On-Demand Routing Using Directional Antennas in Mobile Ad Hoc Networks

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Abstract: We propose the use of directional antennas for improving the efficiency of on-demand protocols in mobile ad hoc networks. These protocols require that routes are found and maintained reactively, as required to handle the offered traffic. However, the process of searching for a route typically involves a network-wide flood of query packets, which consumes a large portion of the wireless bandwidth. We present two protocols that reduce the number of routing packets transmitted during the route discovery by limiting the query flood to a restricted region using directional transmissions. Performance evaluations of the protocols, obtained from computer simulations, are presented.

1 INTRODUCTION

Mobile ad hoc networks do not have any fixed infrastructural support such as base stations or centralized switching units. Communication is maintained by peer-to-peer packet transmission between the mobile hosts. If two hosts are not within transmission range, packets are sent over a sequence of intermediate hosts which act as routers. The capability of quick deployment, the absence of expensive fixed network infrastructure, and robustness against topological changes make ad hoc networks very attractive for a large number of applications.

In ad hoc networks, links between adjacent nodes get frequently broken due to node movements, causing the network topology to change unpredictably. Hence, the hosts need to determine routes to other nodes frequently. Many protocols have been proposed to efficiently perform this task under various mobility models [15, 2, 8, 17, 14, 7, 9, 18]. Of special interest is the class of on-demand protocols, that set and maintain routes from a source to a destination only when needed [2, 17, 15, 8]. These protocols have a lower routing overhead (measured in terms of the number of routing packets transmitted) than the traditional shortest path-based protocols. However, the routing overhead in on-demand protocols may still be very high due to a large number of active peer-to-peer conversations, and/or when the nodes are highly mobile [5]. This is basically due to the large number of routing packets that are transmitted throughout the network every time a new route is required to be found. An efficient search that limits the number of routing packets transmitted during route discovery will reduce the overhead and improve the network performance. Since the hosts are assumed to be moving in random directions and speeds, and there is no information of their locations, the problem of designing special techniques to restrict the spread of query packets during route discovery deserves special attention.

Traditionally, mobile wireless terminals are assumed to be equipped with omnidirectional antennas. This is mostly due to the technical difficulties of determining and maintaining a desired orientation while in motion. For instance, using a directional antenna in a cellular telephone would improve the sensitivity of the receiver, but it would be necessary to point the directional antenna in the handset towards the nearest base-station for highest efficiency. However, the fixed base stations of a cellular system may use directional antennas to reduce the co-channel interference in adjacent cells. Recently, some medium access control (MAC) protocols using directional antennas have been proposed for mobile ad hoc networks in [11, 13]. There, protocols use directional transmissions of data packets to reduce the effect of interference, thus improving the overall throughput in the network. Prior work in [12, 19] also demonstrated the benefits of using directional transmission in wireless packet radio networks.

In this work, we apply directional transmissions to mobile ad hoc networks for minimizing the routing overhead of on-demand routing protocols. We present schemes by which the search area for a new route is limited by using directional transmission of query packets. The process of determining the search space is explained. Results obtained from simulations experiments are presented, demonstrating that the scheme is highly successful in reducing the average number of routing packets transmitted in comparison to the same routing protocol using omnidirectional antennas. This benefit is obtained at the cost of a slightly higher average time for route discovery, which may lead to higher buffer length requirements and delays in packet delivery. But the savings in routing overhead may be considered to be more valuable than these demerits of the proposed schemes.

2 ROUTE DISCOVERY IN ON-DEMAND PROTOCOLS

On-demand protocols [2, 4, 8, 15, 14, 16] create routes on an “on needed” basis. If the sender of a data packet does not have a route to the destination, or if the old route has expired,
then it initiates a search for a new route. This reduces the routing overhead in comparison to shortest-path based protocols such as those using periodic updates of routing tables. However, the on-demand behaviour increases the latency of packet delivery, as the source of a data packet has to wait until it finds a route before transmitting the packet. The route discovery process uses a flooding technique, which is performed by broadcasting a query packet throughout the network from the node requiring the route. Each non-destination node upon receiving the query packet propagates the query packet to each of its neighbors. Special features are included in the flooding process to ensure that a node does not broadcast the same query packet twice. Thus, the destination node eventually receives the query packet (if it is reachable), and responds by sending back a route reply message. For a network with symmetric links, the route reply packet traces the path taken by the query packet to the destination, in the reverse direction. The actual mechanism of building a route from the flooded query packets varies with the protocol used. For example, DSR [2], which uses source routing, builds routes incrementally by adding the identifiers of the nodes visited by the query packet to its header. This enables the destination to know the route taken by the query packet and uses this information to send the route reply packet on the same route. The source learns about the route from the route reply packet. AODV [16], on the other hand, maintains routing tables on all intermediate nodes. For every query, the intermediate nodes remember the last hop taken by the query packet. This hop is used to forward the route reply packet back to the source. The reply packet, in turn, sets up similar routing table entries for forwarding of the data packet.

Irrespective of the technique used for maintaining the routes, on-demand protocols generate a large amount of routing related traffic during the route discovery process. Several optimizations on the basic protocol have been proposed for reducing this routing overhead in on-demand protocols. For instance, Maltz et. al. proposed that when performing a route discovery in DSR, nodes first query from its immediate neighbors about an existing route to the destination. A network-wide flood of query packets is only initiated when this first level search fails. Other optimizations include "early quenching" of flooding by an intermediate node that has cached information on a route to the destination, "gratuitous route replies" from nodes having a shorter path to the destination, but are not on the current route. These replies could be sent by the helpful nodes upon "overhearing" packets that are not addressed to itself. AODV also has several effective optimizations, such as "early quenching" of query packets by nodes having a route to the destination, and "route expiry" in which a cached route is discarded after a certain time-out period.

In addition to these optimizations, several other techniques have been proposed to reduce the extent of query floods in on-demand protocols. In [10], location-aided routing has been proposed, which advocates the use of the Global Positioning System (GPS) to limit the broadcasting of query packets to a restricted "request zone", based on the expected location of the destination node. A query localization technique based on searching within a limited hop-wise distance from the old route has been proposed in [3]. Both of these techniques work on the principle that when a route is broken, it is likely that a new route can be found within the vicinity of the old one that was broken. Hence routing overhead can be reduced by localizing the flood within this restricted region.

3 DIRECTIONAL ANTENNAS IN AD HOC NETWORKS

We propose on-demand routing protocols that use directional antennas to restrict the spread of a query search during route discovery. In this section, we describe the assumed node model and MAC using directional antennas, followed by the proposed routing protocols.

3.1 Node Model and MAC Protocol Using Directional Antennas

We assume that the radio transceiver in each mobile node is equipped with N directional antennas. Each of the antennas has a conical radiation pattern, spanning an angle of 2π/N radians. The N antennas in each node are fixed with non-overlapping beam directions, so as to collectively span the entire plane (see Fig. 1). We use the convention for numbering the antennas from 1 to N as shown in Fig. 1, 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 electronically selecting any one or all of the directional antennas for transmitting a packet. When receiving, 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 each node is equipped with multiple directional antennas, there is only one radio transceiver, which can transmit and receive only one packet at any given time.

Fig. 2 illustrates the underlying MAC protocol used with directional antennas. The scheme is similar to the IEEE 802.11 [6] protocol, adapted for directional transmission [13]. This adaptation allows the sending and receiving nodes to know each other’s relative positions by comparing the signal powers received in its antenna elements. In this protocol, any node that wishes to send a data packet must first establish a link with the desired destination by the exchange of small control packets called “request-to-send” (RTS) and “clear-to-send” (CTS) packets. For example, in Fig. 2, 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 antennas. However, D notes the direction from which it received the RTS 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
3.2 On-demand Routing Using Directional Antennas

We now present two variations of on-demand routing using directional antennas. For convenience, we assume that source routing is used. However, the principle presented here can be applied to other on-demand protocols as well. The principle behind the protocols is described with the help of an example. Consider the scenario in Fig. 3(a), where S is transmitting a sequence of data packets to D over the route indicated by bold directed lines. During the conversation, the route breaks due to the movement of an intermediate node I. All other nodes in the network are assumed to be holding their positions at this point of time. The last node on the existing route, H, detects the broken link from a MAC layer timeout until no acknowledgement is received, and transmits an error packet back to S. This prompts S to initiate a route discovery, by which it sends out a query packet in search for a new route to D. Typically, an on-demand routing protocol with omnidirectional antennas would broadcast the query packet in all directions, causing a query flood that would reach all the nodes in the network.

With directional antennas, we propose that a new route discovery is propagated from S in the direction of D with the help of directional transmissions of a query packet by a restricted set of nodes in the network. We propose two different ways of restricting the search, as described in the following protocols:

- **Protocol 1:** In this approach, when S starts a new route discovery, it transmits a query packet with the same directional antenna which it had been using earlier to transmit the data packets destined for D. This is the directional antenna facing the first node on the last valid route to D. Every node which receives the query packet propagates it in the same direction, i.e., uses the same antenna element for rebroadcasting the query packet. We assume that the flooding technique has provisions for avoiding repeated transmissions of the query packet by the same node, as used normally. The directional transmission of the query packet has the effect of propagating a search in the conical direction starting from S in the direction of D, as shown in Fig. 3(b). Assuming that D has not moved too far since the time the last route was established, our technique restricts the flood of query packets in a region containing the last known location of D. If S does not receive a route reply packet from D within a suitable timeout period, it decides that the localized search for a route to D has failed. In that event, S initiates another route discovery, this time flooding the entire network. The instruction for indicating whether a query flood is directional (using only one directional antenna) or omnidirectional (using all antennas), is included in the query packet header. Similar ideas were used in [10, 3] to restrict the number of routing packets in on-demand routing. In comparison, our scheme is simpler to implement, as very little additional modifications are necessary in the query packet header, such as inclusion of the "request zone" in [10] and the last valid
route from S to D in [3].
A drawback of this mechanism is that the angular span of the antenna element in S that was used to transmit data packets on the first hop of the last valid route to D, may not necessarily include D. This will be true if the first intermediate node on the path to D and the node D do not lie within the angular span of the same directional antenna of S (see Fig. 4). Protocol 2 is designed to reduce the possibility of such events.

- **Protocol 2**: According to this scheme, at the end of a successful route discovery the source also records the directions of the antennas to be used on every hop of the newly discovered route. This information can be easily made available to the source if every node on the newly discovered route adds to the header of the route reply packet, the antenna identifier which it used to receive the packet while forwarding it back to the source. Hence, in addition to the sequence of nodes on the newly discovered route, the header of the route reply packet will also contain the antennas to be used on the path. The source maintains this information in its route cache. This allows the source to get a rough estimate of the angular location of the destination by simply counting the number of times each antenna element was used on the route that has been found. For instance, in Fig. 4(a), at the end of the route discovery that resulted in the initial route from S to D, the route reply packet was received with antenna 4 on 3 occasions and on antenna 1 on one occasion. Hence, when this route is broken, S may conclude that the possibility of finding a new route to D is highest in the region included in the angular span of its antenna 4. In order to maximize the utility of this information, during the next route discovery S broadcasts the query packet to all its neighbors, with instructions for rebroadcasting the packet on antenna 4 only. This has the effect of expanding the search region, while still including the last known angular location of the destination. If this search fails, a network-wide flood is initiated by S after a suitable timeout period.

### 3.3 Performance Tradeoffs

The two protocols for directional flooding are designed on the principle that the search for a new route can be localized within a restricted set of nodes in the network which are included in an approximate angular direction in the vicinity of the destination node. The estimate of the angular direction is obtained from antenna directions used in the past to transmit data packets from the source to the destination. If the directional search is successful, the total number of routing packets sent during route discovery will be smaller than that required to flood the entire network. However, since the network is highly dynamic, and the direction estimated from the last successful route discovery is somewhat stale and approximate, it is possible that the directional flooding will not be successful in finding any route to D. It may also find a route that is longer than necessary, if the destination is not included in the search zone but an intermediate node which receives the query has a route to the destination, and responds to the query with this route. In the former case, a new route discovery with network-wide flooding will eventually find the route, which has the effect of increasing the packet latency. The latter case results in inefficient usage of network resources if the route obtained from this search has larger number of hops than the one that would be found had a network-wide search been used. This will result in a
higher end-to-end delay in packet transmission. However, we expect that the advantage gained from reducing the routing overhead, on the average will overcome the inefficiency caused from unsuccessful or faulty directional floods. In any event, the trade-off between reduction of routing overhead and packet latency and delay due to the use of directional flooding can be controlled by tuning the mechanism for localizing the query flood using directional antennas. For instance, instead of flooding the whole network after the first timeout period for route discovery, the source may initiate another directional flood by using a larger number of antenna elements (as opposed to a single antenna) for transmitting the query packets. This will increase the search zone for the route without including the whole network. But this may increase the latency even further if this search also fails in finding the route. A right balance between this trade-off will depend on the number of antennas used, the mobility of the nodes, the frequency of packet transmissions, and other dynamics of the network.

4 Simulation Results

We now present some results obtained from simulation experiments that were conducted to evaluate the performance of the proposed protocols. We use an event-driven, packet-level routing simulator called MaRS [1]. This simulator has the relevant network layer details that are necessary for our work and has been used earlier for performance evaluations of various ad hoc routing protocols [5, 3]. The original version of the simulator has been modified to incorporate node mobility and its associated issues such as link failures and reconnects. The physical layer and MAC are not simulated, which implies that the effects of interference and packet collisions in the random channel access protocol are not reflected in the results. Though this is a drawback of MaRS, we are able to draw the necessary conclusions about the benefits of our proposed protocols by evaluating the routing overhead which is adequately accounted in the simulator. We also evaluate the number of packets dropped during routing due to broken links and insufficient mechanism for rerouting the packets that are stranded in the intermediate nodes.

We simulated an ad hoc network of 64 nodes, placed in random locations in a square area of size 1000 m x 1000 m. The mobility of the nodes is modeled by a sequence of uncorrelated and random movements of each node. According to the model, for every move, a node finds a new position \( P \) and time \( T \) for reaching the position. The position \( P \) is calculated by using a random distance to be covered in the move, and a randomly chosen direction of movement. The distance is modeled as an exponentially distributed random variable with a mean of 5 m, and the direction of motion is assumed to be uniformly distributed in \([-45^\circ, 45^\circ]\). The time \( T \) of reaching the new position \( P \) is then calculated by using this distance and the node velocity, which is given as a parameter for simulation. There is no pause between successive moves and all nodes move independently of one another. We run the simulator for a fixed duration of time and fixed average traffic intensity, and derive the following outputs: (i) routing overhead, measured in terms of the total number of routing packets transmitted in the network and (ii) average number of packets dropped during delivery. The data traffic in the network arise from 50 conversations, which is defined as a sequence of packets delivered for a given source-destination pair in the network. Every conversation is modeled by a Poisson arrival of packets at the source node with a mean inter-arrival time of 400 ms.

Fig. 5 show how the proposed Protocol-1 with 2 to 4 an-
tennias compare with the omnidirectional source routing protocol (N=1 in the figure). Except for the modifications for directional route discovery, the routing protocol is the same in all the cases. The plots show that there is a significant reduction in the number of routing packets transmitted in the network with the use of directional antennas. For this case, the number routing packets is found to vary inversely with N. However, the number of packets dropped in routing appears to increases almost linearly with N. This behaviour can be attributed to the characteristics of our simulator, in which a data packet is dropped by a node when it is in the process of route discovery. In reality, nodes can buffer the data packets when the route is being searched for, and send them when a route is found. This would affect the packet delay. Our simulation also does not take into account multi-user interference and other channel effects. We expect that with a reduced routing overhead throughout the network, congestion will be reduced, which will actually have an effect of improving the data throughput and speed up packet delivery using directional antennas.

Fig. 6 shows the results with Protocol 2. With this protocol the savings in the number of routing packets is accompanied by fewer number of dropped data packets. Note that, (in the absence of a buffer) a larger number of packets are dropped if it takes longer to find a route to the destination. Since Protocol 2 has a larger search space than Protocol 1, it has a higher probability of succeeding in its directional search for a new route. Hence it has a lower amount of packet loss.

5 CONCLUSIONS

We introduce a new technique for saving the wireless bandwidth consumed in the route discovery process used in on-demand routing. The benefit is obtained by restricting the spread of the query flood during route discovery by the use of directional antennas in the mobile nodes. We show how the directional antennas can be effectively used to (a) estimate the approximate direction of a destination node from the source node, and (b) restrict the search for a new route within the vicinity of this estimated direction. Two different schemes for restricting the search space are proposed. These schemes differ in the probability of success in finding the best route. Simulation results illustrate the effectiveness of these schemes. There is a trade-off between the savings in the number of query packets and the number packets dropped/buffered for latter transmission. However, the right choice of the number of directional antennas and the scheme for performing a directional query search can save a large portion of the wireless bandwidth. This might justify the additional hardware costs of using directional antennas in place of omnidirectional ones in the mobile nodes of an ad hoc network.

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REFERENCES


