An Efficient Directional Routing Protocol for Mobile Ad Hoc Network

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Abstract- This report addresses the issue of routing in mobile ad hoc networks (MANETs) using directional antennas. Existing directional routing schemes either assume a complete network topology or simply use omni-directional routing schemes to forward packets in underlying directional environment. In this report a Directional Routing Protocol (DRP) for MANETs is proposed. DRP is an on-demand directional routing protocol which assumes a cross layer interaction between routing and MAC layer and is inspired by Dynamic Source Routing (DSR) protocol. The main features of DRP include an efficient route discovery mechanism, establishment and maintenance of directional routing and directional neighbor tables and novel directional route recovery mechanisms. Implementation of DRP on top of MDA, a MAC protocol for directional antennas and have compared its performance with the DSR protocol over both omni-directional and directional antenna models. DRP considerably improves the packet delivery ratio, decreases the end to end packet latency, has lesser routing overhead and is robust to link failures.

Keywords: Directional Antennas, Routing Protocols, IEEE 802.11, Mobile Ad Hoc Networks, Medium Access Control

1. INTRODUCTION

Use of directional antennas is getting increasing acceptance in wireless systems. With directional antennas both transmission range and spatial reuse can be substantially enhanced by having nodes concentrate transmitted energy only towards their destination's direction, thereby achieving higher signal to noise ratio (SNR).

A transmitter can use this higher SNR to either increase its transmission range or transmit at higher data rate [1]. Because of these underlying benefits of directional communications, there is a recent interest in the research community to use directional antennas for Mobile Ad Hoc Networks (MANETs).

However, use of directional antennas in MANETs creates new types of hidden terminal problems [3] and node deafness [4]. Fundamental issues such as determination of a node's neighbors have to be properly handled [4]. Deafness is defined as the phenomenon when a node *X* is unable to communicate with node *Y*, as *Y* is presently beamformed in a different direction. In such an event, *X* perceives *Y* to have moved out of its range, thereby signaling its routing layer to take actions, hence affecting the network throughput. Deafness and hidden terminal issues have been extensively studied in [3] a one hop scenario but no solution has been provided.

Although there is plethora of literature towards designing efficient directional MAC schemes, a complete design of a routing protocol tuned to the underlying directional environment still requires to be explored. Here there is a routing protocol specifically tuned to the underlying MAC layer can reap interesting performance benefits. For example, in directional routing, a source node can exploit the antenna beam information towards its destination for an efficient route recovery. In this report a Directional Routing Protocol (DRP) is proposed for MANETs. The salient contributions of this report can be summarized as follows:

1. A detailed study of issues related to routing in directional antenna systems. Outline the behavior of different IEEE 802.11 system parameters in a multihop directional environment.

2. Designing a directional routing protocol called DRP. The main features of DRP include an efficient route discovery mechanism, establishment and maintenance of directional routing and directional neighbor tables (DRT and DNT respectively) and a novel directional route recovery mechanism among others.

3. Comprehensive simulation comparison of DRP with DSR over both omni-directional and directional antenna models. The simulation compares both static and mobile scenarios.

A brief description of the antenna model used in this report and a glimpse of IEEE 802.11 followed by the DSR protocol is then provided. The major issues involved in the design of a directional routing protocol in MANETs are discussed.

2. RELATED WORK

Nasipuri *et.al.* [9] propose a scheme to estimate the direction of the destination relative to the source in order to confine the spread of route discovery packets using directional transmission. However, the strategy is more effective for route rediscovery at the source. In addition, the flooding overheads due to directional sweeping have not been addressed. In DRP a novel mechanism for the direction estimation based on the route to the source has been proposed. This mechanism is used both at source and intermediate nodes to provide a more robust mechanism to handle route failures.

To reduce the MAC layer contention among different flows, in [6], notion of exploiting maximally zone disjoint routes has been introduced. Directional communication is shown to be effective in both route discovery and use of such routes. But, the proposed protocols require all nodes to be completely aware of the topology and ongoing neighborhood communications. A MAC and a proactive routing protocol over ESPAR antennas have been suggested in [9]. This is a complex MAC incurring considerable control overhead. In [5], the authors illustrate the effectiveness of directional antennas by overcoming partitions introduced in the network due to the mobility of nodes. They advocate the use of larger ranges of directional antennas only in the event of a link failure. In. [7], authors evaluate the performance of DSR over DMAC [3] and omni directional antennas. Several issues ranging from directional route discovery to mobility management are explored in the context of directional communication, which is shown to be more effective when topologies are sparse and random. However, DMAC is susceptible to deafness and hidden node problems [3] which limits multi-hop routing performance in many scenarios.

In this report, to provide a complete routing solution over single switched beam antennas so that both the spatial reuse and larger ranges offered by this model can be exploited.

3. PRELIMINARIES

3.1 The Antenna Model

A complete and flexible implementation of a comprehensive switched beam directional antenna system which is cheaper in cost compared to both adaptive array and Multiple Input Multiple Output (MIMO) systems is done. This model can operate in two separate modes: Omni and Directional. This may be seen as two separate antennas: an omni-directional and a single switched beam antenna which can point towards specified directions [3]. The Omni mode is used only to receive signals, while the Directional mode is used for both transmission as well as reception.

In Omni mode, a node is capable of receiving signals from all the directions with

separate antennas: an omni-directional and a single switched beam antenna which can point towards specified directions [3]. The Omni mode is used only to receive signals, while the Directional mode is used for both transmission as well as reception.

In Omni mode, a node is capable of receiving signals from all the directions with a gain of G^O. While idle (i.e., neither transmitting nor receiving), a node stays in the Omni mode. As soon as a signal is sensed, a node can detect the direction (beam) through which the signal is strongest and goes into the Directional mode in that particular direction.

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In the Directional mode, a node can point its beam towards a specified direction with gain G^d (with G^d typically greater than G^O). In addition, the gain is proportional to number of antenna beams (i.e., inversely

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proportional to the beamwidth) given that more energy can be focused towards a particular direction, thus resulting in increased coverage range. A Node provides coverage around it by a total of *M* non-overlapping beams. The beams are numbered from 1 through M, starting at the three o'clock position and running counter clockwise. At a given time, a node can transmit or receive in only one of these antenna beams. In order to perform a broadcast, a transmitter may need to carry out as many directional transmissions as there are antenna beams so as to cover the whole region around it. This is called *sweeping*. In the sweeping process, we assume there is negligible delay in beamforming for various directions. This model has been widely studied in the literature [3, 4, 8, 9]. To model antenna side lobes, we assume that the energy contributed to the side lobes is uniformly distributed in a circular area. Although energy contributed to the side lobes depends on the actual radiation pattern, which is governed by the configuration and weighting of elements in the antenna array [4], for the purpose of our simulation we assume that the side lobe gain is fixed and is set to a very small value. Finally, we assume that all the nodes use the same directional antenna patterns and can maintain the orientation of their beams at all times [8].

3.2 IEEE 802.11

In the IEEE 802.11 [8], the Distributed Coordination Function (DCF) coordinates medium access in ad hoc networks. In DCF, an RTS (Request to Send) and CTS (Clear to Send) handshake precedes DATA communication and the following ACK. DCF in IEEE 802.11 conducts two forms of carrier sensing: physical (by listening to the wireless shared medium) and virtual. Virtual carrier sensing uses the duration field which is included in the header of RTS and CTS frames. The duration included in each of these frames can be used to determine the time when the source node would receive an ACK frame from the destination node. This duration field is utilized to set a station's Network Allocation Vector (NAV), which indicates the remaining time the medium is busy with the ongoing transmission. Using the duration information, nodes update their NAVs whenever they receive a packet. The channel is considered to be busy if either physical or virtual carrier sensing (by the NAV) so indicates. Whenever NAV is zero, a station may transmit if the physical sensing allows.

3.3 Dynamic Source Routing (DSR) Protocol

DSR is a source routed reactive routing protocol [10]. The protocol consists of two major phases: route discovery and route maintenance. When a mobile node has a packet to send for some destination, it first consults its route cache to determine whether it already has a route to the destination. If no such route exists, it initiates a route discovery by broadcasting a Route Request *(RREQ)* packet. This route request contains the address of the destination, along with the source node's address and a unique identification number. All nodes, except the destination node, rebroadcast this packet exactly once. While doing so, they append their own address to the route record field in the *RREQ* packet. Hence, the path followed by this route request gets included in the *RREQ* packet.

On receiving the *RREQ* packet, the destination node responds by sending a route reply *(RREP)* message to the source. Since a bi-directional link is assumed between all the nodes, the route reply is a unicast message, following a path obtained by reversing the route followed by the route request. The route received at the source is cached for subsequent communication. DSR facilitates route maintenance through the use of Route Error *(RERR)* packets. In the event of a link failure at an intermediate node on a source route, a *RERR* packet is generated and sent to the source. All intermediate nodes including the source node remove all the routes in their caches which have that broken link.

DSR also has provisions for nodes to learn and cache routes by overhearing *RREPs* or data packets containing source routes. Such cached routes can reduce flooding overheads in the network and reduce route discovery latencies.

4. DIRECTIONAL ROUTING ISSUES

In this, investigation of different issues related to directional communication and their impact on directional routing. For the discussion below we assume a omni-directional DSR protocol running over a single switched beam directional antenna system. This will serve as a foundation for developing our DRP protocol.

4.1 Directional Broadcasting Overhead

In a single switched beam directional antenna systems, sweeping is needed across all antenna beams in order to cover a node's one hop neighbors. Each forwarding node, in effect, transmits M (the number of antenna beams) packets into the network. For a single switched beam antenna system, this adds to both packet redundancy and delay. Since the Route Request (RREQ) packets are flooded throughout the network, an inefficient broadcasting strategy may negatively impact the quality of routes [7] source node gets.

Hence, a careful route discovery is necessary to obtain optimal routes with minimal Route Discovery Latency (RDL) and redundancy. In DRP, we employ a novel directional broadcasting strategy aimed at reducing the broadcast redundancy and RDL potential issues in directional environment.

4.2 Address Resolution Protocol (ARP) in Directional Environment

Once a destination node receives a RREQ packet, it unicasts a route reply (RREP) back to the source. However, before forwarding the RREP packet, the destination needs to do an Address Resolution Protocol Query (ARP-Query) to obtain the MAC address of its previous hop (this is also true for all intermediate nodes forwarding the RREP packet). Since the ARP-Query is a broadcast packet, nodes will do a sweeping to locate its previous hop (this is also true for all intermediate nodes forwarding the RREP packet). Since the ARP-Query is a broadcast packet, nodes will do a sweeping to locate its previous hop. However, sending ARP-Query through sweeping has some its previous hop. However, sending ARP-Query through sweeping has someits previous hop. However, sending ARP-Query through sweeping has some its previous hop.

4.3 Directional Routing Protocol (DRP)

DRP is an on-demand directional routing protocol, and is inspired in large by omnidirectional Dynamic Source Routing (DSR) [10] protocol used heavily in MANETs. DRP closely couples the routing layer with the MAC layer and assumes a cross-layer interaction between some of the modules. In DRP the Directional Routing Table (DRT) is local to routing layer and maintains the routing information to different destination. The Directional Neighbor Table (DNT) on the other hand is shared with MAC.

Unlike DSR which maintains only the index of the node ID in a forwarding path; DRP also maintains node indices and the beam IDs used by the nodes to receive a packet in the forwarding path. The beam ID stored in the DRT helps the source node to estimate the angular position of its destination relative to itself. Although a similar scheme of maintaining beam IDs has been suggested in [9], DRP uses the beam ID kept in the DRT to do an efficient route recovery.

In addition to the shared DNT, in DRP the network layer is aware of the different antenna beams at the MAC layer. The MAC, in turn, has separate buffers for each antenna beams. Accordingly, the link layer follows this approach by maintaining separate queues for each beam. In order to place the packet in the correct link layer queue, the network layer determines the antenna beam which the MAC will use for transmission of the packet, and puts the packet in the link layer queue corresponding to this antenna beam. It is to be noted that broadcast packets are kept in a separate dedicated queue.

5. DRP Medium Access Control

To minimize the effect of deafness and hidden node problems in directional environment, MAC layer of DRP (termed as

MDA) employs a special form of sweeping of both RTS and CTS, namely, the Diametrically Opposite Directions (DOD) procedure. The DOD mechanism includes two major enhancements over sweeping, firstly, RTS and CTS packets are transmitted in DOD which ensures maximum coverage; secondly, these packets are only transmitted through the antenna beams with neighbors. In addition, the Enhanced Directional Network Allocation Vector (EDNAV) mechanism incorporated in MDA considerably improves performance by accurately differentiating between deafness and collision scenarios. EDNAV mechanism is an extension of Directional NAV (DNAV) scheme outlined in [3] is a simple extension of IEEE 802.11 NAV concept and is employed to handle issues of hidden terminal problem in directional environment. Essentially, DNAV is a table that keeps track for each direction the time during which a node must not initiate a transmission through this direction. Due to space limitations, a brief description of above features, for a complete description MDA protocol [5].

5.1 Diametrically Opposite Directional (DOD) RTS and CTS

MAC protocol for Directional Antennas (MDA) uses an efficient form of RTS and CTS transmission called the Diametrically Opposite Directional (DOD) procedure. The DOD RTS/CTS mechanism in MDA works as follows. Initially, assume that all nodes have the same number of antenna beams equal to M, and that node S has a packet to be sent to its neighbor node R through beam A_{SR}. If A_{SR} is not idle, the backoff procedure is initiated similar to IEEE 802.11. Otherwise, the sender node S has to ascertain a few key points. Firstly, it needs to determine through how many of its sectors, say D, besides the one it communicates with the receiver R it has to transmit a DOD RTS. Right before sending a RTS to R node S first needs to estimate the antenna beam A_{RS} used by R to reach S. Now, out of these D DOD sectors, MDA sends the RTS or CTS packets only to the sectors with neighbors. Hence DOD procedure employed in MDA ensures a maximum coverage of RTS-CTS packets with less overhead compared to sweeping alone. In addition, by employing a DOD procedure, a given node X will be aware which of its neighbor Y is busy in some other transmission/reception.

It would only initiate a transmission towards Y when its DNAV towards the direction of X is free. With this support at the MAC layer, a node may reasonably comprehend that the absence of a CTS in response to a RTS is primarily due to node movement rather than node deafness.

5.2 The Enhanced Directional NAV (EDNAV)

Directional NAV (DNAV) [7] is a simple extension of IEEE 802.11 NAV concept and is employed to handle issues of hidden terminal problem in directional environment. Essentially, DNAV is a table that keeps track for each direction the time during which a node must not initiate a transmission through this direction. However, DNAV is sufficient in handling deafness as it is simply an extension of the NAV as employed in IEEE 802.11. In existing DNAV implementations, node *A* would set its DNAV for beam 4 for the entire transmission duration between nodes *S* and *R*. While this prevents deafness as node A is now unable to communicate with node *S* (and maybe node *R*), it limits performance in case node *A* has a packet to send to node *B* and vice-versa. Note that nodes *A* and *B* could communicate without causing any collision with the ongoing communication between *S* and *R*. However, as node *A*’s DNAV is set for beam 4, it is unable to initiate communication with *B*, thus limiting its performance.

In MDA an Enhanced DNAV (EDNAV) scheme comprised of two components: a DNAV mechanism which is manipulated differently from previous schemes, and a Deafness Table (DT) which is used to handle deafness scenarios. It is important to differentiate applicability of each of these schemes. Whenever a node has a packet to be sent over one direction, both DNAV and DT are consulted. On the other hand, upon reception of a packet the node will either modify its DNAV or its DT, not both. If the node lies in the communication path between the transmitter and the receiver (first RTS/CTS handshake), the DNAV is to be modified. The DT is modified whenever the node receives either a DOD RTS/CTS, that is, once the RTS/CTS handshake is over. In this case, the node is certain not to lie within the communication path of the oncoming transmission.

6. DRP Basic Operation

The key modules of DRP are

6.2 DRP Route Discovery

The route discovery mechanism in DRP works similar to DSR. For a given source *X*, and destination *Y*, if *Y* is not in the DNT of *X*, *X* floods a *RREQ* packet in the network. DRP enforces a broadcast optimizations proposed in [2] to reduce packet redundancy and route discovery latency. Whenever a node receives a *RREQ* packet it starts a delay timer. If the same *RREQ* packet is received again before the expiration of this timer, the node makes a note of all the beams where that packet arrived from. The node forwards the packet in only those beams/directions other than those in which the packet arrived. Amongst the selected beams, DRP initiates a rebroadcast in the beams which are vertically opposite to the beams where the node received the broadcast packet. Next, the beams which are adjacent to these vertically opposite beams are chosen. This shall continue till all the selected beams are covered.

The IEEE 802.11 basic Carrier Sense Multiple Access (CSMA) [5] is followed before transmitting in the first beam of a particular sweep. For subsequent beams of the same sweep, simply carrier sense and transmit. However if a beam has been marked as busy (i.e., the Directional NAV is set in this direction), that beam is ignored and the next free beam amongst the selected beams is chosen. It should be noted that we do not wait for the beam to become free. Deferring in every beam would lead to an extremely high sweeping delay. Further post-backoff after successfully transmitting in a beam and before initiating transmission in another beam. A node post-back offs after completing a sweep of all the selected beams.

The sequence of hops taken by the route request packet as it propagates through the network during the route discovery phase is recorded in a data structure in the packet. It is termed as directional route record. The directional route record appends both the node indices of the intermediate nodes and the beam ID used by these nodes to receive the packets from uplink. An intermediate node *Z* which forwards the route request packet, also adds the antenna beam at which it received the RREQ packet in addition to its own ID.

6.3 DRP Route Maintenance

The function of the route maintenance module is to monitor the operation of the route to a destination and inform the sender of any intermediate link failures or routing errors. In DRP, routes are generally associated with the antenna beam to be used to reach a particular nexthop. Hence any change in the location of the nexthop which changes the beam, even within the transmission range, needs to be handled carefully.

Similar to DSR, in DRP when originating or forwarding a packet using a source route, each node transmitting the packet is responsible for confirming that data can flow over the link. A link layer acknowledgment as in IEEE 802.11 is used for this purpose. As in a directional environment it is necessary to distinguish between the movements of a nexthop within the range (nexthop is accessible through a different antenna beam) or the nexthop has moved out of the range. In the first case the sender need not send a route error packet back to the source and should try to locate the node within its range. Hence in DRP we use separate phases for route maintenance. Location tracking and two-hop directional local recovery phase are local to the node which detect a link breakage. On the other hand, the *Route Recovery Phase* is done at the source. Now provide a comprehensive description of each of these phases and how they interwork.

6.4 Location Tracking Phase

Due to the continuous movement of the nodes, the antenna beam used by a node to reach its next hop and vice versa may change. Several methods have been proposed in the literature to track such movements. The approach in [6] uses two antenna beams to continuously locate the position of a mobile node within the transmission range. This approach requires special hardware support which makes the cost of the overall system largely expensive. The scheme discussed in [8] uses the concept of tones and extensive network state information at each node to track the position of a mobile node. On the other hand, [8] uses the concept of circular directional transmissions of both RTS and CTS packets which eliminates the need of any specific tracking mechanism within the transmission range of a node. However, this results in a considerable overhead in the transmission of control packets. Use of GPS is also suggested as a means to track location of a mobile node [3], however the associated mechanism and control overhead has not been discussed.

DRP employs a two phase location tracking mechanism. Suppose node *X* is presently forwarding a packet to node *Y*. If the transmission of an RTS from *X* to *Y*'s previous location fails for 3 consecutive attempts, node *X* tries to locate *Y* in its adjacent antenna beams for the remaining tries. Hence the 4th, 5th, 6th and 7th RTS is sent at *n* adjacent antenna beams, including i. Clearly, the value of *n* depends on the antenna beam-width. The reason behind scanning adjacent antenna beams is obvious. If a node is not reachable through adjacent antenna beams, the validity of the old directional path to the same destination becomes questionable. we demonstrate two positions of node *Y*, one at position (x1, y1), where *Y* can still maintain the connectivity to *Z*, whereas at position (x2, y2) the path from *Y* to *Z* is already broken. This simple example helps us to understand the antenna beams of *X* at which node *Y* can move, and *may* still have connectivity to *Z*. In addition it also shows the number of antenna beams we need to send our RTS packet to locate *Y*. This approach of locating *Y* to only a subset of antenna beams is different from some of the existing schemes [7], which recommend transmitting an RTS to all beams.

6.5 Two-Hop Directional Local Recovery Phase:

In the two hop directional local recovery in DRP. After detecting a broken link to *Y*, node *X* identifies the second nexthop in its path and generates a directional RREQ packet to find the route to *Z* with maximum propagation limit set to 2. This RREQ packet is sent only towards the direction (beam) of *Z* and intermediate nodes which receive this packet are also supposed to forward the packet in that direction. Call this two-hop directional local recovery in DRP. After sending a two-hop directional RREQ, the sender node starts a timer for duration T_l within which it expects a RREP. Here T_l is selected such that it would allow two hop route recovery to succeed. If a reply is received within this duration, node *X* stops its timer, and informs node *S* about the new route. Use Route Error (RERR) packet to convey route update information to the source. Here used a *LOC_RERY* flag in the RERR packet to identify if it's a two-hop directional route recovery packet. If the *LOC_RERY* flag is set, the RERR packet includes the updated route. A source, after receiving a RERR packet with *LOC_RERY* flag set, updates its route to the corresponding destination.

The following route shows before and after the two hop directional route recovery procedure. If node *X* fails to get any reply in duration T_l it generates a RERR Packet and sends it towards the source. This time *LOC_RERY* flag is set to false.

6.5 Route Recovery Phase

After receiving a *RERR* packet with *LOC_RERY* flag set to false, the source node first tries a *zonal route repair* to locate its destination. The concept of a *zonal route repair* is to limit the zone in which the route request packet is propagated by estimating the location of the destination node relative to itself. Let us revisit and assume that node *A* requires to rediscover a route to *E*, and the previous route to *E* maintained at its route cache. Assuming all the nodes to be equipped with four beam antennas, *A* begins by approximating the relative position of *B*.

Since *B* receives a packet from *A* in its antenna beam 2, by symmetry *B* will lie in the antenna beam 4 of *A*. If the average separation between the nodes is *R*

(which is assumed to be half of the nodes transmission range), then *B* is assumed to lie at distance *R* on the angular bisector of antenna beam 4 of *A*. Hence the co-ordinates of *B* relative to *A* are (*Rcosx*, *Rsinx*). Next the co-ordinates of *D* and then *E* are estimated. Finally, *A* calculates the angular position of *E* relative to itself. *A* will then pad this angle by 45 degrees on either side. It will send the *RREQ* packets in only those beams which lie within this angle. Hence, in above example *A* shall send route request packet in beams 1 and 4. All the nodes receiving this route request packets are supposed to forward the route request in antenna beams 1 and 4 only. This limits the zone of the transmission of route request packets.

Two observations can be made from this. Firstly, the algorithm performs better for lower beam widths. This can be easily explained as we approximate the next hop to lie on the angular bisector. With lower beam widths, the margin of error gets reduced. Secondly, the algorithm estimates destinations to a reasonable degree of accuracy.

7. CONCLUSION

In this Report, a cross layered directional routing protocol (DRP) specifically tuned to the underlying directional antennas has been introduced. DRP attempts to alleviate some of the inherent drawbacks involved in directional communications while exploiting the potential benefits such as increased coverage range and directionality.DRP has a substantial decrease in route discovery latency as well as directional broadcasting overhead as compared to DDSR. The efficient route recovery mechanisms in DRP prevent any throughput degradation due to frequent movements of intermediate nodes. However, it is worthwhile to note that throughput gain in case of directional antenna systems depends on the topology under consideration.

Results have been promising, validating the effectiveness of DRP. The plan to evaluate DRP over varied network topologies and network traffic conditions including different mobility models. A plan can also be made to investigate the performance of TCP over directional antenna systems.

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