www.ietdl.org

Published in IET Communications
Received on 1st June 2007
Revised on 25th October 2007
doi: 10.1049/iet-com:20070249

ISSN 1751-8628

Directional routing protocols for *ad-hoc* networks

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Abstract: A directional routing approach for multihop *ad-hoc* networks, is presented which has been applied to two on-demand routing protocols: namely dynamic source routing (DSR) and *ad-hoc* on-demand distance vector routing (AODV). Both DSR-based and AODV-based directional routing protocols are designed to balance the trade-off between co-channel interferences from nodes hops away and the total power consumed by all the nodes. In order to select the best route, three metrics are considered in the route discovery process. They consist of hop count, power budget and overlaps between adjacent beams. By exploiting the direction of directional antennas, both routing protocols are capable of reducing overlaps between beams of the nodes along the route, thus eliminating interference. Arbitrary networks and random networks are considered in the simulations. The results show considerable performance gains for transmission of real-time traffic over *ad hoc* networks.

1 Introduction

In wireless *ad-hoc* networks smart antenna techniques, capable of providing spatial reuse, longer ranges, interference suppression and other beneficial features, have been investigated to improve achievable performance and system capacity [1–5]. For instance in [1], a brief overview of smart antenna techniques is provided and the issues that arose when applying these techniques in *ad-hoc* networks were then described. Yi *et al.* [2] provided a theoretical framework to understand how much capacity improvement can be achieved in *ad-hoc* networks using directional antennas. Aiming at developing a complete *ad-hoc* networking system with directional antennas, Ramanathan *et al.* [3] propose utilising directional antennas for *ad-hoc* networking, including several new mechanisms such as directional power-controlled medium access control (MAC), link characterisation for directional antennas, proactive routing and forwarding and neighbour discovery with beamforming. These mechanisms, if working cohesively, can provide the first complete systems solution. For instance, in terms of the neighbour discovery aspect, Choudhury *et al.* [5]. use multihop RTSs to establish links between distant nodes, and then transmit CTS, DATA and ACK over a single hop. However, in order to perform neighbour discovery, all nodes are required to synchronise by employing a common clock source, such as GPS. Takai *et al.* [6] present a novel carrier sensing mechanism called directional virtual carrier sensing (DVCS) for wireless communication using directional antennas. In this approach, only information on Angle of Arrival (AOA) and antenna gain for each signal from the underlying physical device would be needed. Specifically, three primary capabilities were combined with the original IEEE 802.11 MAC protocol [7] for directional communication with DVCS: caching the AOA, beam locking and unlocking and use of the directional network allocation vector. In order to allow simultaneous transmissions that are not allowed in the 802.11 protocol, Ko *et al.* [8] propose a directional MAC (DMAC) protocol that exploits the characteristics of both directional and omnidirectional antennas. In [9], Bao and Garcia-Luna-Aceves present a distributed channel access scheduling protocol for *ad-hoc* networks with directional antennas that are capable of forming multiple beams to carry out several simultaneous data communication sessions. Along a different avenue, much attention has also been paid to exploiting the spatial diversity of antenna arrays. In [4], multiple-input and multiple-output (MIMO) techniques are explored for MAC design and routing in mobile *ad-hoc* networks, where the spatial diversity technique is used to combat fading and achieve robustness in the presence of user mobility. Using multiple antenna, Park *et al.* [10] design a novel MAC protocol to mitigate interference from neighbouring nodes by employing the spatial multiplexing capability of MIMO. In addition, multiple antennas with antenna selection has also been developed in [11] to suppress both interference from neighbouring transmitters and fading. However, this scheme inherits the exposed node problem and hidden node problem associated with carrier sense multiple access with collision avoidance (CSMA/CA). Furthermore, all the nodes that participate in the communication are assumed to synchronise with each other.

Most of the above mentioned works focus on the design and development of MAC protocols and ignore the effect of co-channel interference along an active path from source to destination. To the best of our knowledge, there has been little work on the design of routing protocols for wireless *ad-hoc* networks using directional antennas. In this paper, a directional routing strategy has been proposed, mainly to suppress interferences from neighbouring relay nodes while attaining power effectiveness. The approach has been applied to two popular on-demand routing protocols, namely dynamic source routing (DSR) [12] and ad-hoc on-demand distance vector routing (AODV) [13], which will be referred to as the directional DSR (DDSR) protocol and the directional AODV (DAODV) protocol.

The paper is organised as follows: In Section 2, after a brief review of DSR and AODV routing protocols, we present the proposed DDSR and DAODV routing protocols. In Section 3, the performance of the routing protocols is investigated in arbitrary networks and random networks. Finally, we offer our conclusions in Section 4.

2 Direction-routing-protocol

In this section, two directional routing protocols invoked for wireless *ad-hoc* networks are described and characterised. In these protocols, the best route from the source node to the destination node is selected according to hop count, power budget and overlap count. Based on these metrics we have implemented our directional routing strategy for DSR and AODV standard routing protocols.

Both DSR [12] and AODV [13] initiate routing activities on a 'on-demand' basis, which means that routes are created only when required by the source node. In a route discovery process of either DSR or AODV, route request (RREQ) and route reply (RREP) are used to set up the route to the destination. Furthermore, in either protocol, route information is stored in all intermediate nodes on the route. In DSR, hop-by-hop routes to the destination are stored in the route cache of each node. By contrast, in AODV traditional routing tables are used, whereby only the next hop is stored in the routing table entries. Source routing enables DSR to obtain a much greater amount of routing information than AODV. In a single request–reply cycle, all nodes along the route, including the source and the destination, can learn routes to every other node on the route. However, in AODV only routes to the source and the destination are set up in each node. This usually causes AODV to rely on a route discovery flood more often, resulting in a significantly increased network overhead. Furthermore, in DSR the destination replies to all RREQs in a single request cycle. Therefore the source can setup multiple routes to the destination, which will be useful in case the primary route fails. On the other hand, in AODV the destination replies only once to the RREQ arriving first and ignores the rest. The routing table maintains 'at most' one entry per destination [14].

Based on the original DSR and AODV routing protocols we consider a new metric, which is based on the number of overlaps between beams in the route discovery process in order to select the best route. As shown in Fig. 1, when directional antennas are employed, the transmit beam of A → E does not overlap the receive beam of D → F, which means that the transmission from node A to node E does not impact interference on node D. Obviously, the transmit beam of A → B overlaps the receive beam of D → C, meaning that the transmission from node A to node B interferes with node D. Note that in a wireless multi-hop network, the interference from nodes hops away may degrade the throughput greatly [15]. Hence, in this case, the route of A → E → F → D is better than that of A → B → C → D. As shown in Fig. 1, in the proposed routing protocol if the angle between A → B and A → D is less than threshold γ, while the angle between D → C and D → A is also less than threshold γ, they overlap and hence interfere with each other. In our simulations a sharp beam with a beamwidth of $2\beta = 40^\circ$ is used by all nodes to transmit packets. Therefore we have

$$\gamma = \beta \tag{1}$$

2.1 DDSR routing protocol

In order to calculate the overlap count in a specific route, positional information of the current node will be inserted into the RREQ and RREP of the proposed DDSR routing protocol. As shown in Fig. 2, the source node A initiates the route discovery process to destination node J by broadcasting RREQ to its neighbouring nodes. In this RREQ, the position information of node A is inserted into the route record, along with the address of node A. Once node B receives the RREQ from node A, it adds its

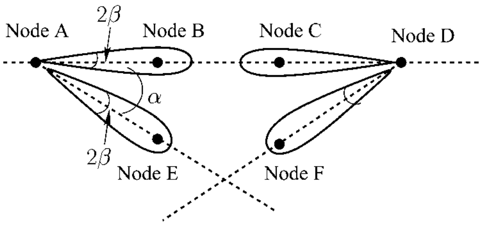


Figure 1 *Example where the beam of A→ E dose not overlap with the beam of D → F, since we have $\alpha > \gamma = \beta$*

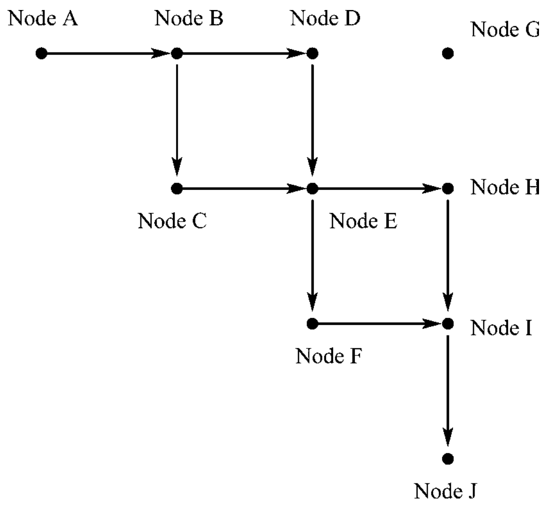


Figure 2 *Directional route discovery process*

own address, along with its positional information to the route record and relays RREQ to its neighbouring nodes. After receiving the RREQ from node B, node D creates a backward route to node A in its route cache. Furthermore, node D calculates the DOAs of A → B, A → D and D → B according to the positional information of node A and B in the received RREQ. Since the transmit beam A → B overlaps with the receive beam D → B, node D increases the overlap count to one and adds it to the route to node A. In node C, the transmit beam of A → B does not overlap with that of C → B, so we have an overlap count of 0. Similarly, when node G receives the RREQ from node D, it sets up a route to node A with the overlap count being 3, since the transmit beam A → B overlaps with the receive beams D → B and G → D while the transmit beam B → D overlaps with the receive beams D → B. The Unicast of RREP has a same procedure of calculating the overlap count.

Note that in the standard DSR [7], since all the duplicated RREQs are discarded, it is unlikely to find the best route to the destination. Fig. 2 illustrates such a example, where route A → B → C → E → F → I → J may not be selected when the RREQ from node H is received by node I earlier than that from node F. To avoid this, we make some modification to the route discovery process of the original DSR. Instead of discarding every duplicate RREQ, intermediate nodes will forward the RREQs whose hop counts are not bigger than that of the previously received RREQs; even if they have the same ID. Therefore the source node may receive multiple RREPs and obtain all possible routes to the destination. According to the three metrics, the source node will select the best route from its route cache for data transmission. However, it is possible that there would be too many potential routes from the source to the destination, especially in an *ad-hoc* network with high node density. To avoid excessive overhead, a threshold is set in the destination node. When the number of RREQs received by the destination is smaller than this threshold, the destination node will keep sending RREPs. Otherwise, the RREQs will be discarded. In our simulations, the threshold is set to ten, which is big enough to find the best route in our scenarios.

2.2 DAODV routing protocol

Similarly, in the proposed DAODV routing protocol, positional information of the current node will be inserted into the RREQ and RREP. As shown in Fig. 2, the source node A initiates the route discovery process to destination node J by broadcasting RREQ to its neighbour nodes. In this RREQ the positional information of node A is inserted. Once node B receives the RREQ from node A, it adds its own positional information to the RREQ and forwards it to the neighbouring nodes. After receiving the RREQ from node B, node D creates a backward route to node A in its routing table entries. According to the positional information of node A and B in the received RREQ, node D calculates the DOAs of A → B, A → D and D → B. Here the overlap count is one and is added on to the route to node A.

In the original AODV, if the intermediate node has a current route to the destination, it generates a RREP and unicasts the RREP back to the source in a hop-by-hop fashion. However, the overlap count between the source and the destination cannot be achieved since there is no positional information stored in the intermediate node's routing table entries. In order to calculate the overlap count between the source and the destination, in the proposed DAODV routing protocol, the intermediate nodes must forward the RREQs, regardless of whether or not it has a route to the destination. The Unicast of RREP from node J to node A has the same procedure for calculating the overlap count. Furthermore, in order to find the best route to the destination, a new mechanism is employed, where a threshold of received RREPs is set in the source node. Once the source node receives the first RREP from the destination node or the intermediate node, it creates a route in its route table to the desired destination node and increases the counter of received RREPs once. If the counter of received RREPs is less than the threshold, the source node re-initiates a RREQ while keeping the sequence number of the RREQ unchanged, instead of immediately transmitting data to the destination node, as in the original AODV routing protocol. Once the destination node receives the RREQ, it generates a RREP and unicasts the RREP back to the source node in a hop-by-hop fashion. The intermediate nodes and the source node which receive the RREP will calculate the overlap count according to the positional information contained in the RREP and compare it with that contained in their route tables. Based on three metrics detailed in the following discussion, the intermediate nodes and the source node will update their route table if a better route is found. If the receiving node is the source node, it increases the number of received RREPs in its counter once and

doi: 10.1049/iet-com:20070249

compares it with the threshold. If the number of received RREPs is still less than the threshold, the source node will re-initiate a RREQ and broadcast it as mentioned above. Otherwise, the source node will initiate data transmission immediately. In the IEEE 802.11 MAC protocol, a back-off mechanism is invoked for contention resolution, where a random back-off interval will be selected by a node once it wants to transmit packets. Therefore the possibility of setting-up a same route in different route discovery cycles is very tiny, especially in multihop *ad-hoc* networks. In our simulations, the threshold is set to 10, which is large enough to find the best route in our scenarios.

In the proposed DAODV, once the next hop becomes unreachable because of the link break caused by mobility and packet collision, the node upstream of the break empties its buffer and propagates a route error (RERR) packet to all active upstream neighbours. Similarly, these nodes, fresh out of their buffer, delete all the related routes and relay the RERR to their upstream neighbours and so on until the source node is reached. A new route discovery procedure will be initiated by the source if the route to the destination is still needed.

2.3 Metrics

In order to select the best route from the route cache after receiving multiple RREPs from the destination node, three metrics are employed to measure the performance of each route as follows:

1) Hop count;

2) Overlap count over a specific route;

3) Power budget: the total power loss of a specific route when transmitting a packet from the source to the destination via this route, which has the form of [16]

$$\text{Power budget} = \sum_{i=1}^{N-1} PL_{i,i+1} \tag{2}$$

where $PL_{i,i+1}$ is the power loss between node i and node $i+1$.

In a multihop network where nodes are continually receiving and forwarding packets, energy efficiency would be a crucial factor in maintaining service over a long period of time. Furthermore, a high power budget may cause high interference among nodes. In the proposed directional routing protocols, the power budget can be calculated based on the position information in RREQ or RREP. Similarly, the parameter of power budget is inserted into the route table of each node, along with the value of overlap count. Therefore according to the information of hop count, power budget and overlap count, the receiving nodes either update their route tables or create new routes in the route tables. Generally, a route with the smallest hop count has the highest priority. As for overlap count and power budget, two schemes are considered. In scheme A, the route with the smaller overlap count has higher priority. In scheme B, the route with a smaller power budget has higher priority.

3 Performance results

In this section, the performance of the proposed directional routing protocols is investigated using our real-time network simulation testbed, where the IEEE 802.11b standard is invoked. In the simulations, the input data generated at a constant bit rate (CBR) is encapsulated into fixed 500 bytes UDP packets. The directional antenna model employed in our simulations is capable of forming a sharp beam with a beamwidth of $2\beta = 40^\circ$, as portrayed in Fig. 3. The maximum antenna gain is 15.56 dB, while the sidelobe gain outside the beam is −4.00 dB. In the MAC layer, the transmit limit is one. For simplicity, there is no fading in our simulation and free space is selected as the path loss model.

The DMAC protocol employed in our simulations is briefly described as follows. In the route set-up stage, node i will broadcast RREQs omnidirectionally to its neighbouring nodes, that is, node j, with transmit power P_T. Therefore the receive power at node j is $P_R = P_T - PL_{i,j}$. If P_R is smaller than the receiver sensitivity at node j, this node will treat the received signal as an interference. Otherwise, node j, which may be selected as the next hop mode in a route from source to the destination, is expected to receive the data packet with a gain of $G_R = 15.56$ dB when operating in the directional mode where we have $P_R = P_T - PL_{i,j} + G_R$. Therefore at the data-transmission stage, node i reduces its transmit power P_T by a value of the maximum antenna gain $G_T = 15.56$ dB. Under these conditions the received power at node j remains the same as in the omnidirectional case as $P_R = P_T - G_T + G_T - PL_{i,j} = P_T - PL_{i,j}$. Once the transmission ends, both the transmitter antenna and receiver antenna will convert back to omnidirectional mode.

The performance of the directional routing protocols is investigated for a network consisting of 24 nodes, as depicted in Fig. 4*a*. We set the initial transmit power for every node at 10.5 dBm. It is possible that route $1 \rightarrow 2 \rightarrow 3 \rightarrow 6 \rightarrow 7 \rightarrow 9 \rightarrow 10$ is selected when using the original DSR or AODV routing protocol. By invoking the DDSR or DAODV routing protocol, route $1 \rightarrow 2 \rightarrow 5 \rightarrow 6 \rightarrow 8 \rightarrow 9 \rightarrow 10$ will be selected as the

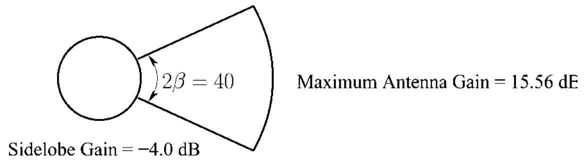
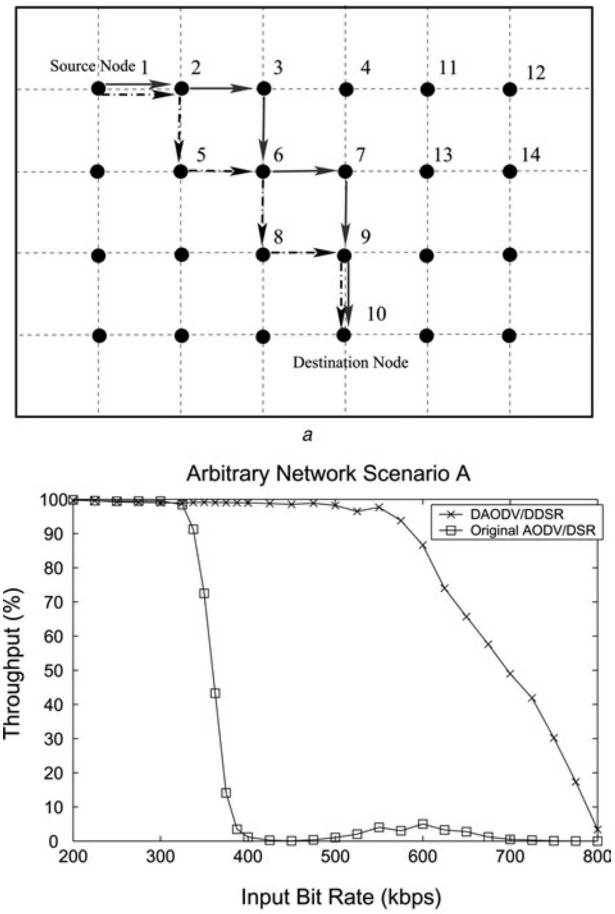


Figure 3 *Directional antenna model employed in our simulations*

doi: 10.1049/iet-com:20070249



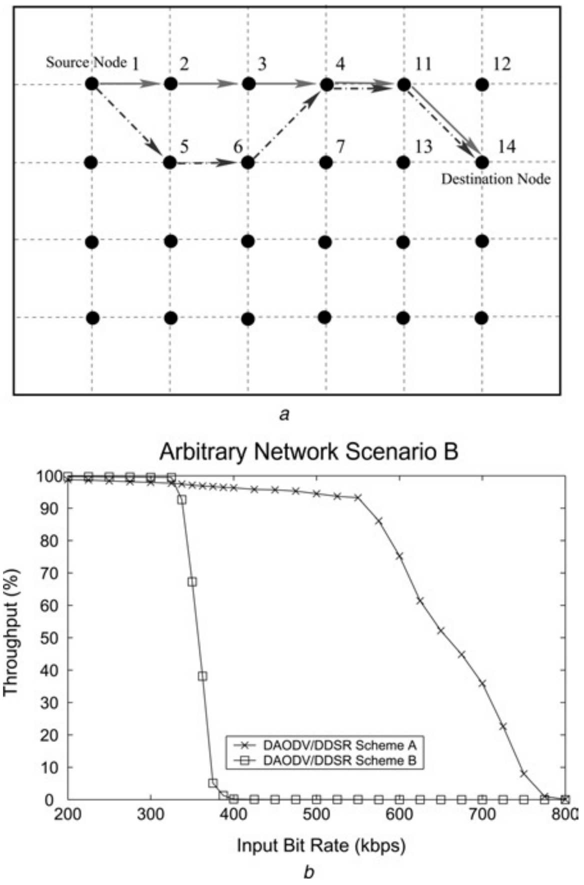
a

b

Figure 4 *Arbitrary ad-hoc network: Scenario A*

a Route $1 \rightarrow 2 \rightarrow 3 \rightarrow 6 \rightarrow 7 \rightarrow 9 \rightarrow 10$ is selected when using the original DSR or AODV routing protocol but in contrast, when invoking the proposed directional routing protocols, route $1 \rightarrow 2 \rightarrow 5 \rightarrow 6 \rightarrow 8 \rightarrow 9 \rightarrow 10$ will be set up
b In the case of transmit power being 10.5, the directional routing protocols-DAODV and DDSR outperform the original DSR or AODV routing protocol significantly

best route in accordance with the metrics described in Section 2. Specifically, in this scenario the original DSR and AODV routing protocols select the same route $1 \rightarrow 2 \rightarrow 3 \rightarrow 6 \rightarrow 7 \rightarrow 9 \rightarrow 10$, while the DDSR or DAODV routing protocol selects the same route $1 \rightarrow 2 \rightarrow 5 \rightarrow 6 \rightarrow 8 \rightarrow 9 \rightarrow 10$. Therefore the original DSR routing protocol achieves the same performance as the original AODV routing protocol as seen in Fig. 4*b*. Similarly, the DDSR routing protocol obtains the same performance as the DAODV routing protocol. As shown in Fig. 4*b*, the directional routing scheme can significantly improve the system's performance. Note that in route $1 \rightarrow 2 \rightarrow 5 \rightarrow 6 \rightarrow 8 \rightarrow 9 \rightarrow 10$, there is no interference from the nodes hops away because of the directionality of the beam. The packet loss in this route occurs mainly because when node i is directionally communicating with node $i+1$, node i cannot receive data from node $i-1$. This kind of packet loss happens frequently when the input bit rate is higher than 600 Kbps. In $1 \rightarrow 2 \rightarrow 3 \rightarrow 6 \rightarrow 7 \rightarrow 9 \rightarrow 10$, in addition to the above-mentioned packet loss, there are four possible kinds of packet loss caused by interferences from nodes hops away. When node 2 is transmitting data directionally to node 3, the receiver power at node 1 is $P_R = P_T - 15.56 + G_{TS} - PL_{2,1}$, where $G_{TS} = -4.0$ dB is the sidelobe transmit antenna gain. It is reasonable that $P_R = P_T - 19.56 - PL_{2,1}$ is smaller than the receiver sensitivity at node 1. In this case, node 1 will not defer signal transmission. Instead, it will initial data transmission to node 2 when required. Consequently, node 3 is interfered by the signal from node 1. Since node 3 is in a directional antennal mode and its beam is overlapped with that of node 1, an interference with a high value will impact node 3. Specifically, in our simulation, the interference impacted on node 3 by node 1 is around -80.26 dBm. The SINR at node 3 is then reduced from 26.73 to 5.99 dB. Similarly, node 7 will be interfered by the signal from node 1 when node 7 is receiving data from node 6, since node 7 is in directional antennal mode and its beam is overlapped with that of node 1. The SINR at node 7 is reduced from 26.26 to 12.31 dB. Furthermore, node 10 is interfered by the signal from node 3 or node 7 when node 10



a

b

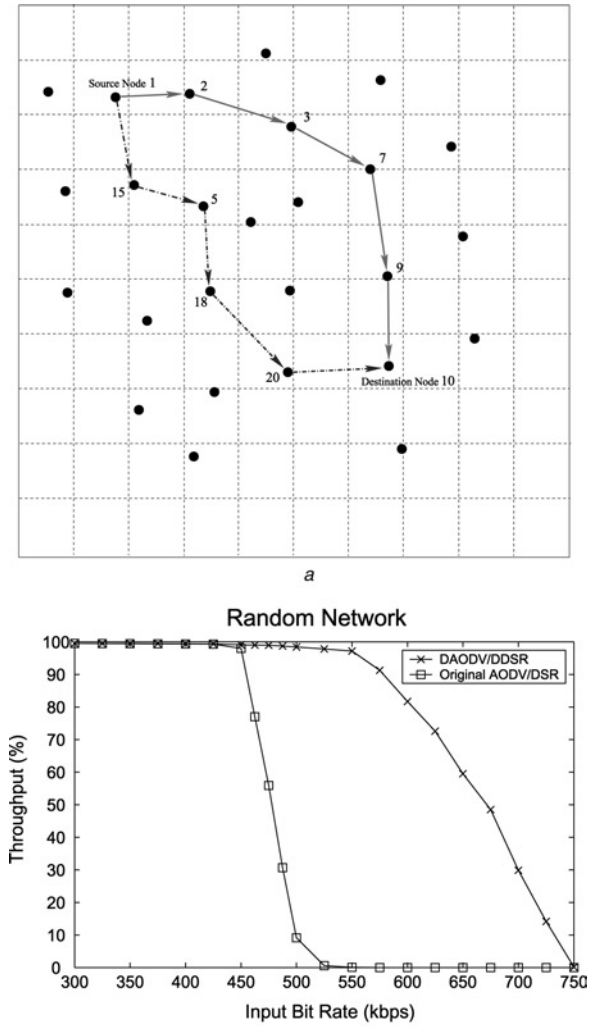
Figure 5 *Arbitrary ad-hoc network: Scenario B*

a In scheme A the route with the smaller overlap count has higher priority over the power budget, whereas in scheme B the route with the smaller power budget has higher priority
b Scheme A achieves a much better performance than scheme B, as there is no overlap and hence, no interference from nodes hops away in the route of scheme A

doi: 10.1049/iet-com:20070249

is receiving data from node 9. The SINR at node 10 is reduced from 26.73 to 12.09 dB or from 26.73 to 6.03 dB, respectively. The interference from node 1 to node 7 and from node 3 to node 10 occurs frequently when input bit rate is higher than 350 kbps.

In Fig. 5*a*, schemes A and B of the proposed directional routing protocols are studied comparatively. In scenario B, the transmit power is 12.5 dBm. Recall that in scheme A, the route with a smaller overlap count has higher priority over the power budget. Therefore as shown in Fig. 5*b*, route 1 → 5 → 6 → 4 → 11 → 14 is selected when using scheme A. By contrast, route 1 → 2 → 3 → 4 → 11 → 14 is set up when employing scheme B, as in this scheme the route with a smaller power budget has higher priority. Since there is no interference from nodes hops away in route 1 → 5 → 6 → 4 → 11 → 14, scheme A achieves a much better performance than scheme B, although the total power loss of route 1 → 2 → 3 → 4 → 11 → 14 is smaller than the former. Specifically, in route 1 → 2 → 3 → 4 → 11 → 14, when node 4 is receiving data from node 3, its SINR will be reduced from 28.82 to 8.99 dBm if it is interfered by the signal from node 1 to node 2. By contrast, in route 1 → 5 → 6 → 4 → 11 → 14, when node 4 is receiving data from node 6, there is no interference from nodes hops away. The SINR of 25.76 dB at node 4 is high enough for a reliable data transmission, although it is smaller than the value of 28.82 dBm in 1 → 2 → 3 → 4 → 11 → 14. The packet loss caused by the interference from nodes hops away occurs frequently when the input bit rate is higher than 350 Kbps and degrades the throughput performance significantly.

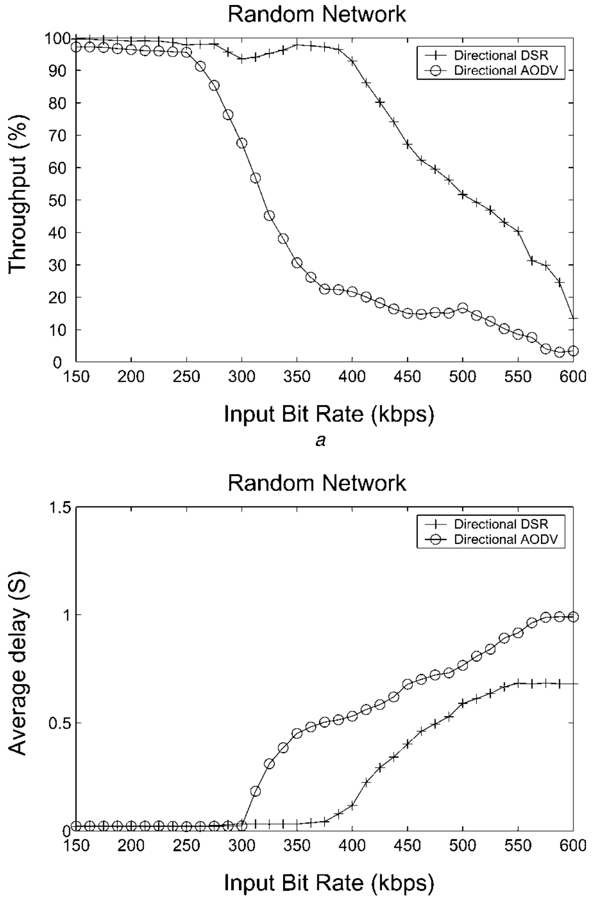


b

Figure 6 *Random ad-hoc network*

a Route 1 → 2 → 3 → 7 → 9 → 10 is randomly selected when using the original DSR or AODV routing protocol but in contrast, when invoking the proposed directional routing protocols, route 1 → 15 → 5 → 18 → 20 → 10 will be set up
b Similarly, as in arbitrary *ad-hoc* networks, the proposed directional routing protocols are capable of achieving considerable performance gains over the traditional DSR or AODV routing protocol

Fig. 6*a* shows a scenario in which the performance of both directional routing protocols is investigated in a random *ad-hoc* network. The results in Fig. 6*b* demonstrate that the



b

Figure 7 *Dynamic ad-hoc networks consisting of 25 nodes where the nodes move randomly at a speed between 0 and 5 m/s*

a Throughput against input bit rate
b Average delay against input bit rate

Table 1 Average route-setup time of the proposed directional routing protocols

Protocols	Arbitrary: Scenario A, s	Arbitrary: Scenario B, s	Random network, s
DAODV	0.388	0.278	0.327
DDSR	0.032	0.029	0.036

directional routing protocols are capable of greatly improving the performance of random *ad-hoc* networks.

In above Figs. 4*b*, 5*b*, and 6*b*, the performance of routing protocols is investigated in static *ad-hoc* networks, where link breakage is blocked. In Figs. 7*a* and 4*b*, the performance of DDSR and DAODV is compared in dynamic *ad-hoc* networks, where the nodes move to a random destination at a random speed between 0 and 5 m/s. It should be noted that, for the sake of comparison between AODV and DSR-based directional protocols, we have made sure that all nodes, once they receive an RERR message in the upstream direction, will empty their buffers. This is particularly useful in the DSR protocol, which normally tries to send waiting packets to the destination via alternative routes (if available). Since the DDSR is capable of learning multiple routes to the destination in a single request cycle, its performance in term of average end-to-end delay is better than that of the DAODV, as seen in Fig.4*b*. Consequently, the DDSR significantly outperforms the DAODV in term of throughput. The average route-setup time of the DDSR and the DAODV routing protocols are shown in Table 1, where the DDSR routing protocol significantly outperforms the DAODV routing protocol. This is attributed to the DSR's capability of learning multiple routes to the destination in a single request cycle.

4 Conclusions

In this paper, we have proposed two directional routing protocols, in order to enhance the performance of *ad-hoc* networks using directional antennas. The proposed directional routing protocols avoid interference from nodes hops away by exploiting the directionality of the beams. The results show considerable performance gains of the directional routing protocol over the DSR or AODV routing protocol, which is designed for transmission of real-time data such as voice and video. It is also shown that the DDSR routing protocol achieves a better performance than the DAODV routing protocol because of its capability of learning multiple routes to the destination in a single request cycle. Finally, we should point out that the novelty of this paper is that, in the proposed routing protocols, the overlap count is considered as an important metric, which is unique in *ad-hoc* networks using directional antennas. Furthermore, power budget is incorporated as a rule for route selection. The route with less power budget has a higher priority to be selected.

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