PERFORMANCE IMPROVEMENT OF AD HOC NETWORKS USING DIRECTIONAL ANTENNAS

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Abstract

We investigate preventive link maintenance scheme to on-demand routing algorithms. The scheme of creating directional link is proposed to extend the life of link that is about to break. We see the performance improvement at network layer by using the proposed scheme. We do a comparative performance study between omnidirectional and directional antennas for DSR (On-demand routing protocol) using simulation with OPNET. By using directional antennas, substantial gain is achieved in terms of end-to-end delay, aggregate throughput, average data packets dropped, packet delivery ratio, and routing overhead. The proposed scheme is general and can be used with any other on-demand routing algorithms.

Keywords: *Directional Antennas, On-Demand Routing Protocols, Dynamic Source Routing, Physical Layer.*

1. Introduction

Typically, in Ad Hoc Networks, omnidirectional antennas have been used to communicate with other nodes for transmission as well as for reception. Omnidirectional antennas may not be efficient due to interference caused by the transmission of packets in all directions (other than target direction) and limited range of communications. Directional antennas may be useful to increase network efficiency by directing the transmitted power in the desired direction towards target location. Due to the mobile nature of Ad Hoc Network nodes in their applications, it is important to observe the effect of directional antennas on network layer. We propose novel scheme of link life extension by using directional radiation pattern, which helps to avoid or delay route rediscovery operation in routing protocol.

Recently, there has been increasing interest in developing protocols at link layer and network layer for Ad Hoc Networks where nodes are equipped with directional antennas [1, 3, 5, 6, 8, 10]. Previous researchers have shown, directional antennas based communications increase throughput because of better spatial reuse of the spectrum [2, 4, 5, 7, 9].

In traditional routing algorithms of wired, wireless and mobile networks, a change of path (route) occurs in one of two cases: (i) a link along the path fails; or (ii) a shorter path is found. A link failure is very expensive since: (i) multiple retransmissions/timeouts are required to detect the link failure; (ii) a new path has to be found and used (in on-demand routing) since spare path may not be readily available. In wired networks, route rediscovery is not very expensive since paths don’t fail very frequently. Routing protocols in mobile and wireless networks also follow the same model although they have significantly higher frequency of path disconnections.

A preventive link maintenance scheme proposed here initiates local recovery action early by detecting that a link is likely to break soon and uses directional antenna pattern to prevent link failure and thus extend the life of the link and reduce the cost of link failure. Note the similarity to on-demand protocols: we replace link failure, with the likelihood of failure as the trigger mechanism for directional antenna orientation instead of sending RERR (Route Error packet) to source node, which initiates costly operation of route rediscovery for new path from source to destination. We study the effectiveness of proposed preventive link maintenance scheme by simulating with OPNET software for DSR routing algorithms. Our scheme can be used for any other kinds of routing algorithm.

We have organized our paper in the following way. Section 2 overviews ad hoc routing algorithms and DSR (Dynamic Source Routing) in detail. Section 3 discusses the related work in this area. Section 4 discusses the antennas model used in the proposed scheme. Section 5 explains our preventive link maintenance scheme. We discuss performance evaluation in Section 6, in which we discuss simulation environment and results. At the end, we made some concluding remarks.

2. Ad Hoc Routing Algorithms

For multihop wireless networks, traditional Internet routing protocols are no longer efficient since the network topology is being changed dramatically due to node(s) movement. It presents a great challenge for a routing protocol to keep up with the frequent and unpredictable topology changes. Existing multihop wireless routing protocols can be generally categorized into two classes: table-driven (such as DSDV [12] and WRP [14]) and demand-driven (or Source-initiated such as DSR [11] and AODV [13], ZRP [15], LAR [16].

Table-driven routing protocols of wireless networks are similar to the routing protocols used in the wired network. They attempt to maintain consistent, up-to-date routing information from each node to every other node, regardless of the need of such routes. They respond to topology changes by propagating updates throughout the network. In contrast, on-demand (reactive) routing protocols attempt to discover a route to a destination only when it is needed or when it senses some activities to forward to the destination. These discovered routes are maintained by a route maintenance procedure until either the destination becomes inaccessible along every path from the source or until the route is no longer desired. The major advantage of the on-demand routing comes from the reduction of the routing overhead, as high routing overhead usually has a significant performance impact in low bandwidth wireless networks.

Overview of DSR protocol is presented here briefly since DSR is used to integrate with 802.11 and directional antennas as representative of on-demand routing protocols. DSR is a reactive (on-demand) routing protocol that is based on the well-known concept of source routing [17]. The protocol includes two major operational components: Route Discovery and Route Maintenance, and three types of route control messages, i.e., Route Request (RREQ), Route Reply (RREP), and Route Error (RERR). When a source node in the mobile ad hoc network attempts to send a packet to a destination but it does not have a route to that destination in its route cache, it initiates a route discovery process by broadcasting a route request packet (RREQ). This route request packet contains the source node address, the destination node address, unique sequence number, and an empty route record. Each intermediate node, upon receiving a route request for the first time, will check its own route cache. If it has no route to the destination, the intermediate node will add its own address to the route record and rebroadcast the RREQ. If it has a route to the destination in its route cache, the intermediate node will append the cached route to the route record and initiates a route reply (RREP) back to the source node. The route reply contains the complete route record from the source to the destination. The intermediate node ignores the late arrival of the same route request by examining the sequence number. If the node receiving the route request is the destination node, it will copy the route record contained in the route request and send a route reply back to the source. In most simulation implementations, the destination node will reply to all the route requests received as DSR is capable of caching multiple paths to a certain destination and the replies from the destination most accurately reflect the up-to-date communication topology.

In DSR, each node transmitting the packet is responsible for confirming that the packet has been received by the next hop along the source route. This can be done by either a link layer acknowledgement (as in IEEE 802.11), or a "passive acknowledgement" (in which the first transmitting node confirms the receipt at the second node by overhearing the second node transmitting the packet to the third node), or a DSR-specific software acknowledgement returned by the next hop. Thus, once a route is entered into the cache, the failure of the route can only be detected when it is actually used to transmit a packet but fails to confirm the receipt by the next hop. It is very critical to find a mechanism, which helps to avoid such link failure. We have proposed such a mechanism in this paper.

3. Related Work

Recently there have been several papers that have looked into the problem of data link layer and routing layer design for Mobile Ad Hoc Networks where nodes are equipped with directional antennas [1, 3, 5]. Most of the work towards the use of directional antennas has concentrated on MAC layer. The directional antenna models used in various papers include switched beam antennas (the antenna is sectored and one of these sectors is used depending on the direction of the communicating node), multi-beam antennas (here more than one beam can be used simultaneously), and adaptive antenna arrays.

The transmitters use omnidirectional antennas to transmit RTS frames and the receiver antennas remain in omnidirectional mode. Assuming the receiver is idle; it receives the RTS and transmits CTS, again using an omnidirectional antenna. The transmitter estimates the angle of arrival (AoA) of the CTS being received and transmits data using the directed antenna beam. Since the transmissions and receptions involving omnidirectional antenna patterns are susceptible to collisions, this mechanism suffers from high probability of packet error.

Takai, et al. [4] extended by proposing the use of a caching mechanism to store information about angular location of neighboring nodes. This information is obtained from AoA estimation for frames received by each node. Whenever the medium access control layer receives a packet from an upper layer, it would look in the cache to determine whether it has the information about the angular position of the destination node.

Choudhury, et al. [5] and Takai, et al. [4] have suggested the use of directional virtual carrier sensing (DVCS), in which a Directional Network Allocation Vector (DNAV) is constructed. The DNAV table stores the angle of arrival of RTS packets along with the duration of data transmission in any given direction. Thus, when the medium access control layer receives a packet from an upper layer, along with the angular profile of the destination node with respect to the source node, the DNAV table is consulted to determine whether the angle overlaps with any of the ongoing transmissions.

In other work, Choudhury and Vaidya [17] have done rigorous analysis of using directional antennas and performance evaluation for on-demand routing protocols such as DSR. They used only single switched beam antennas. They have considerable sweeping delay due to the sequential transmission of same packet with different beam of antennas to cover the entire 360-degree. We use multiple directional antennas to solve the problem of sweeping and deafness.

We exploit this capability of directional antenna for extending the life of link. In addition, we use the location information to decide the direction of communication while Takai [4] used AoA estimation for frames received by each node. In this paper, we focus on preventive link maintenance scheme for improving the performance of reactive routing protocols such as DSR, while Ramanathan [7] discussed proactive routing protocol over ESPAR antennas.

4. Antenna Model

A directional antenna module is implemented in OPNET. There are two separate modes of operations of this model: omnidirectional and directional [5]. In normal operation, the omnidirectional mode is used, while the directional mode is used for both transmission as well as reception after preventive warning has been generated due to decreasing signal strength in received packet. Node can interchange the modes with negligible latency. We use multiple directional antennas (N) to avoid the sweeping operation and sweeping delay [17] that present in the case of single switched beam antenna.

In Omnidirectional mode, a node is capable of receiving signals from all the directions with a gain of GO. In the Directional mode, a node can point its beam towards a specified direction with gain Gd (with Gd typically greater than GO). Moreover, the gain is proportional to the number of antenna beams (i.e., inversely proportional to the beamwidth). Since more energy can be focused towards a particular direction, this results in an increased coverage range. Though it is not feasible to have a complete nonoverlapping pattern practically, we assume the nonoverlapping pattern for directional antennas. To model antenna side lobes, we assume that the energy contributed to the side lobes is uniformly distributed in a circular area. For simulation purpose, we also assume that the side lobe gain is fixed and is set to a very small value.

5. Preventive Link Maintenance Algorithm

In this section, we propose a novel directional link maintenance scheme based on signal strength. We name it Preventive Link Maintenance (PLM) scheme since we take preventive action before link actually breaks. We replace weak omnidirectional link with high quality directional link to extend the life. More specifically, the scheme consists of two components: (i) detecting that a link is likely to be broken soon; and (ii) establishing a directional link to it. Determining when link quality is no longer acceptable (which generates a preventive link maintenance warning) is a crucial component of the proposed scheme. The link quality can incorporate several criteria such as signal strength, the age of a link, and rate of collisions. In this paper, we assume the link quality to be a function of the signal strength of received packets. Since most link breaks can be attributed to link failures due to *node motion* in a typical ad hoc scenario, the signal strength offers the most direct estimate of the ability of the nodes to reach each other.

If directional link is established successfully before the omnidirectional link breaks, the cost of overhead for detecting a likely broken omnidirectional link (the retransmit/timeout time) is eliminated using preventive link maintenance. In other words, the cost for creating directional link is justified since the route recovery is initiated locally before the current link actually breaks. Eventually, it helps to improve the performance in terms of reduced latency (end-to-end delay), higher throughput, higher packet delivery ratio and reduced routing overhead.

When the signal power of a received packet drops below an orientation threshold, the preventive link maintenance warning is generated. The value of this threshold is significant to the effectiveness of the algorithm – if the value is too low, there will not be sufficient time to create directional pattern before the link breaks. However, if the value is too high, the warning is generated too early with negative side effects of unnecessary computing for creating directional link.

The decision to create directional link is made by a node based on measured signal strengths of its neighbors with whom it forms part of an active route. We maintain power information at nodes in terms of the *received power*. The decision to create high quality directional link because of weak signal strength is made when one end of the link senses that the *received power* has dropped below an *Orientation Threshold* and preventive link maintenance warning is generated. Operation of switching to the directional link from an omnidirectional link is called an *Orientation Handoff*. We incorporate *Orientation Handoff* into the DSR protocol by making these changes: Each node maintains a *Neighbor Received Power List* containing the received signal strength for last three received packets originating from each neighbor. This list is updated whenever a packet is received.

Use of time varying directional antenna patterns is envisioned to help in the establishment of directional links in multihop wireless networks that might otherwise not be possible with the use of omnidirectional antennas. We establish the links using directional antennas depending on the condition (signal strength) of the links within network between active nodes. Creation of directional link requires a priori knowledge of the location of the neighbor nodes or transmission/receiving direction. In this paper, we assume that wireless nodes can employ the techniques such as GPS to determine the direction of communications by having position information of nodes and can use that information to orient their antennas.

While establishing the link, the transmitter and receiver may fall into one of the following scenarios. 1) If the transmitter and the receiver are neighbors and the link between them is established by using an omnidirectional antenna, nodes are called *near neighbors.* 2) If two nodes are not near neighbors, they may be *far neighbors;* the link between them is established by using directional antenna. In this scenario, the source and destination node may establish a directional link between *far neighbors* by orienting their receiver and transmitter antennas towards each other. In this case, link is called an *extended link* and neighboring nodes are called *far neighbor.* The decision to establish an extended link between *far neighbors* for data transmission, instead of relying on multiple hops, depends on a number of factors, such as delay in establishing the link, feasibility of a directed link and the cost of the link in terms of its effect on aggregate throughput in the network.

The establishment of an extended link between *far neighbors* requires communications between the transmitter and receiver nodes through immediate link (when they are near neighbors) to allow appropriate orientation of transmitter and receiver antennas. The establishment of extended links can result in decreasing the end-to-end delay between end nodes (source and destination) since directional link between those intermediate nodes would eliminate (or reduce) the costly operation of route rediscovery. Depending on communication traffic load and relative positions of other nodes, the extended link will have the varying effect of increasing the overall network throughput.

We keep updating the *Neighbor Received Power List* on all the nodes while using directional link. In some mobility pattern, it may be possible to go back and use omnidirectional antenna when received signal strength is more than orientation thresholds for at least three consecutive received packets.

6. Performance Evaluation

6.1 Simulation Environment

This powerful simulation environment enables designers to create realistic wireless scenarios. In this work, we have modified the MANET node model to make it to work with four individual antennas. We have used predefined and fixed beams and created an antenna pointer model. The antenna gain pattern specified in the Antenna Pattern Editor is used to provide the gain values. Model includes four different antennas to cover four different directions (North-East, North-West, South-East, South-West). Antennas maintain this configuration with respect to the earth's meridian even if the node changes its orientation. Modern antennas can achieve it with the aid of magnetic needle that remains collinear to the earth's magnetic field. The antenna patterns have directional gain of 10 dBi with 90-degree beamwidth.

Parameters	Value
Area	2500 x 2500 sq. m
Number of Nodes	50
Directional Gain	10 dBi
Orientation Threshold	3 dBi
Packet Size	1024 Bytes
CBR Packet Arrival Interval	1 ms to 10 ms
Simulation Time	10 minutes
Number of simultaneous Connections	5 with a starting time lag of 10 seconds
Mobility Model	Random way point mobility model

Table 1 – Simulation Parameters

We use the network of 50 nodes placed randomly over area of 2500 x 2500 sq. meter. We have 5 random sources of CBR (constant bit rate) each of which generates 1024 bytes data packets to a randomly chosen destination at a rate of 2 to 50 packets per second. All five sources start data transmission with different times. All connections/communications end when simulation ends. For realizing realistic transmission range, the Hata Okumara path loss model [18, 19] is adopted. We use random waypoint mobility model to simulate different patterns of mobility (speed of nodes and pause time). The 802.11 standard protocol is used as MAC layer protocol for simulation. Simulations are run for 600 seconds and all results are averaged over 5 different seeds. We compare our results with original DSR over omnidirectional antennas. Table 1 shows the set of parameters used for our simulations.

We also modified the MANET node model to implement our scheme and to provide all necessary interfaces with the antenna models. The designed model is shown in Figure 1.

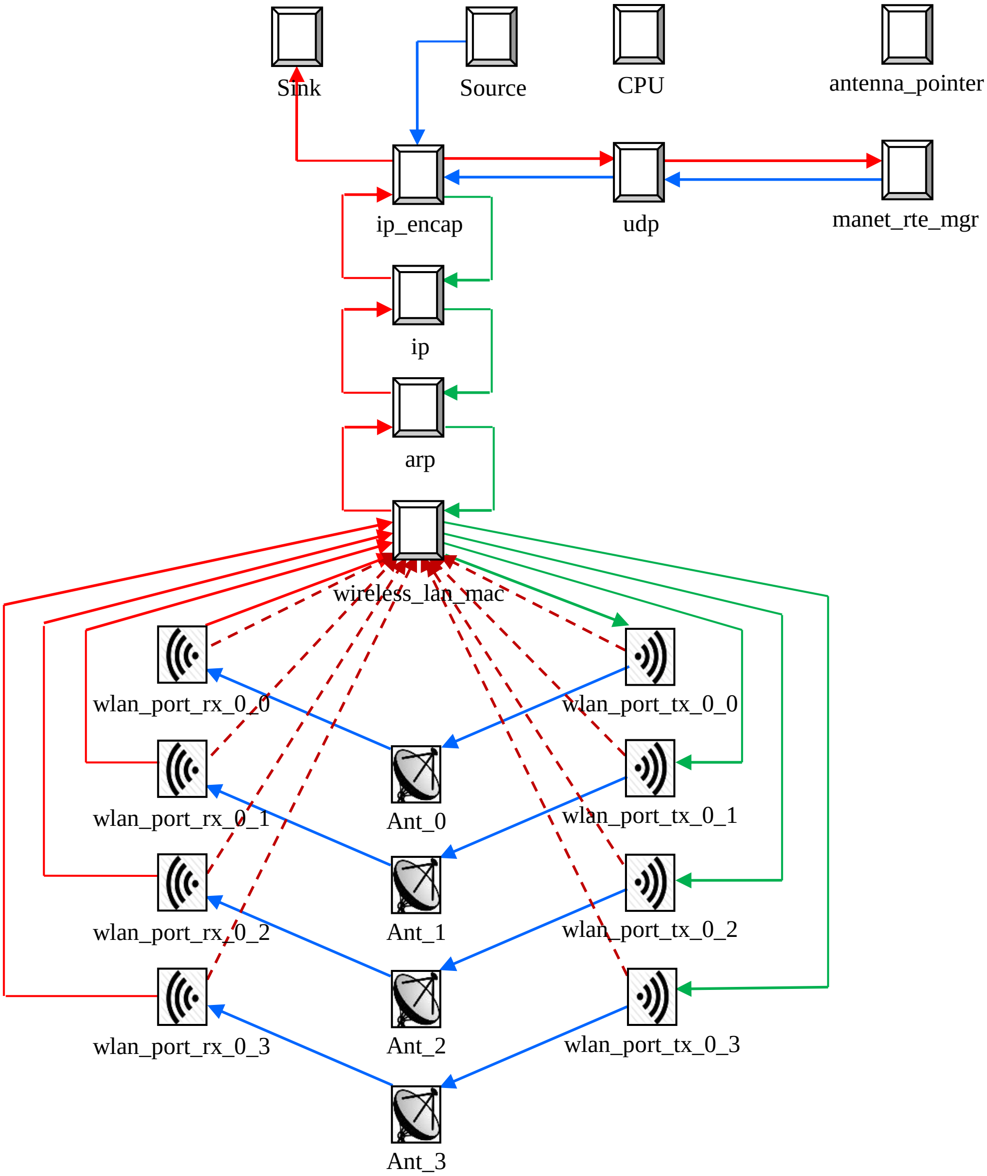

Fig.1 OPNET Node Model

6.2 Simulation Results and Discussions

In this subsection, we analyze the simulation results in terms of aggregate throughput, end-to-end delay (latency), number of packets dropped, packet delivery ratio, and routing overhead. Aggregate Throughput is the total number of bits transmitted from one node to other nodes in the network per unit of time. We collected this statistic in our simulation scenario and compared with original DSR (with omnidirectional antenna nodes). Our PLM scheme performs better in different scenarios since preventive link maintenance scheme allows link to live longer than omnidirectional case. Figure 2 shows that aggregate throughput is higher in our scheme using directional antenna. Aggregate throughput (performance) of entire network for our scheme is about 75% higher than original DSR for higher packet/data rate.

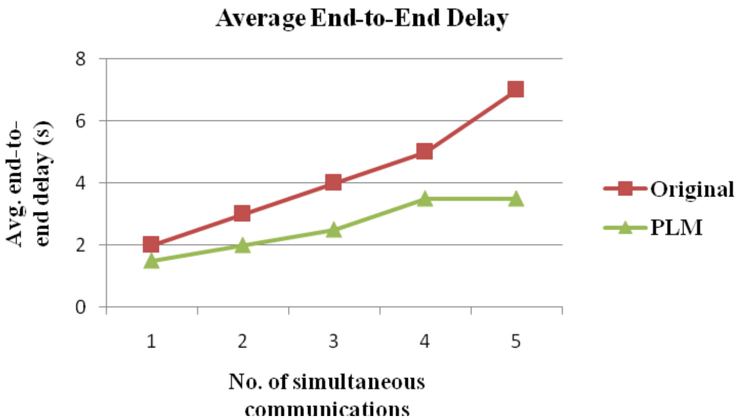

Fig. 2 Aggregate Throughput

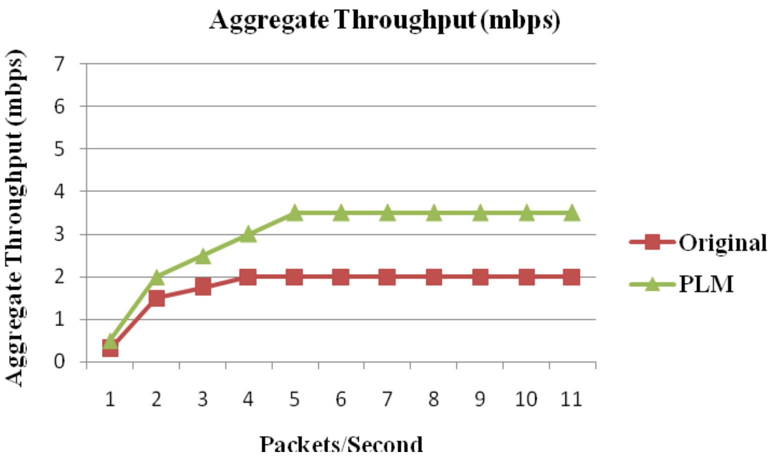

Fig. 3 Average end-to-end delay (latency)

End-to-end delay (latency) of packets for the entire network is the time elapsed between the creation of the packet at its source and its destruction at its destination. It is almost half in case of our scheme when we have five flows communicating simultaneously in compare to smaller number of simultaneous flows. In other words, the average end-to-end delay per packet increases much more sharply for original DSR algorithm than our scheme as shown in Figure 3. It can be concluded that routing performance improves when we have many simultaneous connections. It is also because of the number of directional antennas (four) we use in our simulation.

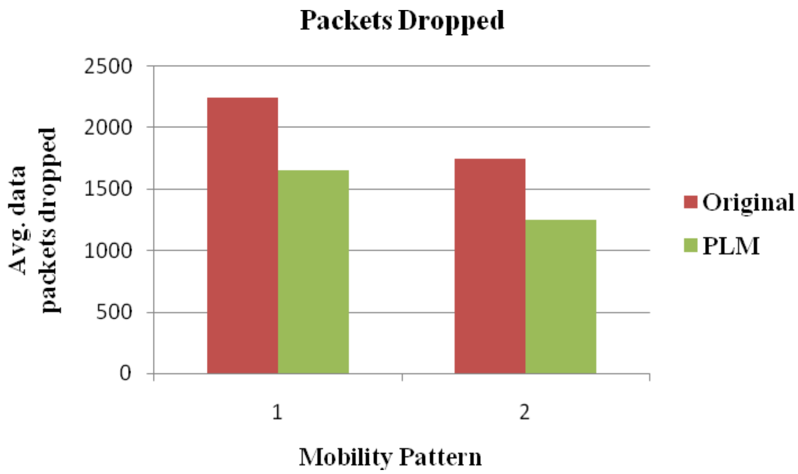

Fig. 4 Average Data Packets Dropped

When route is not found to the destination or the next hop reachability confirmation is not received (ACK not received), the node drops the packets queued for the destination after maximum number of attempted transmissions. This statistic represents the total number of application packets discarded by all nodes in the network. Average data packets dropped are about 20% less in case of our PLM scheme than for original DSR. We have simulated two different types of mobility pattern by choosing the different pause time (0 second pause time/continuous mobility and 20 seconds pause time) in random waypoint mobility model in OPNET as shown in Figure 4.

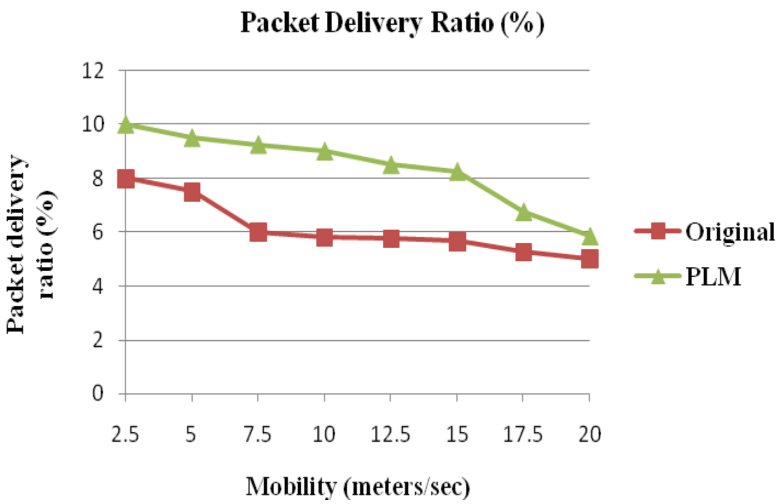

Fig. 5 Packet Delivery Ratio (%)

Packet delivery ratio is the ratio of the packets received to packets generated. Figure 5 shows this statistics. Packet deliver ratio is about 50% higher for PLM scheme than original DSR for mobility of 10-meters/second. This is also because of PLM scheme protects the link failure by creating directional link preventively. Packet delivery ratio drops down drastically for our scheme for higher mobility (20 meters/second), as we do not encourage using our scheme for higher mobility scenario. Still performance is better than original DSR with omnidirectional antennas.

Routing overhead per received packet is the ratio of the total number of routing control packets (including RREQ, RREP and RERR) generated/forwarded to the data packets received correctly at the destination. Figure 6 shows that routing overhead is about 40% to 60% less than original DSR. For high mobility scenario, original DSR produce larger routing overhead where as our scheme has lower routing overhead. Routing overhead increases as speed of mobile node increases, but the increment is slight. In summary, our result is consistent with what is expected in different scenarios.

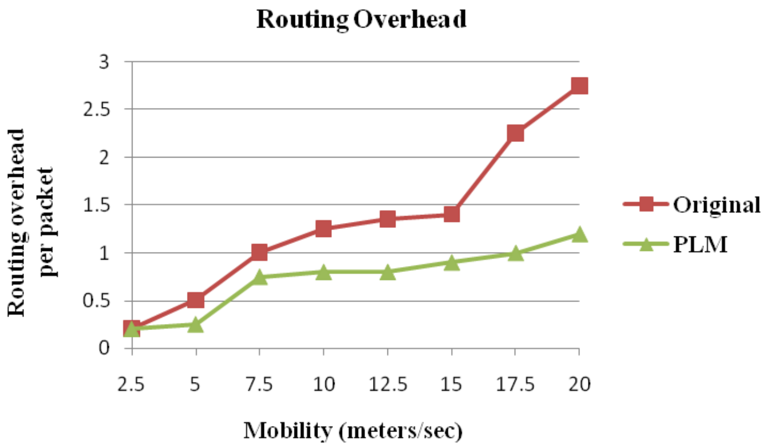

Fig. 6 Routing Overhead per Packet

7. Conclusion

A directional antenna module is implemented in OPNET simulator with two separate modes of operations: omnidirectional and directional. The antenna module has been incorporated in wireless node model and simulations are performed to characterize the performance improvement of DSR Ad Hoc routing protocol. The simulation model is developed to evaluate performance improvement when we use directional antennas to extend the life of link, which is about to break. Link breakage happens due to the node movement and subsequent reducing signal strength of receiving packets. A novel preventive link maintenance scheme using directional antennas is proposed to characterize the performance gain. It is achieved by orienting neighboring nodes antennas towards each other by using the position/location information of nodes. It helps ad hoc source nodes to avoid or postpone costly operation of route rediscovery in on demand routing protocols. We compare the simulation results of our Preventive Link Maintenance (PLM) scheme with omnidirectional scheme (original DSR algorithm) by collecting the statistics of aggregate throughput, end-to end delay, number of data packets dropped, packet delivery ratio, and routing overhead. Use of directional antennas has been found encouraging for on demand routing protocols of MANET using our proposed preventive link maintenance scheme.

References

01. Nasipuri, A., Ye, S., You, J., & Hiromoto, R. (2000). A MAC protocol for mobile ad hoc networks using directional antennas. Proceedings of the IEEE Wireless Communications and Networking Conference, 3, 1214-1219.
02. Huang, Z., & Shen, C., (2002). A comparison study of omnidirectional and directional MAC protocols for ad hoc networks. Proceedings of IEEE Globecom.
03. Bao, L., & Garcia-Luna-Aceves, J.J. (2002). Transmission scheduling in ad hoc networks with directional antennas. ACM/SIGMOBILE MobiCom, 23-28.
04. Takai, M., Martin, J., Bagrodia, R., & Ren, A. (2002). Directional virtual carrier sensing for directional antennas in mobile ad hoc networks. Proceedings of the ACM MobiHoc. 183-193.
05. Choudhury, R., Yang, X., Ramanathan, R., & Vaidya, N.H. (2002). Using directional antennas for medium access control in ad hoc networks. Proceedings of the MOBICOM. 59-70.
06. Huang, Z., Shen, C., Srisathapornphat, C., & Jaikaeo, C. (2002). A busy-tone based directional MAC protocol for ad hoc networks. Proceedings of the IEEE MILCOM. 1233–1238.
07. Ramanathan, R., (2001). On the performance of ad hoc networks with beamforming antennas. Proceedings of the ACM MobiHoc. 95-105.
08. Roy, S., et al. (2003). A network aware MAC and routing protocol for effective load balancing in ad hoc wireless networks with directional antenna. Conference of the ACM Mobihoc.
09. Horisawa, S., Bandyopadhyay, S., Hausike, K., & Tawara, S., (2001). An adaptive MAC and directional routing protocol for ad hoc wireless networks using ESPAR antenna. ACM/SIGMOBILE MobiHoc.
10. Sanchez, M., Giles, T., & Zander, J. (2001). CSMA/CA with beam forming antennas in multi-hop packet radio. Proceedings of the Swedish Workshop on Wireless Ad Hoc Networks.
11. Johnson, D., & Maltz, D. (1996). Dynamic source routing in ad hoc wireless networks. Kluwer Academic Publisher. 153-181.
12. Perkins, C., & Bhagwat, B. (1994). Highly dynamic Destination Sequence Distance-Vector (DSDV) routing for mobile computers. ACM SIGCOMM Symposium on Communication Architectures and Protocols.
13. Perkins, C., & Royer, E., (1998). Ad-hoc On-demand Distance Vector (AODV) Routing (Internet-Drift).
14. Murthy, S., & Garcia-Luna-Aceves, J.J. (1996). An efficient routing protocol for wireless networks. Journal of the ACM Mobile Networks and Applications.
15. Haas, Z.J. (1997). A routing protocol for the reconfigurable wireless network. *IEEE 6th* International Conference on Universal Person Communications Record. Bridging the Way to the 21st Century, 2, 562–566.
16. Ko, Y.B., & Vaidya, N.H. (1998). Location-Aided Routing(LAR) in mobile ad hoc networks. *Proceedings of the Fourth MobiCom*. 66-75.
17. Choudhury, R., & Vaidya, N.H. (2004). Performance of Ad Hoc Routing using Directional Antennas. Journal of Ad Hoc Networks - Elsevier Publishers.
18. Okumura et al. (1968). Field strength and its variability in VHF and UHF band-mobile radio service. Review of the Electrical Communications Laboratory, 16.
19. Hata. (1980). Empirical formula for propagation loss in land mobile radio services. IEEE Transactions on Vehicular Technology, 29.