating the broken link.

As in the base DSR protocol, a node receiving a ROUTE ERROR removes the indicated link from its Route Cache.

As explained above, whenever a node considers the next hop to be a long hop, the node uses higher transmit power (transmitting the packet directionally). Without a feedback mechanism to control this transmission power, the node would waste power when the receiving node moves nearer and would also needlessly interfere with other nearby nodes. A receiver successfully receives a packet if the bit error rate is below a threshold. This indirectly implies a lower bound on the signal-to-interference-and-noise-ratio (SINR). Hence, in order to model whether a node is near enough to consider it a normal hop away rather than a long hop away, we need to model the SINR at the receiver. However, for implementation, we take a much simpler approach that considers just the received signal strength. Whenever a node receives a packet with the *long hop* flag set, the node calculates the difference in the received signal strength and the minimum threshold required to correctly sense a packet. If this difference is greater than a fixed threshold, then the receiving node piggybacks on the MAC acknowledgement packet an indication that the hop need no longer be considered a long hop. This fixed threshold is key to avoiding oscillations between treating the next hop as a long hop and treating it as a normal hop. Upon receiving this indication, the sender treats the next hop to be a normal hop.

B. Evaluation Methodology

We use the *ns-2* network simulator, with mobility extensions from the Monarch project [6]; version 2.1b8a of *ns-2* was used. Additionally, we extended the antenna model to simulate the antenna pattern of a directional antenna, and extended the propagation model to consider the direction of transmission along with the transmission power. The simulator, however, does not model the time or the energy required to change the attributes (Section II) of a directional antenna. This version of *ns-2* models the physical layer and the MAC layer and includes modeling of contention, collisions, capture, backoff, and propagation, for both omnidirectional and directional antennas. The network interface has a nominal transmission range of 250 m and a data rate of 2 Mbps; for the omnidirectional antenna case, the network interface uses the IEEE 802.11 Distributed Coordination Function (DCF) [2] MAC protocol, which employs physical and virtual carrier sensing for collision avoidance. When a directional antenna is used, the MAC protocol sends RTS and CTS omnidirectionally and sends DATA and ACK directionally.

In evaluating our partition bridging mechanism, we computed 3 metrics for each simulation run:

- *Packet Delivery Ratio*: The total fraction of application-level data packets sent that are actually received at the intended destination node.
- *90th Percentile Packet Latency*: Computed as the 90th percentile of the packet delivery latency, which is the time elapsed from when a data packet is first sent to when it is first received at its destination.

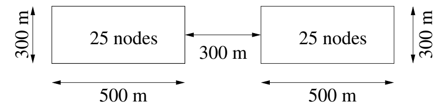

Figure 4. Scenario for evaluation of partition bridging protocol

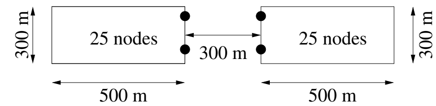

Figure 5. Modified scenario for evaluation of partition bridging protocol (the solid black circles represent stationary nodes)

- *Packet Overhead*: The number of transmissions of routing packets; for example, a ROUTE REPLY sent over three hops would count as three overhead packets in this metric.

We evaluate the partition bridging mechanism in two ways. First, we verified that in the case of a network without permanent partitions (the network is generally connected), our protocol performs on par with the unmodified DSR protocol, on all of the metrics above; due to space constraints, we do not present these results in this paper. Second, we evaluate the protocol in scenarios that have a permanent partition. We use a beamwidth of 60°, since any beamwidth, which would allow a directional transmission to transmit over a longer distance as compared to an omnidirectional transmission (both using the same transmit power), suffices for the purpose of bridging a network partition. Varying the beamwidth while keeping the transmission power fixed affects the distance that the directional transmission is able to reach.

For evaluating the protocol in the presence of network partitions, we used scenarios in which there are a total of 50 mobile nodes, 25 of which are moving about (according to the random waypoint model [1]) in an area $500\,\text{m} \times 300\,\text{m}$, while another 25 are moving about in a similar $500\,\text{m} \times 300\,\text{m}$ area, with the short ends of the areas separated by 300 m (the nominal omnidirectional transmission range is 250 m), as shown in Figure 4. and 5. For these experiments, we used a pause time in the random waypoint model of 0 s, 30 s, 60 s, 120 s, 300 s, and 600 s.

We used two types of these scenarios. In Figure 4, all nodes in both areas are mobile, whereas in Figure 5, we modified this scenario by making two of the nodes in each area stationary, located along the border adjoining the separation between the two areas. This modified scenario design ensures that nodes on each side are located close enough together to be able to bridge the partition with the longer transmission range. In addition, this modified scenario approximates the effect of more precise tracking of the direction for transmission between these border nodes (e.g., assuming that the border nodes use GPS or other source of location information, perhaps along with location prediction of the border nodes in the opposite area based on the nodes' trajectories). However, although these border nodes are stationary in this evaluation, the protocol is not directly aware of this and does not treat these nodes in any special way.

The communication model uses a number of different flows from nodes in one rectangular area to nodes in the other area. Since all flows cross the partition, having too many flows would seriously degrade the performance by congesting the links near the partition.

A concern in using directional antennas is the accuracy with which the antenna can identify the angle of arrival of a packet (and hence can estimate the direction of the sender), and how this accuracy affects the performance of the protocol. Hence, for the scenarios having permanent partitions, we evaluate our protocol using three different accuracies in estimating the arrival of a packet for mobile nodes: $10°$, $20°$, and $40°$.

C. Results

Figures 6 and 7 show the packet delivery ratio and delivery latency for the original scenario design, as illustrated in Figure 4, for different errors in estimating the direction of arrival for packets; the communication model in these scenarios used 5 flows across the partition. The performance of the protocol was much better than a protocol using omnidirectional antenna (which would give packet delivery ratio of *zero*), but we found that a large number of packets experienced very high latency due to the fact that as the nodes move about, the links which bridge the partition have a greater chance of breaking since these are directional links. Once a route is broken, Route Maintenance detects this, leading to a new Route Discovery, which takes longer than the Route Discovery in base DSR. Also, if one Route Discovery fails, then the next Route Discover attempt is made after an exponentially increasing back off period. All these contribute to the delay that a packet (waiting in the Send Buffer of the source) experiences. Such frequent route breaks also affect packet delivery ratio and packet overhead. The fact that the performance improves as the mobility in the network reduces also supports this reasoning.

Figures 6 and 7 also show that the protocol is not particularly sensitive to the accuracy in identifying the angle of arrival of packets. There is noticeable difference in the performance when the accuracy decreases to $20°$ from $10°$, but when the accuracy further decreases to $40°$ the performance degradation is barely noticeable.

Figures 8, 9, and 10 summarize the performance of the protocol in the modified scenarios illustrated in Figure 5. With this scenario design, the performance was better, and we could thus increase the number of flows in the communication model; we present results for 10 flows rather than 5.

As expected, adding the stationary nodes at the border of the partition (which actually means that the nodes at the edge are better able to track each other) improves our performance. These results are similar to those with no permanent partitions, even though here all flows must bridge the 300 m separation between the two rectangular areas. Specifically, our protocol achieves high packet delivery ratio, has low mean packet delivery latency, and modest packet overhead. The packet delivery latency is higher than the base version of DSR because the protocol first attempts to find a source route to the destination using base DSR and only when it fails does the protocol try to bridge the permanent partition.

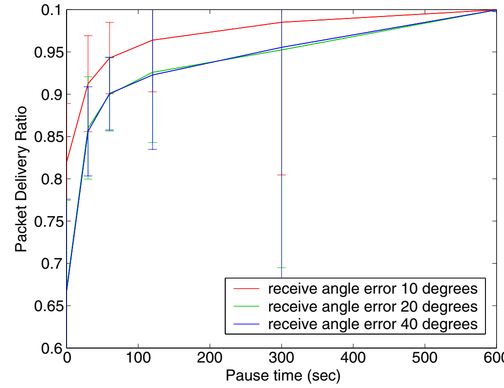

Figure 6. Packet Delivery Ratio for 5 flows transmitting across a partition

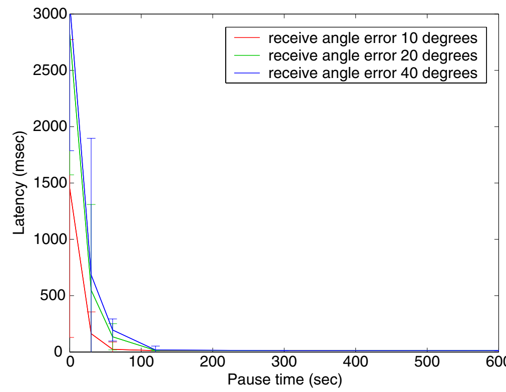

Figure 7. Mean latency for 5 flows transmitting across a partition

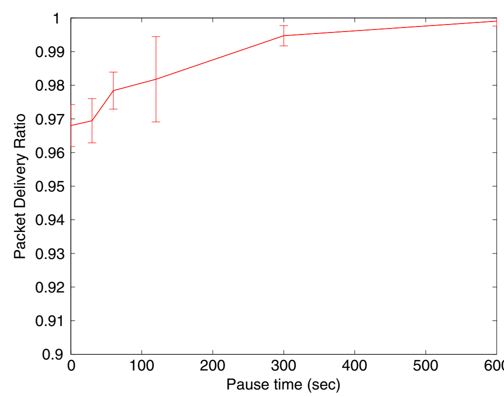

Figure 8. Packet Delivery Ratio with all 10 flows transmitting across a partition

We do not report path optimality results since the computation of path optimality considers only links up to length 250 m and is thus not defined in these scenarios.

1) Scenarios in which Partition Bridging Would Not Work: There are certain conditions under which the partition bridging protocol as proposed would not work. In particular, if the directional antenna at the other end of the partition is unable to estimate the angle of arrival of a packet (say, because of interference with other packets), then the partition cannot be bridged using directional transmission. However, instead of the receiver being unable to estimate the angle of arrival of a packet, if the antenna is able to estimate but with a large error,

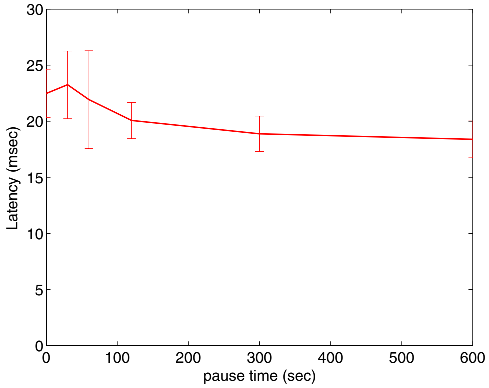

Figure 9. Mean Latency with all 10 flows transmitting across a partition

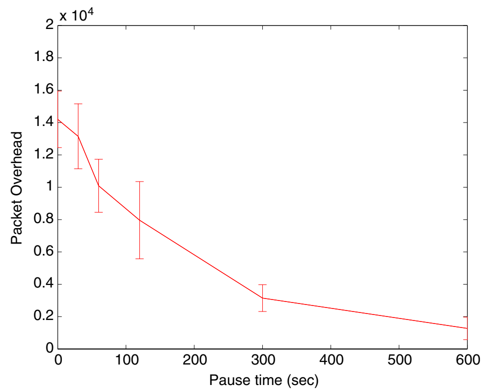

Figure 10. Packet Overhead with all 10 flows transmitting across a partition

then the problem is still solvable using directional antennas. This problem is also less severe because, for long hops, the area swept by the main lobe of the directional area is quite large. Thus, even if the beam is misdirected, the receiver may still lie in the main lobe of the antenna.

However, to bridge partitions in the case that the antenna is unable to give any estimate of the angle of arrival of a packet, we would have to increase the transmission power and try to bridge the partition with omnidirectional transmission. This is similar to the idea proposed by Ramanathan and Hain [9].

From the results, we can deduce that if node mobility is very high then the protocol is less able to bridge partitions. Even if the protocol can bridge the partition, the delay incurred by the packets may be prohibitively high.

IV. Repairing Broken Routes using Directional Antennas

We now propose a new technique to use directional antennas to augment the operation of Route Maintenance in a network without permanent partitions.

A. Protocol Description

Here as well, we use the capability of a directional antenna to transmit over longer distances, and use this capability *only* when necessary, for *selected* packets. When forwarding a packet along some route, an intermediate node detects that the next-hop node is unreachable and attempts to bridge over that node to reach the following next-hop node, thus avoiding (or

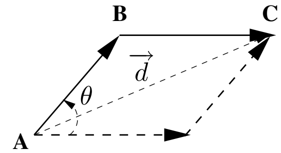

Figure 11. Estimate of direction and beamwidth

lessening) routing disruption. Most packets are still transmitted using the directional antenna over a normal, shorter distance.

1) Data Structure Modifications: In addition to maintaining the estimated direction of all next-hop neighbors, a node also maintains the direction of what the next hop node considers to be the direction of the following next-hop node (the next-to-next hop). For example, in Figure 11, node A not only keeps the estimated direction of B but also maintains the estimated direction of C relative to B. Node B piggybacks the estimated direction of C in the ACK packet that B sends to A. This requires B to have received at least one packet from C in the recent past.

Each node also maintains a counter associated with each next-hop node. We name this the *skip counter*, and it identifies the number of consecutive times that this next-hop node was skipped. The source route in a packet is also modified to include an additional field that indicates the number of *long hops* the packet has already encountered.

2) Modifications to Route Maintenance: When an intermediate node receives a packet to forward, it first checks how many times the next-hop node has been skipped recently (i.e., checks the value of the *skip counter*). The following three cases might arise. First, if *skip counter* $= 0$ (the next hop has not been skipped), then the intermediate node has been successfully forwarding packets to the next hop, and so the packet is forwarded normally. Second, if $0 <$ *skip counter* $<$ THRESHOLD (the next hop has been skipped consecutively but not more than THRESHOLD number of times), then the MAC layer tries to send this packet to the next hop just once (instead of trying multiple times). If the transmission succeeds, then the MAC layer resets the *skip counter* associated with the next hop to zero. This threshold is important in order to avoid deciding to skip a next hop just because a small number of data packets were lost. Third, if *skip counter* $\geq$ THRESHOLD (the next hop has been skipped consecutively for more than THRESHOLD number of times and hence is most likely to have moved away topologically), then the intermediate node modifies the source route in the packet to point to the next-to-next hop (thus skipping the next hop present in the original source route).

Even after multiple MAC layer retries, if the intermediate node cannot verify that the packet reached the next hop as listed in the source route, the node, instead of sending a ROUTE ERROR (as in base DSR), tries to estimate the direction of the next-to-next hop in the source route. The node also utilizes these estimates to estimate the beamwidth to be used. Once the estimated direction and beamwidth are known, the intermediate node transmits the packet using its directional antenna over longer distance. The transmission power is set

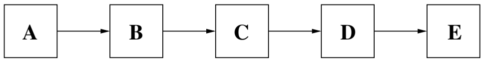

Figure 12. Scenario used for preliminary evaluation of route repair protocol

such that the packet can travel (in the direction of transmission) at least twice the omnidirectional transmission range (since if we assume that the next-to-next hop has not moved, then the next-to-next hop can be at most at a distance of twice the omnidirectional transmission range). Also, once the intermediate node decides to skip the next hop, the intermediate node increments the *skip counter* associated with the next hop.

As explained above, the protocol will try to avoid generating ROUTE ERRORS as long as possible by skipping broken links. However, skipping broken links introduces long hops into the source route and thus makes the route more fragile. Hence, only a limited number of hops are allowed to be skipped.

As shown in Figure 11, the estimated region in which the next-to-next hop node C (from node A) is expected to lie is given by the parallelogram. This is true because node B could lie at any point on the line joining A and B. Similarly, node C could lie anywhere on the line between B and C. The expected direction of node C is given by the direction of the diagonal from A to C.

B. Evaluation

We perform a preliminary evaluation our protocol in the scenario shown in Figure 12; only adjacent nodes are within omnidirectional transmission range of each other. In the scenario, source node A sends packets to destination E. After the initial Route Discovery has succeeded in finding a route to E and some packets have been delivered to E (so that the next-to-next hop directions can be known), we simulate a periodic problem with node C (or C periodically moving away). In alternating 5-second periods, node C is first prevented from receiving packets for 5 seconds and then allowed to receive packets normally for 5 seconds.

Figure 13 shows the packet delivery latency over time for the base DSR protocol (without our protocol modifications) and for our modified DSR including the use of directional antennas to repair broken routes by skipping nodes. When base DSR is used, a ROUTE ERROR is generated by B shortly after C stops receiving packets; this is followed by a ROUTE REQUEST from A, which does not succeed until C again begins receiving packets. When we add our route repairing modifications to DSR to go directly from B to D, skipping C, we are able to deliver packets without any ROUTE ERRORS or new ROUTE REQUESTs. In our scheme, the small delay incurred is because of the retries that B does before it can decide to skip C. Once C has been skipped, the node decides to retry for C for some number of times and finally skips C for subsequent packets. However, after a timeout, C is again given a chance, so that any transient problems with C do not permanently skip and isolate C. The much higher latency with base DSR is due to the delay of packets waiting in the Send Buffer until the Route Discovery can reconstruct the original route including C.

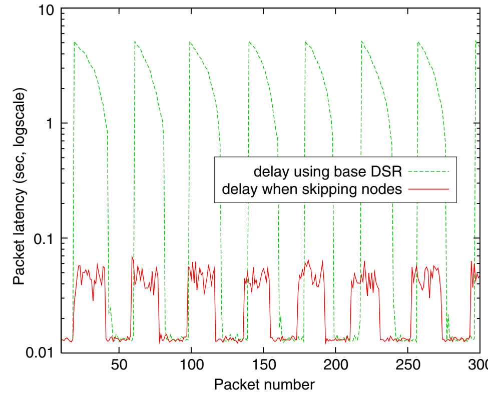

Figure 13. Packet delivery latency

V. CONCLUSION

In this paper, we have presented the initial design and evaluation of two techniques for routing improvement using directional antennas in mobile ad hoc networks. First, we use directional antennas to bridge network partitions by adaptively transmitting selected packets over a longer distance yet still transmitting most packets shorter distance. The modified protocol is able to effectively bridge network partitions yet is otherwise equivalent to the original protocol when no partitions are present. Second, we use the capability of a directional antenna to selectively transmit packets over a longer distance, thus bridging the break in the route caused, for example, by the original next-hop node's movement. This reduces packet delivery latency by avoiding dropped packets and additional routing overhead.

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