On an Ad Hoc Routing Protocol using Directional Antennas

MASANORI TAKATA† MASAKI BANDAI†† TAKASHI WATANABE†††

Directional antennas have great potential such as high spatial reuse and range extension. To fully exploit the benefits of directional antennas in ad hoc networks, efficient routing protocols as well as MAC schemes are to be considered. This paper proposes Load-Aware Directional Routing (LADR) to establish routes with fewer loads. Each node maintains current load information for each beam. In LADR, a route request packet is sequentially transmitted from the beam with few loads to establish a fewer loads route. LADR realizes load balancing without additional control overhead. Simulation results show that LADR outperforms DDSR and DSR in terms of the packet delivery ratio, throughput, and end-to-end delay, especially when the sending rate is high and the number of the sessions is large.

1. Introduction

Wireless ad hoc networks [1] are the autonomous system of mobile nodes which share wireless channels to communicate with one another without any fixed networking infrastructure. The previous works on wireless ad hoc networks assume the use of omni-directional antennas at the physical layer that radiate or receive power equally well in all directions. Traditional MAC (Medium Access Control) protocols using omni-directional antennas such as IEEE 802.11 DCF (Distributed Coordination Function) [2] cannot achieve high throughput in ad hoc networks because they waste a large portion of the network capacity as discussed in [3].

Directional antennas or smart antennas [4] are expected to provide significant improvements over omni-directional antennas in ad hoc networks, such as high spatial reuse and range extension. It can potentially establish links between nodes far away from each other, and it prevents network partitions and the number of routing hops can be fewer than that of omni-directional antennas. While most of the previous works on ad hoc networks using directional antennas have focused on medium access control [5-7], routing protocols using directional antennas are still in its infancy. Existing ad hoc routing protocols [8] have been intrinsically designed for omni-directional antennas and these cannot be applicable directly when using directional antennas. To fully exploit the benefits of directional antennas in ad hoc networks, efficient routing protocols as well as MAC schemes are to be designed. There are a few existing works on ad hoc routing using directional antennas. Choudhury and Vaidya evaluate the performance of DSR (Dynamic Source Routing) [9] using directional antennas called Directional DSR (DDSR) [10]. In DDSR, a route request (RREQ) packet is transmitted sequentially over multiple directions in order to cover all one hop neighbors. Although directional transmissions can enlarge the transmission range and provide fewer hop routes, the sweeping process incurs the delay and large control overhead. Therefore, the established route may not optimal because of the sweeping delay.

This paper proposes Load-Aware Directional Routing (LADR) to establish routes with fewer loads. Each node maintains current load information for each beam. Load is defined as busy time in a unit time. When a source node needs to send data to a destination node, it checks its routing table. If a route does not exist, the node broadcasts a RREQ packet to all directions (i.e., sweeping). When an intermediate node receives a RREQ packet that it has not seen before, it forwards the packet using beams that are diagonally opposite to the beam with which the packet arrived. The packet is sequentially transmitted from the beam with few loads. The first arrived RREQ went through a path with fewer loads, and the destination node can obtain the optimal route. Simulation results show that LADR outperforms DDSR and DSR in terms of the packet delivery ratio, throughput and end-to-end delay.

2. Antenna Model

We assume that each node is equipped with a switched beam antenna system which is comprised of M fixed beam

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† Graduate School of Science and Engineering, Shizuoka University
†† Faculty of Informatics, Shizuoka University
††† Graduate School of Science and Technology, Shizuoka University

patterns (**Fig. 1**). Non-overlapping directional beams are numbered from 1 to M, starting at the three o'clock position and running clockwise. The antenna system possesses two separate modes: Omni and Directional. In the Omni mode, a node receives signals from all directions with gain G^o. While idle (i.e., neither transmitting nor receiving), a node waits for signals in the Omni mode to receive frames from other nodes. After a signal is sensed in the Omni mode, the antenna detects the beam (direction) on which the signal power is strongest and goes into the Directional mode. In Directional mode, a node can point its beam towards a specific direction with gain G^d ($> G^o$).

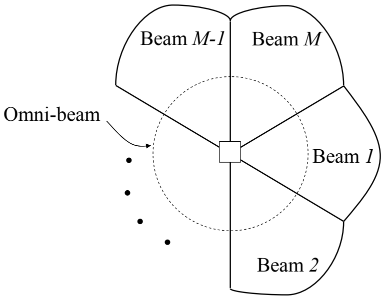


Fig. 1 Antenna Model

3. Related Work

3.1 DSR

DSR is a reactive routing protocol based on source routing [9]. When a node does not have a route cache entry for a destination node to which it needs to send data packets, it initiates a route discovery by broadcasting a RREQ packet. The RREQ packet contains the identities of the source and the destination. Any node that receives a RREQ packet adds its identity to the header of the RREQ packet and rebroadcasts it. When a RREQ packet reaches the destination, a RREP packet is sent back to the source node following the same route that was traversed by that RREQ packet in the reverse direction. The RREP packet contains the entire route to the destination, which is recorded in the source node's route cache. When an existing route breaks, it is detected by the failure of forwarding data packets on the route. On detecting the link failure, the node sends a route error (RERR) packet to the source. All intermediate nodes that receive the RERR packet delete existing routes from their route caches that contain the broken link. If a route is still needed, a route rediscovery is initiated.

3.2 Directional Routing Protocols

Work on routing protocols using directional antennas is limited. Choudhury and Vaidya propose DDSR [10] and evaluate the benefit of the higher transmission range of directional antennas, and therefore shorter hop routes. In DDSR, RREQ packets are transmitted sequentially over all antenna beams (i.e., sweeping) in order to cover a node's one hop neighbors. In addition, they propose a selective forwarding optimization whereby a node forwards a RREQ packet with only n ($n \leq M$) beams. The n beams used to forward control packets are the ones that are diagonally opposite to the beam with which the control packet was received. **Figure 2** shows an example scenario of DDSR with the selective forwarding. Node S transmits a RREQ using all beams. After receiving the RREQ using beam 5, node A forwards it with beam 1, 2 and 3. We use $M = 6$ and $n = 3$ for our simulations same as in [10]. Refs. [11] and [12] also propose similar approaches to mitigate the broadcast storm problem. However, the transmission order of the selected beams is not discussed, and therefore the established route may not optimal because of the sweeping delay. Refs. [10] and [12] suggest the delayed route reply optimization, in which destination nodes delay sending the RREP by a certain duration in order to collect the different routes and select the best among all the routes that arrive within the duration. However, this optimization increases the route discovery latency. In this paper we consider the load to determine the transmission order of the selected beams.

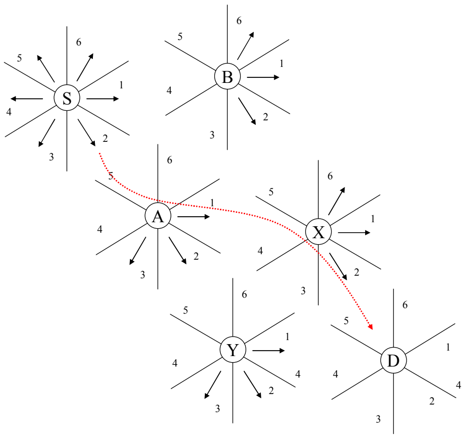


Fig. 2 DDSR with the selective forwarding

In [13], Nasipuri et al. propose a route discovery scheme in which query packets are propagated from a source node in the direction of a destination node with the help of directional transmissions in order to restrict the flood of query packets. However, this scheme is only applicable to the route rediscovery because the source node should know the direction of the destination node.

Cheekiralla et al. [14] evaluate a Load-Sensitive Routing [15] using directional antennas. LSR uses the aggregate queue size of all nodes in a path as the load metric for choosing routes. However, there is no discussion how to propagate RREQ packets. This paper proposes a load-aware routing protocol in cooperation with a novel RREQ propagation scheme without additional control overhead.

4. LADR

This section proposes LADR, a novel load-aware on-demand routing protocol for ad hoc networks using directional antennas. LADR is based on DDSR, and the only difference between LADR and DDSR is the transmission order of the selected beam for forwarding RREQ packets. Therefore, LADR realizes load balancing without additional control overhead. The details of LADR are presented next.

4.1 Underlying MAC Protocol

Because this paper focuses on the routing layer, we use Directional MAC (DMAC) [4] as the simple directional MAC protocol. In DMAC, all frames (i.e., RTS/CTS/Data/ACK) are transmitted and received directionally, and physical and virtual carrier sense functions are also performed directionally. Directional virtual carrier sensing is realized by DNAV (Directional NAV), a directional version of NAV. Each node maintains a neighbor table with one record for every node that it has heard. Initially, the neighbor table is empty and it is continuously updated upon overhearing any transmission. In every record the node maintains node ID and beam number to point the beam in the appropriate direction.

4.2 Sector Table

In LADR, each node has a routing table and a sector table to maintain routes and load of each beam, respectively. The routing table maintains the routing information to known destinations, and it is same as in DSR. The sector table maintains current load information for each beam. Load is defined as busy time in a unit time (i.e., utilization). Busy time includes the own communication duration (i.e., transmitting or receiving) and channel busy duration (i.e., physical or virtual carrier sense). This information can be readily obtained from the lower layers without any signaling overhead.

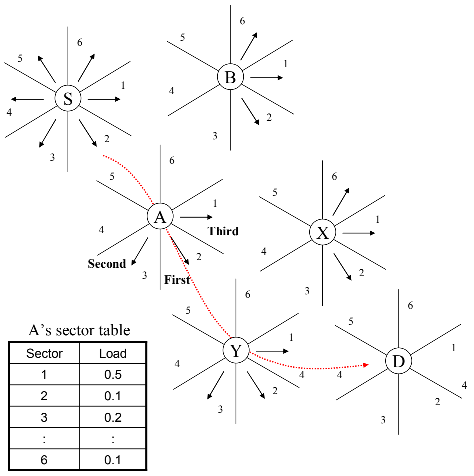
4.3 LADR Operation

We use **Fig. 3** to explain the procedure of LADR. Assume that node S is the source node and node D is the destination node. When node S needs to send data to node D, it checks its routing table. If a route does not exist, the node broadcasts a RREQ packet to all directions (i.e., sweeping). However, if the DNAV of S does not allow the transmission of RREQ packet towards a specific direction, S does not send the RREQ towards that direction. While performing a sweep, packet transmissions are not preceded by backing off as similar to DDSR.

Node A receives the RREQ transmitted by node S, and it has not seen before. We use the selective forwarding optimization proposed in [10]. Node A receives the RREQ using beam 5, and beams 1, 2 and 3 are selected to forward the RREQ. The sector table of node A is presented in Fig. 3 and we assume that the loads of beams 1, 2 and 3 are 0.5, 0.1 and 0.2, respectively. The packet is sequentially transmitted from the beam with few loads. Therefore, node A forwards the RREQ using beam 2 first. Then the RREQ is transmitted by using beam 3 and followed by beam 1. This process is repeated until the RREQ packet reaches the destination node.

On receiving RREQ, node D responds by sending the RREP packet to node S using the route <*D-Y-A-S*>. The first arrived RREQ went through a path with fewer loads, and the source node can obtain the optimal route (i.e., <*S-A-Y-D*>). On the other hand, DDSR uses the route <*S-A-X-D*> as illustrated in Fig. 2, and it is not optimal in terms of the traffic load even though it is a shortest path.

LADR reduces a correlation between routes and avoids route coupling dynamically as similar to maximally zone-disjoint routing in [16]. LADR is a reactive routing protocol and requires no additional overhead whereas the protocol in [16] is a proactive routing protocol and incurs the large control overhead to obtain the network topology and the communication events going on in the network.



A's sector table

Sector	Load
1	0.5
2	0.1
3	0.2
:	:
6	0.1

Fig. 3 Operation of LADR

5. Performance Evaluation

5.1 Simulation Model

To evaluate the performance of LADR, we developed an event driven simulator. We make the following assumptions. A hundred nodes are arranged at random in a square area with dimensions of 1500 m. Random source-destination pairs of CBR traffic are chosen at random. Transmission range of the omni-directional antenna is 250 m and that of the directional antenna is 500 m. The number of beams M is 6. The data size is 1024 bytes and the data rate is 11 Mbps. Because this paper focuses on the efficiency in terms of load balancing, we do not consider mobility in our simulations. All our simulations run for 300 seconds and results are the average of 10 runs. In addition to LADR, we evaluate the performance of DDSR over DMAC and DSR over IEEE 802.11 DCF.

5.2 Simulation Results

Figures 4 and **5** shows the packet delivery ratio and throughput of three protocols, respectively, when the number of session is 10 and sending rate of each session is changed. The results show that LADR and DDSR achieve the higher packet delivery ratio and throughput than DSR. This is because the directional routing protocols can establish shorter hop routes, and this reduces the consumption of the wireless channel. In addition, DMAC reduces the interference between nodes using directional transmissions, and consequently more node pairs can communicate simultaneously compared with IEEE 802.11. Therefore, it is shown that the benefits of directional antennas (i.e., range extension and high spatial reuse) can improve the network performance.

LADR outperforms DDSR especially when the sending rate is high (e.g., up to 15% improvement). This is because that the first arrived RREQ goes through a path with fewer loads and the route coupling is reduced in LADR. In DDSR, route coupling among routes increases the contention among neighboring nodes and reduces the throughput.

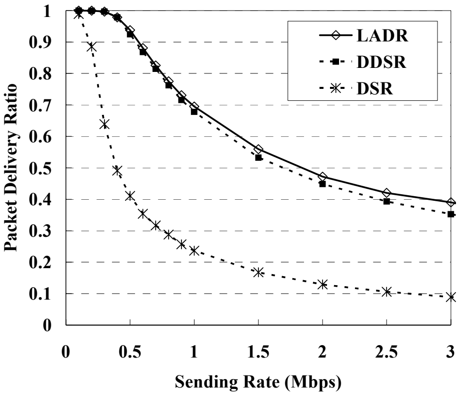


Fig. 4 Packet delivery ratio

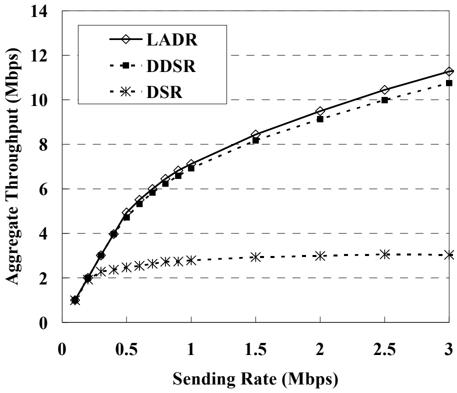


Fig. 5 Throughput

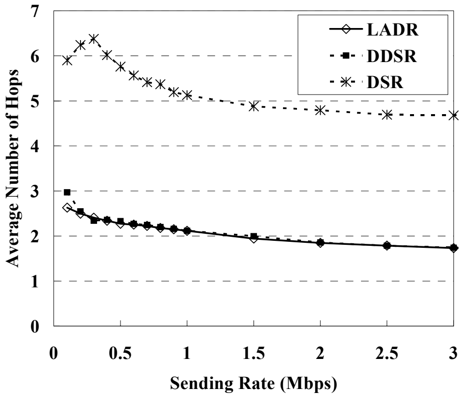


Fig. 6 Average number of hops

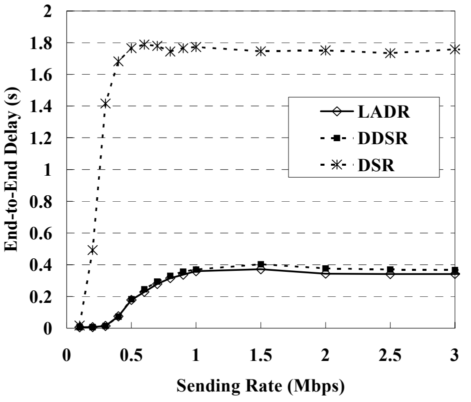


Fig. 7 End-to-end delay

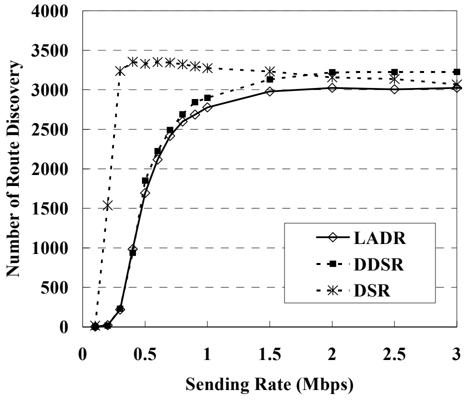


Fig. 8 Number of Route Discovery

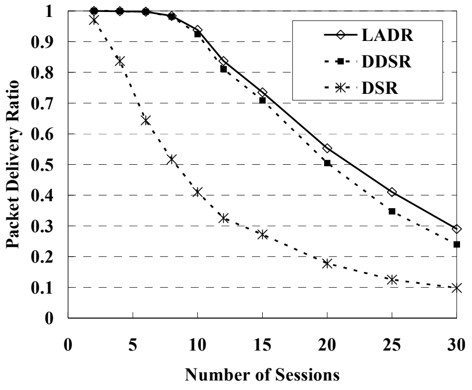


Fig. 9 Effect of the number of sessions

The average number of hops is shown in **Fig. 6**. It is evident that the directional routing protocols can establish shorter hop routes due to the longer transmission range of directional antennas. The results also show that there is no significant difference between LADR and DDSR in terms of the number of hops.

Figure 7 shows the average end-to-end delay. It can be observed that LADR has remarkably less delay than DSR. This is because the packets are delivered to the destination in fewer hops, and the store-and-forward overhead is reduced. Furthermore, LADR selects a route with fewer loads, and therefore the queuing delay is also reduced.

Figure 8 shows the number of route rediscovery of three routing protocols. Route rediscovery is initiated when a link is broken due to exceeding the maximum retry limit, which is set to 7 in our simulations. Because we do not consider mobility in our simulations, reason for a link failure is collision or deafness [17]. The number of route rediscovery of LADR is smaller than that of DDSR because LADR reduces the contention and collision. In directional MAC protocols, deafness is one of the major problems, caused when a transmitter repeatedly attempts to communicate with its intended receiver, but it fails because the receiver is engaged in communication with another node (i.e., either transmitting or receiving) and it has its beam pointed away from the transmitter. We have confirmed that deafness accounts for more than half of the failure factors. In [17], two directional MAC protocols, DMAC/DA (Directional MAC with Deafness Avoidance) and RI-DMAC (Receiver-Initiated Directional MAC), which handle the deafness problem, are proposed. Evaluating the effects of these protocols on the network layer is projected for our future work.

The effect of the number of sessions is shown in **Fig. 9**. The sending rate of each flow is set to 0.5 Mbps. LADR outperforms others especially when the number of session is large. This is because other protocols suffer from the heavy route coupling and introduce congestion. On the other hand, LADR balances the loads of the entire network. The results show that our proposed load-aware forwarding scheme is more effective when the number of sessions is large.

6. Conclusion

This paper has proposed LADR (Load-Aware Directional Routing) protocol for ad hoc networks using directional antennas. LADR is an on-demand routing protocol and based on DDSR. In LADR, RREQs are sequentially transmitted from the beam with few loads to establish a fewer loads route. LADR realizes load balancing without additional control overhead.

We have evaluated our protocol through simulation study. Simulation results show that LADR outperforms DDSR and DSR in terms of the packet delivery ratio, throughput, and end-to-end delay (e.g., up to 300 % improvement compared with DSR and up to 15% improvement compared with DDSR).

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References

1) R. Jurdak, C. V. Lopes and P. Baldi, “A Survey, Classification and Comparative Analysis of Medium Access Control Protocols for Ad hoc Wireless Networks,” IEEE Communications Surveys and Tutorials, Vol. 6, No. 1, First Quarter 2004.

2) ANSI/IEEE Std 802.11, “Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) specifications,” 1999.

3) S. Xu and T. Saadawi, “Does the IEEE 802.11 MAC Protocol Work Well in Multihop Wireless Ad Hoc Networks?,” IEEE Commun. Mag., Vol. 39, No. 6, pp. 130-137, June 2001.

4) P. H. Lehne and M. Pettersen, “An Overview of Smart Antenna Technology for Mobile Communications Systems,” IEEE Communications Surveys and Tutorials, Vol. 2, No. 4, Fourth Quarter 1999.

5) R. R. Choudhury, X. Yang, R. Ramanathan and N. H. Vaidya, “Using Directional Antennas for Medium Access Control in Ad Hoc Net-works,” Proc. MobiCom, pp. 59-70, Sept. 2002.

6) M. Takata, K. Nagashima and T. Watanabe, “A Dual Access Mode MAC Protocol for Ad Hoc Networks Using Smart Antennas,” Proc. IEEE International Conference on Communications (ICC), pp. 4182-4186, June 2004.

7) T. Korakis, G. Jakllari, L. Tassiulas, “A MAC protocol for full exploitation of Directional Antennas in Ad-hoc Wireless Networks,” Proc. MobiHoc, pp. 98-107, June 2003.

8) E. M. Royer and C-K. Toh, “A Review of Current Routing Protocols for Ad Hoc Mobile Wireless Networks,” IEEE Personal Communications, Vol. 6, No. 2, pp. 46-55, April 1999.

9) D. Johnson, Y. Hu and D. Maltz, “The Dynamic Source Routing Protocol (DSR) for Mobile Ad Hoc Networks for IPv4,” IETF RFC 4728, Feb. 2007.

10) R. R. Choudhury and N. H. Vaidya, “Impact of Directional Antennas on Ad Hoc Routing,” Proc. IEEE PWC, pp. 590-600, Sept. 2003.

11) C. Hu, Y. Hong and J. Hou, “On Mitigating the Broadcast Storm Problem with Directional Antennas,” Proc. IEEE ICC, pp. 104-110, May 2003.

12) H. Gossain, R. Joshi, C. M. Cordeiro, and D. P. Agrawal, “DRP: An Efficient Directional Routing Protocol for Mobile Ad Hoc Networks,” IEEE Transactions on Parallel and Distributed Systems, Vol. 17, No. 12, pp. 1438-1451, Dec. 2006.

13) A. Nasipuri, J. Mandava, H. Manchala, and R. E. Hiromoto, “On-Demand Routing Using Directional Antennas in Mobile Ad Hoc Networks,” Proc. IEEE ICCCN, pp. 535-541, Oct. 2000.

14) S. Cheekiralla, A. Quattoni and D. Engels, “Load-Sensitive Routing with Directional Antennas,” Proc. IEEE PIMRC, Sept. 2006.

15) S-J. Lee and M. Gerla., “Dynamic Load-Aware Routing in Ad Hoc Networks,” Proc. IEEE ICC 2001, pp.3206-3210, June 2001.

16) T. Ueda, S. Tanaka, S. Roy, D. Saha, and S. Bandyopadhyay, “A Priority-Based QoS Routing for Multimedia Traffic in Ad Hoc Networks with Directional Antenna Using a Zone-Reservation Protocol,” IEICE Transactions on Communications, Vol. E87-B, No. 5, pp. 1085-1094 , May 2004.

17) M. Takata, M. Bandai and T. Watanabe, “Performance Evaluation of Directional MAC Protocols for Deafness Problem in Ad Hoc Networks,” IPSJ Journal (in press).