Analysis of Multipath Routing for Ad Hoc Networks using Directional Antennas

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Abstract— **Ad hoc network with directional antennas has become an active research topic because of the potential capacity increase through spatial reuse. Currently researchers have attempted to apply conventional ad hoc routing protocols (e.g. DSR, AODV) on this type of networks. The routing schemes are typically based on the shortest path metric. However such routing approach often suffers long transmission delay and frequent link breakage at the intermediate nodes. This is caused by a unique feature of directional transmission commonly known as "deafness"[1]. To address this problem, we have introduced a new multi-path routing scheme to explore the advantage of spatial reuse for reducing per hop medium access delay. In this work, an analytical and numerical analysis of the directional ad hoc network behavior is presented, along with an introduction of our multi-path routing scheme and a discussion on the effectiveness of this scheme in balancing per-hop delay and hop-count for packet forwarding. Simulation results demonstrate a clear performance improvement by using multi-path routing for directional ad hoc networks.**

I. INTRODUCTION

As progress being made on "smart antenna" or "adaptive antenna" technologies in recent years, directional transmission using beamforming antenna array becomes an attractive option for wireless systems. Directional antennas partition the omni-directional transmission plane into a number of sectors, known as antenna elements. Transmission in one sector will not affect signal propagation in other sectors. Therefore, a spatial region previously occupied by one omni-directional transmission may now be shared by several directional transmissions. It can effectively reduce channel interference and therefore increase channel capacity.

Although directional antenna has the potential to increase network capacity, it can also cause new problems. For example, with directional transmission, a broadcast requires the same packet to be transmitted over all antenna elements sequentially - "sweeping". At MAC layer, sweeping may increase medium access delay and cause synchronization problem for medium reservation in CSMA/CA mechanism. At network layer, routing protocol has to be modified so that each route request will be sent multiple times to sweep through all antenna elements. A more fundamental problem is caused by the fact that directional antenna can only communicate over one or a few elements at a given time, which makes a mobile node temporary "deaf" and invisible on all the other directions. This problem will cause unstable routing behaviors because any identified route can be easily broken if one of the node is steering to a different direction.

In this work, we attempt to investigate the effects of directional transmission on routing performance in ad hoc networks. The "deafness" problem is studied analytically and numerically, after which the evaluation of our multi-path routing scheme for directional networks is presented.

II. RELATED WORK

Although the application of directional antennas in cellular networks has been extensively studied, research on directional multi-hop networking is relatively limited and mainly confined to medium access control protocols. A few related studies involving routing schemes are reported in [2][3][4][1]. In [2], the authors suggested of using 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. The authors assumed that every node knows its directions to other nodes. When a transmission is broken, the re-discovery process only sends route request to the previous direction of the destination. In [3], the directional antennas were used to improve routing performance in two situations. One was in the case of dynamic network partitioning due to mobility, and the other was during route repair process caused by the movement of intermediate node. The proposed method takes advantage of an important feature of the directional antenna, i.e. longer transmission range. In [4], a simple Medium Access Control (MAC) protocol named DiMAC was proposed and the DSR routing protocol was evaluated based on DiMAC. Several modifications were also introduced to improve DSR performance for directional transmissions. Because of the unsolved "deafness" 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. ANALYTICAL AND NUMERICAL ANALYSIS OF NODE "DEAFNESS"

In this section, the occurrences of link breakages in omni and directional networks are analyzed. The number of link breakages is defined as the number of times the MAC protocol experiences an RTS failure or a DATA handshake failure. A handshake failure is normally caused by a CTS or ACK failure.

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In omni-directional networks, the link breakage is mainly caused by the movement of mobile nodes. When a node D moves out of the range of a neighbor node S, and if S wants to transmit packets to D, then S will experience a number of RTS failures. When this number of failures reaches a limit, S assumes that D has moved out of the transmission range, and a control message of link breakage is generated. However, in directional networks, the major cause for link breakage is node "deafness".

A. Analysis of link breakage in Omni-directional networks

Due to the randomness behavior, it is difficult to accurately model the node movement. In our study and simulation, we adopt the "random waypoint mobility model" [5]. Suppose the dimension of an omni-directional network is $a \times b$, and there are N nodes inside the network. Each node randomly selects a destination in the field, and moves to that point at a speed randomly selected from the range [0, *maxspeed*]. When the destination is reached, the node pauses for p seconds, then selects another destination. Here, the variable *maxspeed* and p can be used to adjust the mobility of the network.

The transmission range of the omni-directional antenna is defined as R, then the average number of neighbors for each node is:

$$a_n = \frac{n}{ab}\pi R^2, \tag{1}$$

Because we want to compare the numerical results with the simulation results, the numerical analysis are based on the simulation parameters.

In the simulation, the transmission range is set to be 250m and the maxspeed is set to be 5 m/s, then the average speed for each node is around 2.5 m/s. Assuming the experimental time is 100 seconds. So for the most dynamic scenario, i.e. pause time equals to 0 (i.e. the node is always moving), the average travel distance during the simulation for each node is 250m. Since the travel distance and transmission range are comparable, it is reasonable to assume that the average occurrence of link breakage for each node is about once per simulation duration. Based on this assumption, it is not difficult to find an upper bound for the total number of link breakages for the omni-directional network. Suppose all the nodes are active nodes and each node has an active communicating link with a half of its neighbor nodes, then the total number of link breakages is less than *Lb*, where *Lb* has the expression,

$$L_b = n\frac{1}{2}\frac{n\pi R^2}{ab}, \tag{2}$$

For some travel directions, the neighbor node will remain in the transmission range of the source node even if it travels up to 250m away. In this case, an active communication will not break during the whole simulation. Also considering that the many communications may not start from the very beginning of the simulation, the actual number of link breakages may be far less than this upper bound value.

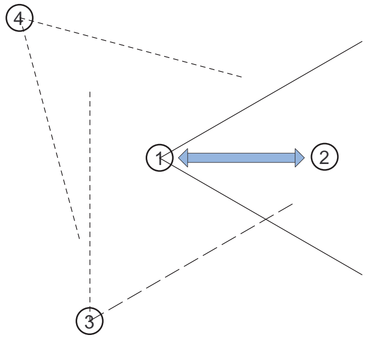

Fig. 1. Illustration of node deafness.

B. Analysis of node "deafness" in directional networks

"Deafness" [1] is a unique and critical problem for directional MAC protocol such as DiMAC. As shown in Fig. 1, when Node 1 is communicating with Node 2 over one of its antenna element, it can not hear (nor can it respond to) any signal from other directions. The problem is caused by the fact 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.

In this section, we assume that all packet packets are transmitted directionally, which include data packets, RTS/CTS, and ACK packets. We adopt the network model used by Takagi and Kleinrock [6] and follow a similar approach as described in [7].

In this network, mobile nodes are spatially distributed based on a 2-D Poisson density λ, i.e. the probability $p(i, S)$ of finding i nodes in the area of S can be expressed as:

$$P(i, S) = \frac{(\lambda S)^i}{i!}e^{-\lambda S} \tag{3}$$

All the nodes are assumed to operate in time-slotted mode, given the time slot length is much shorter than the packet length. The transmission time of all packets are normalized with regards to the slotted time, and they are denoted as $L_{rts}, L_{cts}, L_{data}, L_{ack}$. Each node begins its transmission with a probability p at the beginning of each time slot. p is protocol-specific and depends on the working mode of collision avoidance.

The node can only be in three different states as shown in Fig. 2. *Wait* is the state where the node is deferring or backing off; *Succeed* is the state where the node can complete a successful transmission with other nodes; and *Fail* is the state where the node initiated a handshake which turns out to be unsuccessful.

We list the known values for most of the parameters in Fig.

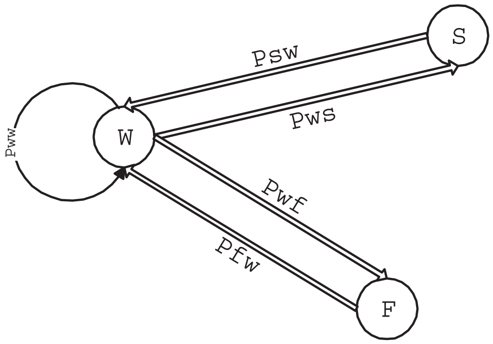

Fig. 2. Markov Chain Model

2 as follows:

$$\begin{aligned} T_{succeed} &= L_{rts} + L_{cts} \\ &+ L_{data} + L_{ack} + 4 \\ T_{wait} &= 1 \\ P_{sw} &= P_{fw} = 1 \\ P_{ww} &= (1-p)e^{-p'N} \end{aligned} \tag{4}$$

where, $p' = p\theta/2\pi$. Let π_s, π_w, π_f denote the steady-state probability of the state $Succeed, Wait, Fail$ respectively. Based on the Markov chain:

$$\begin{aligned} \pi_w &= \pi_w P_{ww} + \pi_s + \pi_f \\ \pi_w &= \frac{1}{2-P_{ww}} \\ \pi_s &= \frac{P_{ws}}{2-P_{ww}} \\ \pi_f &= 1 - \pi_w - \pi_s \end{aligned} \tag{5}$$

In order to get the steady-state probability, we also need to know T_{fail} and P_{ws}. Because the communication can be interfered anytime between $L_{rts}+1$ and $T_{succeed}$, the mean value T_{fail} can be represented by:

$$T_{fail} = \frac{1-p}{1-p^{T_2-T_1+1}} \sum_{i=0} p^i (T_1 + i) \tag{6}$$

where, T_1 equals to $L_{rts}+1$ and T_2 equals to $T_{succeed}$. The calculation of P_{ws} is quite complicated. Since our analysis in this section is focused on "deafness", we will skip the derivation of P_{ws}, which can be found in [7].

In directional ad hoc networks, when one node has a packet to send and the channel is not busy, it can initiate a successful handshake with a neighbor node under the condition that the neighbor is in the Wait state. After taking into account the staying time of each state, the probability of a neighbor node that is in the Wait state is:

$$P_w = \frac{\pi_w T_w}{\pi_w T_w + \pi_s T_s + \pi_f T_f} \tag{7}$$

The occurrence of "deafness" depends on two conditions: 1. the neighbor node is not in its Wait sate. 2. the neighbor is busy in one of the directions other than the direction of the source node. So the probability of a node trying to initiate a handshake with a deaf node is:

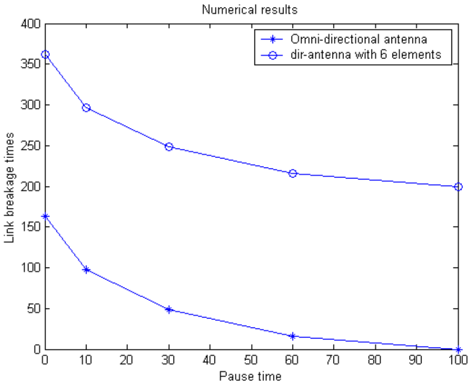

Fig. 3. Analytical study of link breakage in omni and directional networks

$$P_d = \frac{2\pi - \theta}{2\pi}(1 - P_w) \tag{8}$$

After a certain number of handshake initializations fail, a link breakage will be claimed. Let N_t denote the total number of handshake initializations for each node, and the link breakage threshold is *k*. The problem can be modelled as a binomial distribution with N_t number of tries and the probability of each try is P_d. The probability of a link breakage can be calculated by evaluate the probability of *k* consecutive Bernoulli tries. The total number of link breakages can be estimated as the mean value. For the sake of simplicity, we give a low bound for this mean value as:

$$N_{lb} = N_{node} \frac{N_t}{k} (P_d)^k \tag{9}$$

Where, N_{node} denotes the total number of nodes, N_t denotes the total number of tries.

The number of tries is a parameter related to the probability that a silent node initiates a transmission at each time slot. This probability, denoted as *p*, is a protocol-specific parameter, but is slot (or time) independent. According to [7], *p* must be kept very small due to the effects of collision avoidance and resolution. For directional networks, the number of communication tries is set to be 100, which is very conservative as simulation time is 100 seconds. k equals to 7 according to the IEEE 802.11 standard. Because the objective of the analysis is to provide an approximate comparison of link breakage frequency, our assumption is sensible.

Based on the analysis and assumption above, the analytical results are shown in Fig. 3.

C. Simulation of link breakage in omni and directional networks

The simulation is conducted on Network Simulator (ns-2). The objective is to investigate and compare the link breakage situation in omni and directional networks.

A fixed 64-packet send buffer is maintained at each node for the packets waiting for available routes. All traffics in

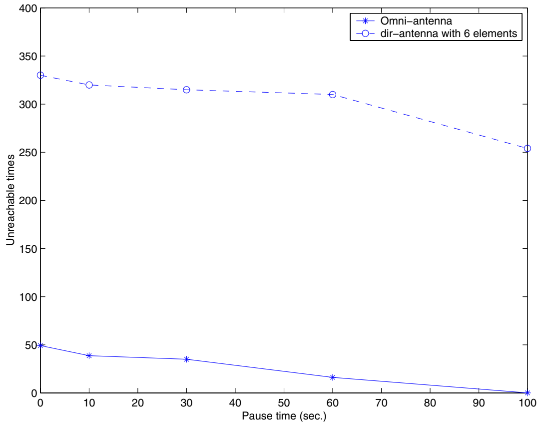

Fig. 4. Simulation results of link breakage in omni and directional networks.

the networks are set to have constant bit-rate (CBR) pattern. The source/destination pairs are selected randomly from the entire nodes set, and for each flow the transmission rate is four packets per second with packet size of 512 bytes.

To simulate the node movement, we assume a random waypoint mobility model [5] in a rectangular field with a dimension of 2500×600 square meters. Fifty mobile nodes are simulated in the network, and their initial locations are assigned randomly at the beginning of the simulation. The total simulation time for all nodes is 100 seconds, and each source node chooses its starting time for sending packets from the range of [0, *stime*]. *stime* is set to be 30 seconds in the simulation. To compare the results in a fair manner, identical traffic and mobility scenarios are applied to each protocol and each data point in the result graphs is an average of ten simulation runs.

Fig. 4 shows the link breakage for omni-directional and directional antenna systems. In omni-directional case, when the pause time equal to the total simulation time, that is, the mobile nodes keep still all the time, the link breakage is close to zero. This is because there is usually no broken link in a static network. When the pause time is less than the simulation time, there are some link breakages caused by node mobility. In directional case, the link breakage is almost ten times of the omni-directional. This is consistent with our analytical analysis, which confirms that directional antenna system has much higher topology dynamic because of node deafness.

IV. A MULTI-PATH ROUTING FOR DIRECTIONAL NETWORKS

In this section, we provide a brief description of the proposed routing protocol together with the directional MAC protocol.

A. *MAC Protocol*

The directional Medium Access Control protocol (DiMAC) [4] is adopted as the MAC protocol in our study. DiMAC is based on IEEE 802.11 Distributed Coordination Function (DCF) [8] 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, including a channel reservation mechanism for each antenna element, a sweeping function for broadcasting, and a neighbor table.

B. *Routing Protocol*

Most existing routing protocols for ad hoc networks select a single route for packet delivery based on least hop-count. We argue that these conventional routing schemes are inefficient for ad hoc networks with directional antennas. The major problem is the “deafness” at intermediate nodes, which may causes temporary but frequent link breakages. To address this problem, we introduce a reactive source routing protocol for ad hoc networks using directional antennas. It is based on Dynamic Source Routing (DSR)[5] and referred to as Delay-sensitive Multi-path Directional ad hoc routing (DSMDR). In DSMDR, every node maintain a routing table, which lists the paths from the sender to each potential destination. Each node updates the routing table according to the overheard packets no matter what their destinations are. DSMDR share the same route discovery and maintenance scheme with DSR, except for some modifications made for directional networks. One distinctive feature of DSMDR is that the routing table may record multiple routes to each destination, so when one route encounters a busy channel, an alternative route can be selected immediately. Some other modifications are listed as follows:

- Reducing broadcast storm. The conventional routing protocols require an intermediate node to forward a route request packet to all its neighbors if it does not have available routes. For directional networks, this requires the intermediate node to perform a sweeping to all directions. However, the re-broadcast in the back direction is unnecessary. Therefore an optimization can be made by limiting the broadcasting directions, i.e. on to the directions that are opposed to the source node. This may limit the spread of the route request packets, but it can save a lot of redundant receptions.
- Reducing the number of MAC retransmission. A conventional MAC protocol may try to retransmit a packet several times (default is seven in IEEE 802.11) if no response is received. This may introduce a long delay before the sender comes to realize that the receiver is not available. In a conventional ad hoc network, retransmission failure indicates a broken link, which only happens if a node is moved away or taken off-line. But it may happen frequently in a directional ad hoc network because of temporary node “deafness”. This number of retransmission becomes unacceptable and should be reduced.
- Keeping a temporarily non-responding node in the routing tables. In conventional routing protocol, a broken link will be removed from routing tables immediately, and a costly route re-discovery will be initiated. In

directional ad hoc network, this situation is mostly caused by temporary node "deafness", and the node may be still reachable and can be used in future transmissions. With the help of multi-path routing, usually no route rediscovery is immediately needed.

C. Simulation and evaluation

In this section we study the performance of two protocol sets, i.e. DSR/DiMAC and DSMDR/DiMAC, in various network topologies and mobility situations. Please refer to the previous section for a detailed description of the simulation environment.

Two metrics are used to study the routing performance, namely "packet delivery fraction" and "end-to-end packet delay".

1) Delivery fraction (DF) 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.

The simulation results are shown in Fig. 5 and Fig. 6. It should be noted that these two parameters are related to each other. Because the end-to-end delay is based on the successfully transferred packets, so low delivery fraction may imply high end-to-end delay in some situations.

In general DSMDR/DiMAC clearly outperforms DSR/DiMAC. The first reason is that DSMDR can find shorter routes with the help of longer transmission distance, and it can also bridge the gap in the network. The second reason is that the channel capacity is increased by spatial reuse. The third reason is that "deafness" problem is mitigated by utilizing multi-path routing.

The delay metric is presented in Fig. 6. For most mobility scenarios, DSMDR/DiMAC outperforms DSR/DiMAC. However, the performance is comprised by the long sweeping delay and other effects in directional MAC protocol. Especially when the network is static (i.e. longest pause time), DSR has less delay. The major reason is that there is almost no link breakage in this case and therefore, without the effect of route rediscovery, data packets do not need to wait for new route at intermediate nodes. But for the directional case, the link breakage is still a problem even in the static network. Thus, the extra route rediscovery lead to more delay. Another reason is that the delivery fraction in this case is very low, i.e. not many of packets can successfully reach the destination. Since the end-to-end delay is based on the successful delivered packets, it will reduce the delay when the delivery fraction is low. Also, the number of traffic flows in the network is not big enough to congest the network.

V. CONCLUSION

The effects of applying directional antennas to wireless ad hoc networks are studied analytically and numerically. It is demonstrated that the link breakage occurrence in directional networks is much higher than in omni-directional networks, which is caused by node "deafness". A multi-path routing for directional ad hoc networks is introduced to address this problem. The simulation results show that, with proper design of MAC and routing protocols, the directional antenna can improve the ad hoc network performance in some situations.

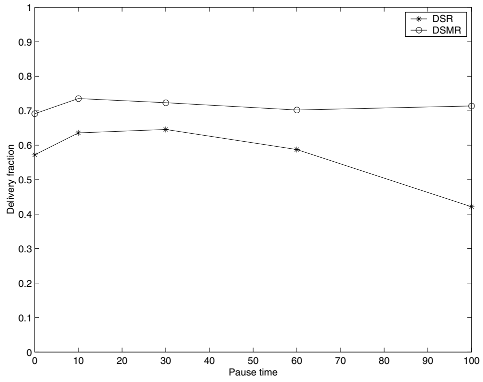

Fig. 5. Delivery Fraction.

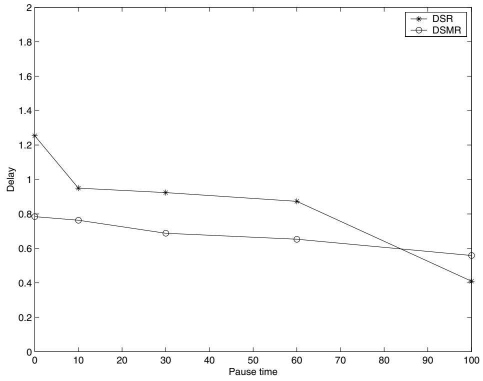

Fig. 6. End-to-end Delay.

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