Multipath Routing in Ad Hoc Networks Using Directional Antennas

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***Abstract*— A new routing scheme for ad hoc networks using directional antennas is introduced in this paper. Ad hoc network with directional antennas has become an active research topic because of the potential capacity increase through spatial reuse. Currently researchers have applied conventional ad hoc routing protocols (e.g. DSR, AODV) [1] [2] on this type of networks, and routing schemes are based on the shortest path metric. However such routing approach often suffers long transmission delay and frequent link breakage at the intermediate nodes along a selected route. This is caused by a unique feature of directional transmission commonly known as "deafness" [6]. In this work, we take a different approach by exploring the advantage of spatial reuse through multipath routing. A study on the effectiveness of conventional routing schemes in ad hoc networks with directional antennas is presented, and a special design of a multipath routing algorithm for directional transmissions is proposed. Experimental results demonstrate a clear performance improvement in terms of throughput and delay.**

I. Introduction

In wireless ad hoc networks, mobile devices are normally equipped with omnidirectional antennas. Omnidirectional antennas transmit and receive electromagnetic signals equally in all directions. Because of the broadcasting nature, conventional MAC protocols for ad hoc networks specify that while one node is transmitting, all the nodes within the transmission range have to pause their possible transmissions until the channel becomes idle again. This MAC scheme poses a certain capacity limit for the ad hoc network. As researches on "smart" or "adaptive" antennas making significant progress in recent years, the technology of directional transmission becomes available to mobile ad hoc networks. Directional antennas partition the omnidirectional transmission area into a fixed number of sectors, Fig 1(a). Transmission in one sector will not affect signal propagation in other sectors. Therefore a spatial region previously occupied by one omnidirectional transmission may now be shared by several directional transmissions. This feature is referred to as "spatial reuse". Although directional antennas have potential to increase network capacity and throughput, they also cause some new problems, such as increased route discovery overhead, complicated MAC and routing protocols etc. For example, with directional transmission, a broadcast requires the same packet to be transmitted over all antenna elements sequentially – "sweeping". This may causes long medium access delay and different receiving times at different neighbor nodes. Route specification also becomes more complicated because each node needs to know not only the next hop but also the antenna element (i.e. the direction) for the next hop. This implies longer routing messages and larger routing tables.

In this work we attempt to study the effects of directional transmissions on routing schemes in ad hoc networks. A typical directional MAC (DiMAC) protocol [5] is employed in our study. Three routing schemes are presented. First we apply the conventional dynamic source routing (DSR) protocol directly on DiMAC. Secondly, we introduce some necessary modifications to adapt DSR for directional transmissions, the resulting protocol is referred to as DiDSR. Finally we propose a new Multipath Directional Antenna ad hoc Routing (MDAR) protocol that can effectively take the advantage of spatial reuse and improve the routing performance.

II. Relate Work

Although the application of directional antennas in cellular networks has been extensively studied, research in multi hop ad hoc networks is relatively limited and mainly confined to medium access control protocols. A few studies involving routing schemes for ad hoc networks using directional antennas are reported in [5] [6] [3] [4] . In [3], the authors use directional antennas to improve the efficiency of on-demand routing protocols in mobile ad hoc networks. The idea is to use directional re-broadcasting during the route re-discovery process. In a conventional route re-discovery process, route request is flooded throughout the network once again. However, this flooding is not necessary in most cases, because of the knowledge of previous direction of the destination node. In this paper, the authors assume that every node knows its direction to other nodes. When a transmission is broken, the re-discovery process only sends route request to the previous direction of the destination. By this means, the overall routing overhead can be reduced. In [4], the directional antennas are used to improve routing performance in two situations. One is in the case of dynamic network partitioning due to mobility, and the other is during route repair process caused by the movement of intermediate node. The proposed method takes advantage of an important feature of the directional antenna – longer transmission distance. In [5], a simple Medium Access Control (MAC) protocol named DiMAC is proposed and the DSR routing protocol is evaluated based on DiMAC.

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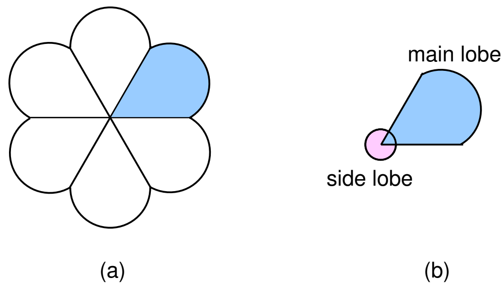

Fig. 1. Antenna sector partition and radiation pattern.

Several modifications are also introduced to improve DSR performance for directional transmissions. Because of the unsolved "deafnes" problem, the authors concluded that the advantage of using directional antennas in ad hoc network was not guaranteed and in some scenarios it would be better to use omnidirectional antennas.

III. Antenna and MAC Models

The antenna model in our study consists of N beam patterns, Figure 1(a). We assume the main lobe of each beam has a conical radiation pattern with $2\pi/N$ radians, Figure 1(b). The antenna can work in two modes: Omnidirectional and Directional. In directional mode, only one beam can be used at one time with a gain of G_d, and in Omnidirectional mode, signals are received with a gain of G_o. G_d is inverse proportional to the number of beams used. The transmission distance of the antenna is proportional to the transmission gain. So, the directional transmitters can reach longer distance than omnidirectional transmitters at the same transmission power.

A. MAC protocol

A "directional Medium Access Control" protocol (DiMAC) [5] is adopted as the MAC protocol in our study. DiMAC is based on IEEE 802.11 Distributed Coordination Function (DCF) [7] and it also uses RTS and CTS for channel reservation. With DiMAC, RTS/CTS packets are both sent and received by directional antennas over a single specified antenna element. According to DiMAC specification, three modules have been implemented based on 802.11 DCF:

1. Channel reservation mechanism for each antenna element. This includes timers for "send" and "receive", as well as NAV status to indicate the channel situation for this element and the sent/received packets.

2. Sweeping function for broadcasting. Broadcasting is necessary in route discovery phase. Sometime sweeping on certain antenna elements may fail because these elements may encounter busy channel. There is a tradeoff between the number of retry attempts and route discovery delay. In our DiMAC implementation, only one retry is performed for each element if that channel is busy. And also, when a neighbor node receives a broadcasted packet, it will not reply back immediately, since the sender may be transmitting over other antenna elements. The receiver has to wait for a time period which allows the sender to finish its sweeping.

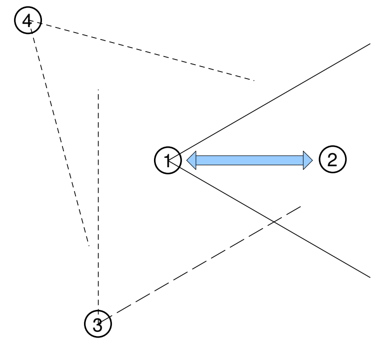

Fig. 2. Illustration of node "deafness".

3. Neighbor table. For single hop delivery, the sender has to know not only the next hop station, but also the antenna elements for the next hop. To do this, a neighbor table has to be created and maintained for updating and looking up information related to each antenna element.

Deafness [6] is a unique and critical problem for directional MAC protocol such as DiMAC. As shown in Figure 2, when Node 1 is communicating with Node 2 over one of its antenna element, it can not hear (or can not respond) any signal from other elements. The problem is that DiMAC uses directional transmission for RTS/CTS exchange between Node 1 and Node 2. Therefore any other node (e.g. Node 3 or Node 4) lies in a different direction will not hear this RTS/CTS channel reservation. If Node 3 or Node 4 attempts to communicate with Node 1 during its data transmission with Node 2, it will not receive any reply before its timeout. After a number of retransmissions, Node 3 or Node 4 will conclude that Node 1 has moved away and any route through Node 1 is broken. Clearly this feature will affect both MAC performance and routing performance.

IV. Routing Protocol Description

The routing protocols in ad hoc networks can be generally classified into two categories: reactive and proactive protocols. Most existing routing protocols for ad hoc networks are reactive protocols. Reactive protocols perform route discovery if there are packets need to be sent and no route available to the destination. Reactive protocols achieve low routing overhead at the cost of extra route discovery delay.

Most existing routing protocols for ad hoc networks select a single route for packet delivery based on least hop count. In this paper, we argue that these conventional routing schemes are inefficient for ad hoc networks with directional antennas. The major problem is the deafness phenomena at intermediate nodes. More specifically, assume a data flow **F** is routed through the antenna element ***e*** of an active intermediate node **X**. If Node **X** has frequent data exchanges over other antenna elements, flow **F** will soon suffer a link breakage because of the deafness of Node **X** over element ***e***. Conventional routing protocol will initiate costly route rediscovery and data retransmission processes, although node **X** may become available to flow **F** very soon. The deafness of all active nodes significantly increases the dynamics of instantaneous topology of an ad hoc network. Its effect is even greater than that of mobility, because switching from one antenna element to another can be very fast, and the duration of each session of data exchange is highly unpredictable. This poses a major challenge to routing design for ad hoc networks with directional antennas.

We proposed a reactive source routing protocol for ad hoc networks using directional antennas. It is referred to as Multipath Directional Antenna ad hoc routing (MDAR). In MDAR, every node maintain a routing table, which lists the paths from the sender to each possible destination. Each node updates the routing table according to the overheard packets no matter what their destinations are. A distinctive feature of MDAR is that the routing table records multiple choice of routes to each destination, so when one route encounters busy channel, an alternative route can be selected immediately. The source node puts the whole path into the packet header, and intermediate nodes forward the packet according to the specified path in its header. When there are packets to be sent and there is no available route to the destination, a route discovery process is initiated.

During the route discovery process, the sender broadcasts a route request message using sweeping mechanism. When a neighbor node receives the route request, it will search through its own routing table. If it finds no available route to the destination, it will re-broadcast the route request immediately over all its antenna elements except for the one where it received the message. If it has available route(s), it will send a route reply message back to the sender after a short delay, which allows the sender to finish its sweeping. In the packet forwarding process, each node delivers the packet to the next hop according to the route specified in the packet header. If the first attempt fails, MDAR assumes a possible collision and will try two more times. If all these attempts fail, MDAR assumes that this neighbor node is busy and an alternative route is used immediately. If an alternative route is not available or it is much more costly than the original route in term of hop count, the node will keep using the original route until it assumes that this link is indeed broken. The idea here is to forward the packet to the next hop as soon as possible. Because of possible spatial reuse provided by directional antennas, the chance of finding an alternative route is much higher than the situation in omnidirectional transmission environment. Multipath routing can minimize per hop delay, and therefore effectively reduce the overall end-to-end delay. The number failures for each next-hop attempt is recorded and when it exceeds some threshold, MDAR assumes that this neighbor node may have moved to another location. A scan function of neighbor table is performed to locate this neighbor node in adjacent antenna elements. If the scan process fails, a broken link is assumed and the node performs a routing update.

The forwarding process requires that an alternative route exists and with a cost similar to that of the original route. This depends on the number of alternative routes stored in the intermediate node. To increase multipath knowledge, the intermediate node can forward an old route request if it comes from a different sender or it has a shorter length. This will certainly generate more routing packets, which increases the routing overhead. However the benefit of this approach is that the destination and the intermediate nodes can learn more disjoint routes. A special feature of using directional antenna is the sweeping delay caused by broadcasting. Therefore the first received route request may not represent the shortest route [5]. In MDAR, the destination node delays its route reply for a short period, which may equal to the sweeping delay. It may also send out alternative routes with reasonable route costs.

Because of the longer transmission range of directional antennas, the links are not as easily to be broken as seen in networks using omnidirectional antennas. The node may take longer time to move out of neighbor's range under the same topology changing speed. However, in directional ad hoc networks, the node may frequently move into adjacent antenna elements of the same node, especially when there are many antenna elements. This requires a handoff mechanism. The handoff function is implemented in MAC protocol, in which the locations of antenna elements of a neighbor node is regularly updated in the "neighbor table". For routing protocol, handoff and real link breakage should be processed separately.

The routing table and the neighbor table in a mobile node should be kept up-to-date. There is a timer for each entry in these tables. A staled entry will be deleted promptly. Antenna element entries in the neighbor table are updated reactively whenever a handoff happens. A "route error" packet is generated when there is a broken link. Any nodes overhearing this route error packet will update its routing table according to the error information.

V. Simulation results and analysis

Simulations are conducted on the Network Simulator (ns-2) developed by UC Berkeley. We also use the simulation module developed by the Monarch research group at CMU for ad hoc networks with physical, MAC, and network routing protocol on ns-2. At the MAC layer, a directional MAC is implemented according to the specifications described in Section 2, which includes the directional RTS/CTS handshake and neighbor table features. Lucent's WaveLAN is assumed for the radio model, with a nominal radio range of 250 meters. Please refer to [1] for a detailed description of the physical environment.

In all scenarios, a send buffer with a size of 50 packets is maintained to store data packets waiting for a route. All senders use continuous bit-rate (CBR) as traffic sources, and the source node as well as the destination node are selected randomly over the network. All flows contribute to network traffic and their packet sizes are set to be 512 bytes with a four packet per transmission rate. 40 traffic flows are used to test the overall performance.

Movements of the mobile nodes are modelled using the random waypoint mobility model [1] in a rectangular field with a dimension of 1000×1200 square meters. A total of 50 nodes are simulated. At the beginning, each node has a random initial location, it will move to a random destination with a

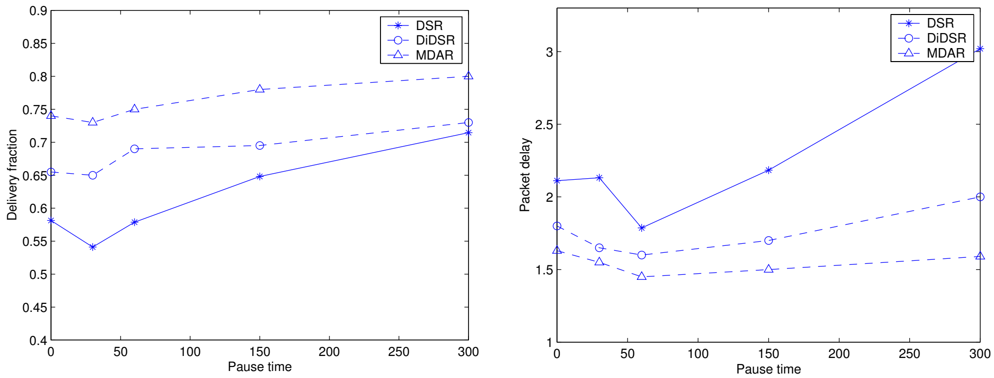

Fig. 3. Performance comparisons of three routing and MAC protocol combinations. (a) Delivery Proportion, (b) End-to-End Delay (sec.).

randomly selected speed (uniformly distributed between 0 to 10 m/sec). When the destination is reached, another destination node is chosen after a pause. Pause time also varies to change the relative speed of mobile node. For the purpose of fair comparison, identical traffic and mobility scenario files are simulated for different protocols. Simulations are run for 300 seconds. Each data points are calculated as an average of 10 runs with different mobility scenarios.

Two metrics are used to test the performance: delivery proportion and end-to-end packet delay.

1) Delivery proportion (DP) is the ratio of the number of received packets to the number of packets generated by the source node, i.e.

2) End-to-end packet delay is calculated only based on the successful transferred packets. It includes the route discovery delay, the queuing delay at each intermediate node, the contention delay at MAC layer and the transmission delay for each hop.

There are tradeoffs when choosing the number of antenna elements. Longer transmission distance can be achieved by more antenna elements with narrow beamwidth, however at the costs of longer sweeping delay, higher control overhead, and more handoff operations. The simulation is based on a six-element antenna system.

The performance curves in Figure 3(a) and 3(b) represent three routing and MAC protocol combinations: DSR over 802.11 DCF, DSR over DiMAC (DiDSR) and MDAR over DiMAC.

Figure 3(a) shows that DiDSR and MDAR achieve higher packet delivery fraction than DSR. The reason has two folds. One is the longer transmission range of directional transmission reduces the number of hops for the selected routes. And also because of the longer transmission distance, route error and route rediscovery become less frequent. The routing overhead is reduced accordingly. The other reason is that directional antenna reuses the space among antenna elements and thus increases the channel capacity. MDAR uses multiple paths to further reduce the number of route rediscovery and then increase the time fraction for sending the data packet, which contributes to the superior performance. MDAR also distinguishes handoff, busy and link breakage, and it performs different actions accordingly. This approach effectively reduces the number of route discovery.

Figure 3(b) presents the average end-to-end delay for successfully delivered data packets. DiDSR and MDAR have shorter delay than DSR, but the improvement is limited. Several features of MDAR increase packets' end-to-end delay. First, the sweeping operation used in both DiDSR and MDAR??? will cause longer delay for broadcasting. Second, the destination also has a delay after the route request packet arrival. MDAR has better delay performance because at intermediate nodes, it does not wait for many retries before it turns to alternative route.

VI. Conclusion

A multipath routing in directional antenna ad hoc networks (MDAR) is proposed in this paper. Several issues related to effective routing in directional antenna ad hoc networks are addressed and modifications to adapt multipath routing for directional antennas are introduced. The performance improvement demonstrates that with proper routing and MAC protocols, the directional antenna can in fact improve the performance of ad hoc networks.

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