A Directional Antenna Based Path Optimization Scheme for Wireless Ad Hoc Networks*

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Abstract. Using directional antennas in wireless ad hoc networks is an attractive issue due to its potential advantages such as spatial reuse, low power consumption and low chance of interference. To acquire these advantages, we propose a new routing scheme called DAPOS (Directional Antenna based Path Optimization Scheme). The proposed scheme enables us to acquire an efficient path by considering the characteristics of directional antennas, resulting a routing performance improvement. DAPOS focuses on shortening the length of routing path gradually by considering the higher gain of directional antennas at a receiver side. Simulation results show that DAPOS significantly reduces the number of hops in route, thereby it improves the overall network performance.

1 Introduction

A wireless ad hoc network is an infrastructure-less network consisting of mobile nodes that are typically equipped with an omnidirectional antenna for communicating with each other through wireless links. An omnidirectional antenna has an uniform radiation pattern from the view of top so it emits the signal over a whole sphere and receives the signal from all directions. On the contrary, a directional antenna has a preferential direction which has a more powerful communication capability. Due to this property, we can expect that using directional antennas instead of omnidirectional antennas gives us several benefits such as spatial reuse, low energy consumption and increased signal to interference and noise ratio (SINR).

In this paper, we propose a new routing protocol, DAPOS (Directional Antenna Based Path Optimization Scheme), by which each node tries to optimize the route by considering the high *reception gain* of directional antennas. Fig. 1 shows the characteristic of a directional antenna which our DAPOS protocol utilizes. In Fig. 1(a), node A equipping a directional antenna transmits

* This research was supported by the MIC (Ministry of Information and Communication), Korea, under the ITRC (Information Technology Research Center) program, and the Ubiquitous Computing and Network project (part of the MIC 21st Century Frontier R&D program). It was also partially supported by grant No. R05-2003-000-10607-02004 from the Korea Research Foundation Grant funded by the Korean Government.

X. Jia, J. Wu, and Y. He (Eds.): MSN 2005, LNCS 3794, pp. 317–326, 2005.

its signal intended to node B having an omnidirectional antenna, but B can't do a successful reception because the receiving signal is too weak. However, in Fig. 1(b), the reception process by node B is successfully completed even though the transmission profile of node A is same as Fig. 1(a). This is possible because the reception capability of B (now being equipped with a directional antenna) can be improved by setting its direction of main lobe to A. This implies that if a transmission condition (such as a transmission gain, a transmission power, a direction of transmission) doesn't become different, the range of possible communication between two nodes is dependent on a reception condition (such as a reception gain, an antenna type). Motivated by this, DAPOS shortens the length of route by including the link shown in Fig. 1(b) to the route.

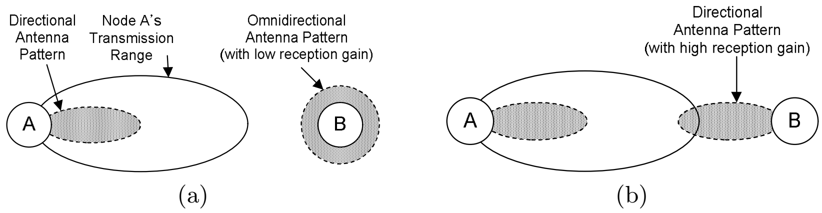


Fig. 1. An example showing the effect of the receiver's different antenna pattern on the success of communication

This paper is organized as follows. In Section 2, we discuss related work on routing schemes using directional antennas and explain our directional antenna model. The problems occured when past routing protocols designed for omnidirectional antennas is used with directional antennas are discussed in Section 3, and our new routing protocol DAPOS solving the problem is proposed in Section 4. We evaluate the performance of DAPOS with simulation in Section 5. Finally, Section 6 is for the conclusion.

2 Preliminaries

2.1 Related Works

To expolit the capabilities of directional antennas at the network(routing) layer, not a little researches have been proposed. In [1], the authors have investigated the impact of directional antennas over the dynamic source routing (DSR) [2] protocol and suggested some efficient routing schemes by considering the properties of directional antennas. The authors of [3] have proposed MAC and routing protocols suited to electronically steerable passive array radiator (ESPAR) antenna which allows an arbitrary radiating structure. In case of [4], they proposed routing scheme finding mutually disjoint routes which minimizes the effect of route coupling. It is observed that the proposed routing schemes above have a tendency to focus on a secondary point such as improving network throughput or network connectivity, rather than finding more efficient route. As mentioned earlier, this observation motivates our work here.

2.2 Antenna Model

We assume a switched beamforming antenna system as in [1, 7]. Fig. 2 shows the simplified pattern of directional antenna. Antenna system supports two mode, omnidirectional mode and directional mode, and a node must exist in only one mode at a time. A node stays in omnidirectional mode while in idle to receive the signal from all directions because it is impossible to know where the signals may come from. Also omnidirectional mode is used when a node wants to transmit the signal to all directions. Whereas, a directional mode is used when it can know the direction of coming signal and when it tranmsits the signal directionally. The angle of arrived signal can be acquired by the assumption of the ability to detect the beam-of-arrival of the signal. Each node receiving the signal caches the angle and uses it when the direction is needed to know. We assume that a node reduces the transmit power when transmitting in directional mode such that communication range becomes equal in omnidirectional mode and directional mode.

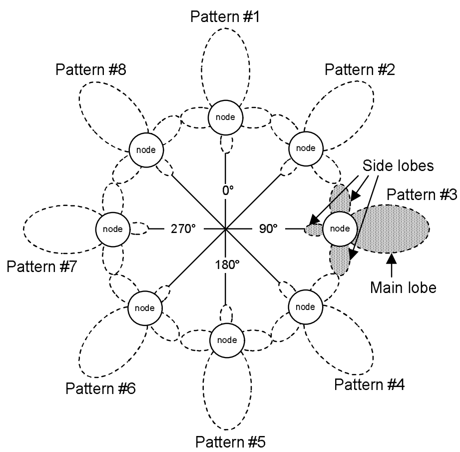


Fig. 2. The simplified pattern of directional antenna

3 Problems of Existing Ad Hoc Routing Protocols

As investigated in [1], most of omnidirectional antenna-assumed routing protocols for ad hoc networks such as AODV [5] and DSR also may work in the environment of directional antennas. However they experience the effect of using directional antenna and miss an opportunity of obtaining the advantages. They also provide a bad performance in acquiring shortest path, as seen later.

In case of typical reactive routing protocols, the flooding of route request (RREQ) packet is performed to elect the nodes that need to be included in route. Each node receives flooded RREQ in omnidirectional mode because nodes can't know when it comes and where it comes from. So the signal strength of received RREQ is proportional to a multiplication of the transmitter's gain in omnidirectional mode (G^o) and the receiver's gain in omnidirectional mode (G^o). The friss equation explains the relationship between transmission, reception gain (G_T, G_R) and transmittion power, reception power (P_T, P_R) [6].

$$P_R = \frac{P_T \times G_T \times G_R}{d^{\alpha} \times L} \tag{1}$$

As a result, two nodes composing a link of acquired route communicate with each other by $G^d \times G^o$ if a sender can be in directional mode. However, if sender and receiver are all in directional mode, communication can be accomplished by $G^d \times G^d$. In this case, communication range is expanded because reception strength is enlarged by Eq. 1. This implies that two nodes which are far away to communicate properly can communicate directly if they adjust their patterns properly as shown in Fig. 1.

Most of existing reactive routing protocols find the route comprised of links bounded by $G^d \times G^o$, although $G^d \times G^d$ links exist. Fig. 3 shows an example of this situation. We assume that each node equips a directional antenna and node S and D can communicate directly by beamforming to each other. That is to say, the link between S and D is a link bounded by only $G^d \times G^d$, not $G^d \times G^o$. At first, node S which wants to tranfer data to D initiates the flooding of RREQ to acquire the route. This RREQ is relayed by node A, B and C, and finally arrives in destination node D. As a result, acquired path is path 1, {S, A, B, C, D}, although shorter path {S,D} (path 2) can also be used.

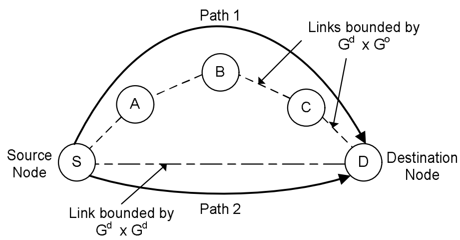


Fig. 3. Two possible routes between S and D

In this paper, we propose a new routing scheme to find more efficient route (i.e., path 2 in Fig. 3) by including $G^d \times G^d$ and $G^o \times G^d$ links into the route. For the simplicity of explnanation, we will refer the link requiring receiver node to be in directional mode ($G^d \times G^d$ and $G^o \times G^d$ links) as directional link and the link which can be used in omnidirectional mode ($G^d \times G^o$ and $G^o \times G^o$ links) as omnidirectional link.

4 DAPOS: Directional Antenna Based Path Optimization Scheme

4.1 Basic Mechanism of DAPOS

DAPOS performs following procedures to use directional links. While in the period of flooding RREQ, some node which received RREQ packet determines the link status between itself and the previous intermediate nodes relayed this RREQ before. If the link with a node which is more than 1 hop away is a directional link, it means that they can communicate directly without intermediate nodes. Then a node can exclude intermediate nodes from the path to shorten the length of path. In example of Fig. 3, node B received RREQ from A may know that the link between itself and S is a directional link and modifies the path {S,A,B} to {S,B}. This procedure is performed by each relay node until the RREQ packet is received by destination node D.

The question is how to determine the link status whether it is a directional link or not. We suggest utilizing wireless channel propagation model to estimate the communication range. Eq. 2 represents one of well-known propagation model, two-ray ground path loss model. By using this equation, we can estimate received power(P_R) if we know transmit power(P_T), the distance between two nodes(d), antenna gain(G_T, G_R) and antenna height(H_T, H_R).

$$P_R = \frac{P_T \times G_T \times G_R \times ({H_T}^2 \times {H_R}^2)}{d^4 \times L} \quad (2)$$

To simply provide distance information d, we assume that each node is able to know its own location information by location detection device like GPS. Each node relaying RREQ packet puts its own location information and transmit power level into RREQ. A node receiving RREQ gets distance d from location in RREQ and its own location, then calculates the received power P_R by using directional antenna gain G^d as G_R. If P_R is greater than receving threshold RX_Thresh, the node determines the link as an directional link.

4.2 DSR Variation with the Proposed Scheme

Flooding of Route Request Packet

Some extra information must be offered to enable the determination, so we modified the packet structure of RREQ. Observe that the information of node deleted from path are not needed anymore after optimization procedure. Therefore, the number of information newly attached to RREQ is limited to two sets, each consisting of location information and transmit power information. One set is for the node X which is the target of directional link determination and the other set is for the next potentional target node Y. The information of Y is used when optimization can't be performed anymore. The optimized path created by optimization procedure is also attached to RREQ. The followings are additional information must be attached to RREQ.

- Transmit power 1 ($TxPower_1$): Transmit power of node X
- Transmit power 2 ($TxPower_2$): Transmit power of node Y
- Location information 1 ($Location_1$): Location information of node X
- Location information 2 ($Location_2$): Location information of node Y
- Optimized Path($OptPath$): Path which is optimized by DAPOS

Fig. 4 shows the flooding of RREQ with DAPOS. Initially, source node S initiating RREQ stores its location information (L_S) and transmit power (T_S) in $TxPower_1$ and $Location_1$ fields of genereated RREQ packet. $TxPower_2$ and $Location_2$ are set to zero. $OptPath$ is same as DSR route request option header, {S}.

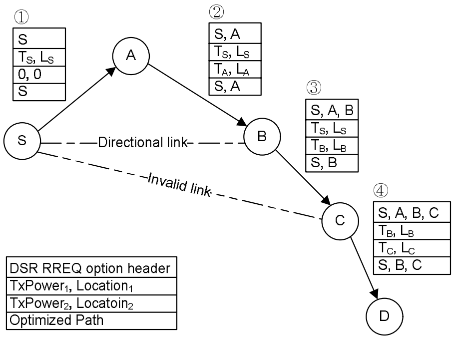


Fig. 4. Flooding of RREQ with DAPOS

Node A receiving RREQ from source node S doesn't need to optimize the path because it is a neighbor node of source node. A fills $TxPower_2$ and $Location_2$ with its own information T_S and L_S, and attaches its id to $OptPath$. Please note that $OptPath$ is also same as DSR route request option header, {S, A}. A relay the RREQ by broadcasting.

When node B receives RREQ from A, it performs the directional link detection algorithm. By algorithm, B knows that the link between S and itself B is a directional link so does optimization by deleting A from the path. With this optimization, $OptPath$ {S, A, B} becomdes {S, B}. Observe that the informations of deleted node A doesn't need anymore. $TxPower_2$ and $Location_2$ are set by the information of node B, T_C and L_C and these informations are needed in future when S cannot be an one end of directional link anymore. At that time, node B becomes a new target node for directional link detection.

Next, RREQ packet relayed by B is received by C and C knows that it can't communicate with S directly. This implies that the path {S, B} can't be optimized anymore. Therefore, $TxPower_1$ and $Location_1$ are replaced by the value of $TxPower_2$ and $Location_2$ which are the information of the next target node B. C puts its information T_C and L_C into $TxPower_2$ and $Location_2$, then rebroadcast the RREQ.

Finally, RREQ arrives at the detination node D. D determines that it can't construct a directional link with B and no optimization is performed here. D knows the passed sequence {S, A, B, C} by original DSR RREQ option header and also gets the optimized path {S, B, C} by *OptPath*. With DAPOS, destination node gets the opportunity of providing optimized path to source node.

Return of Route Reply Packet

For use of directional link, each node using directional link must know each other's direction. It is possible by caching the location informations in relayed RREQ and by providing the location information of previous hop in RREP packet. Therefore one location information field is needed. One another field for optimized path, *OptPath* is also attached to original DSR RREP packet. The followings are the additional field of RREP packet.

- Location information (*Location*): Location information of one end node using directional link
- Optimized Path (*OptPath*): Path which is optimized by DAPOS

In Fig. 5, we can know how RREP packet return to source node. While in back of RREP, found directional links can not be used because a node relayed RREQ doesn't know whether it woulde be included in path at the conclusion and also doesn't know the direction of corresponding node of directional link. Therefore, RREP is sent back by sequence {D, C, B, A, S}. One important thing is that node A doesn't update *Location* to give location information of B to S.

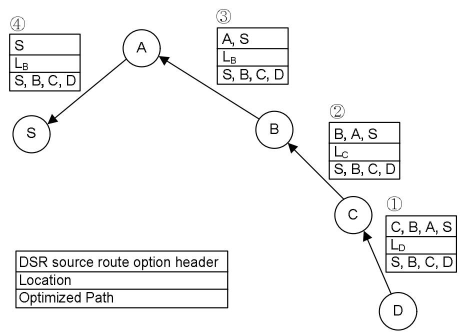


Fig. 5. Return of RREP with DAPOS

5 Performance Evaluation

We use the Qualnet simulator [8] version 3.8 for simulating our proposed protocol DAPOS and comparing it with DSR which is one of the most famous routing protocol. In all considered scenarios, constant bit rate (CBR) traffic is used at each source node. Transmission range is set to 250m in $G^d \times G^o$ and $G^o \times G^o$

condition. Note that power control is used to equal the transmission range in directional mode and omnidirectional mode. The gain in omnidirectional mode G^o is 0.0dBi (no gain) and the peak gain in directional mode G^d is 15.0dBi. Of course, the gain of side lobes are weaker than that of main lobe.

5.1 Grid Topology

We simulated grid topology illustrated in Fig. 6 to investigate the routing control overhead in order to evaluate the performance in more simplified scenario. The distance between adjacent node is 200m and three CBR traffics are placed in centered 3 rows. Source nodes are the leftmost three nodes (12, 23, 34) except top and bottom, destination nodes are selected by varying the distance between source and destination node from 200m to 2000m. In Fig. 6, black solid lines indicate the path acquired by DSR and dotted lines indicate DAPOS, in distance 1000m. Gradual optimization by each relaying node enables local optimization and this leads to acquire more efficient path compared to DSR as seen Fig. 6.

The effect of packet's increased size can be found in Fig. 7(a), route discovery latency (the time for route discovery) of DAPOS is slightly higher than that of DSR. However, route discovery is successfully complished without any packet drops and average end-to-end delay of DAPOS is much lower than DSR, shown in Fig. 7(b).

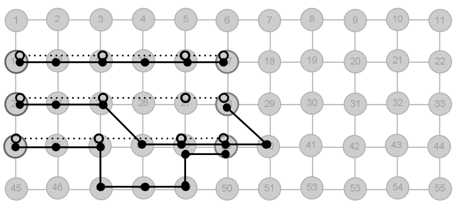
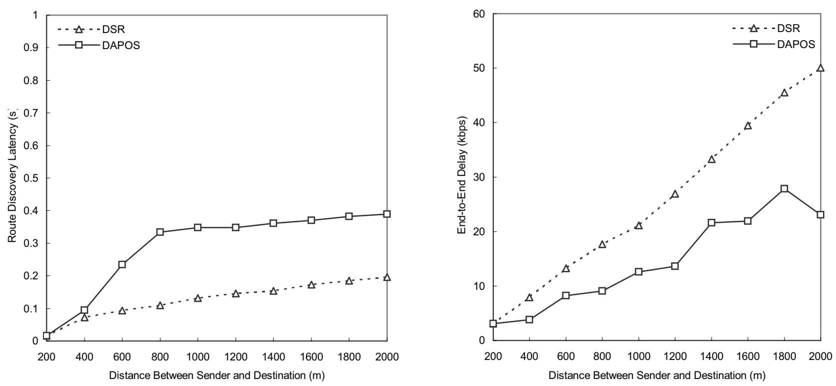


Fig. 6. Grid topology



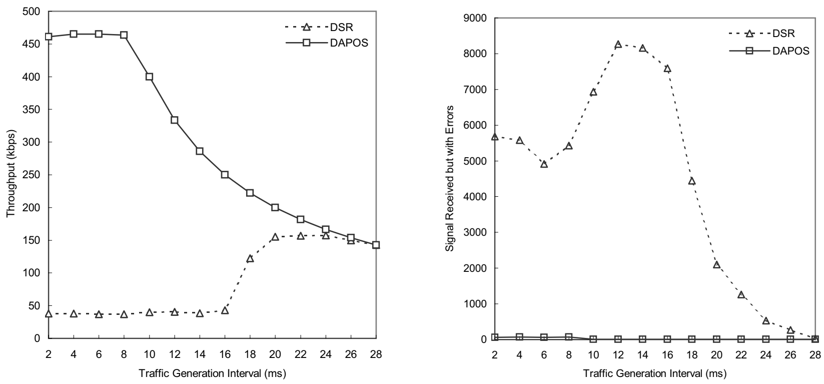
(a) Route discovery latency (b) Average end-to-end delay

Fig. 7. Performance comparison between DAPOS and DSR in grid topology

5.2 Simple Linear Topology

Finally, simulation is performed in a simple linear topology to evaluate the effect of traffic load and the level of interference. Five nodes called A, B, C, D, E (from left to right) are located in linear position separated by 200m. One CBR traffic from leftmost node A to rightmost node E is used during 900 seconds simulation time.

Fig. 8 shows the performance of DAPOS and DSR in various aspect. Fig. 8(a) shows throughput by varying traffic load. From 2ms to 8ms of traffic generation interval, throughput of DAPOS is about 450kbps, the maximum throughput this network can provide. From 8ms to 28ms, DAPOS fully utilize the network capacity. However, in case of DSR, througput is under 50kbps from 2ms to 16ms and increases slowly. Performance barely becomes same with DAPOS in 28ms. In all cases, DSR can't provide full capacity so packet delivery ratio is relatively low.



(a) Throughput (b) Number of signals received but with errors

Fig. 8. Performance comparison between DAPOS and DSR in linear topology

This is because of the interference between adjacent nodes. After node B receives data from A, it communicates with next node C. While in this communication, node C beamforms to the direction of B to increase the SINR. At that time, A may want to initiate communication with B for delivery of next data packet, thus RTS frame transmitted from A can interfere C. This is because directional link between A and C becomes available temporarily if C is in directional mode toward A. As traffic load increases, the probability of interference also increases. Observe that route may be consisted of directional link like {A, C} in case of DAPOS, so the probability is very low. Fig. 8(b) shows the number of collision. As you can see, collision of DSR is much higher than DAPOS. This is why the performances are very different from each other in this scenario.

6 Conclusion

In this paper, we investigated the problem and limitation of existing routing protocols and proposed a new routing protocol, directional antenna based path optimization scheme (DAPOS), to overcome the problem. DAPOS aims to shorten the length of path by including directional link to the route at the first route discovery phase. By simulation, we show that overall network performance can be improved with DAPOS. Future work would include more simulations with mobility scenarios and more realistic environment with a random topology.

References

1. R. Roy Choudhury and N. H. Vaidya, “Impact of directional antennas on ad hoc routing,” in *Proceedings of Personal and Wireless Communication (PWC)*, September 2003.
2. D. Johnson and D. Maltz, “Dynamic source routing in ad hoc wireless networks,” in *Mobile Computing, Kluwer Academic Publishers*, 1996.
3. S. Bandyopadhyay, et. al., “An adaptive MAC and directional routing protocol for ad hoc wireless networks using ESPAR antenna,” in *Proceedings of ACM MobiHoc*, October 2001.
4. S. Roy, et al., “A network-aware MAC and routing protocol for effective load balancing in ad hoc wireless networks with directional antenna,” in *Proceedings of ACM MobiHoc*, June 2003.
5. S. Das, C. Perkins, and E. Royer, “Ad hoc on demand distance vector (AODV) routing,” Internet-Draft Version 4, IETF, October 1999.
6. T. Rappaport, “Wireless communications principles and practice,” Prentice Hall, 2002.
7. R. Roy Choudhury and N. H. Vaidya, “Deafness: A MAC problem in ad hoc networks when using directional antennas,” in *Proceedings of IEEE International Conference on Network Protocols (ICNP)*, October 2004.
8. Scalable Network Technologies, “Qualnet simulator version 3.8,” www.scalable-networks.com.