DSR-Based Directional Routing Protocol for Ad Hoc Networks

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***Abstract*— In this paper, a Dynamic Source Routing (DSR)-based directional routing protocol is invoked for wireless ad hoc networks using directional antennas. This is designed to balance the trade-off between co-channel interferences from nodes hops away, and the total power consumed by all the nodes. Three metrics are considered in the route discovery process in order to select the best route: hop count, power budget and overlaps between adjacent beams. By exploiting the directionality of directional antennas, the proposed DSR-based directional routing protocol is capable of reducing the overlaps between beams of the nodes along the route, hence eliminating the interference. Arbitrary networks and random networks are considered in our simulations. The results show considerable performance gains for transmission of real-time traffic over ad hoc networks.**

***Index Terms*—Ad hoc netwroks, routing protocols, DSR, directional antennas, directional routing.**

I. Introduction

In wireless ad hoc networks smart antenna techniques have been investigated to improve the achievable performance and system capacity, they are capable of providing spatial reuse, longer ranges, interference suppression, and other beneficial features [1], [2], [3], [4], [5]. In [1], a brief overview of smart antenna techniques was 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 using directional antennas.

Aimed at developing a complete ad hoc networking system with directional antennas, including the unique challenge of real-life prototype development and experimentation, Ramanathan [3] proposed utilizing directional antennas for ad hoc networking (UDAAN). This consists of several new mechanisms: directional power-controlled MAC, neighbor discovery with beamforming, link characterization for directional antennas, proactive routing and forwarding-all working cohesively to provide the first complete systems solution. Based on neighbor discovery [3], Choudhury [5] proposed MultiHop RTS MAC (MMAC), which uses multihop RTSs to establish links between distant nodes, and then transmit CTS, DATA, and ACK over a single hop. However, in order to perform neighbor discovery, all nodes are required to synchronize by employing a common clock source [5], such as GPS. Takai proposed a novel carrier sensing mechanism called Directional Virtual Carrier Sensing (DVCS) for wireless communication using directional antennas in [6], which only needs information on Angle of Arrival (AOA) and antenna gain for each signal from the underlying physical device. Specifically, three primary capabilities were combined with the original IEEE 802.11 MAC protocol for directional communication with DVCS: caching the AOA, beam locking and unlocking, and use of Directional Network Allocation Vector (DNAV). Ko et al. [7] presented a Directional MAC (DMAC) protocol that exploits the characteristics of both directional and omnidirectional antennas to allow simultaneous transmissions that are not allowed in the 802.11 protocol. In [8], Bao and Garcia-Luna-Aceves propose Receiver-Oriented Multiple Access (ROMA), 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] 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. Park [9] designed a novel MAC protocol, Mitigating Interference using Multiple Antennas MAC (MIMA-MAC), for MIMO aided ad hoc wireless networks, which mitigates interference from neighboring nodes by employing the spatial multiplexing capability of MIMO. Based on MIMA-MAC, Mitigating Interference using Multiple Antennas with Antenna Selection (MIMA/AS-MAC), was developed in [10], which uses multiple antennas to mitigate both interference from neighboring transmitters and fading. However, these two schemes inherit the exposed node problem and hidden node problem associated with CSMA/CA. Furthermore, all the nodes that participate in the communication are assumed to synchronize with each other.

Most of the above-mentioned works focused on the design and development of MAC protocols. 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, an DSR-based directional routing protocol is proposed for wireless ad hoc networks using directional antennas, which is designed to suppress interferences from nodes hops away, while attaining power effectiveness.

This paper is organized as follows. In Section II, after a brief introduction to the DSR routing protocol, we propose a DSR-based routing protocol. In Section III the attainable performance of the proposed routing protocol is investigated in arbitrary networks and random networks. Finally, we offer our conclusions in Section IV.

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II. DSR-Based Directional Routing Protocol

In this section, DSR-based directional routing protocol invoked for wireless ad hoc networks is described and characterized, where the best route from the source node to the destination node is selected according to hop count, power budget and overlap count.

DSR [11] is a source-initiated on-demand routing protocol, which means that routes are created only when desired by the source node. When a source node desires to send a message to an unknown destination, it initiates a route discovery process to locate the destination node. A route request (RREQ) packet is broadcast to neighbor nodes by the source node. This RREQ contains the source node's address, the destination node's address, and a unique identification (ID) number. The receiving node will add its own address to the route record of the RREQ and forward it to its neighbors if it is not the destination and does not have a route to the destination. To limit the number of RREQs propagated on the outgoing links, the receiving node only forwards the RREQ if it has not yet received this RREQ and if its address does not already appear in the route record [11]. If the receiving node has already processed this RREQ, it will discard the duplicate RREQ silently. Furthermore, according to the information contained in the RREQ packet, the receiving nodes update their information for the source node and set up backwards route to the source node in the route tables. A Route Reply (RREP) is generated when the receiving node is either the destination or has a current route to the destination. If the node generating the RREP is the destination, it places the route record contained in the RREQ into the RREP. By contrast, the intermediate responding node will append its cached route to the route record and then generate the RREP [11]. The RREP is then returned to the source node along the reverse route in the route record. As the RREP propagates back to the source, each intermediate node creates a route to the destination. Once the source node receives the RREP, it create the route to the destination and may begin sending data. If a link break occurs while the route is active, Route Error (RERR) messages are generated. When a RRER is received, the receiving node removes the hop in error from its route cache and truncates all routes containing this hop [11].

A. Directional Routing Protocol

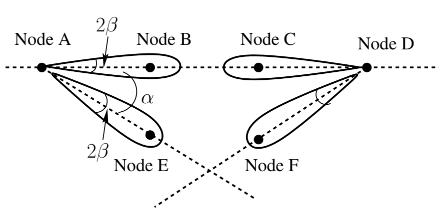

Fig. 1. An example where the beam of A→E does not overlap with the beam of D→F, since we have $\alpha > \gamma = \beta$.

Based on the original DSR routing protocol, 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 with 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 with 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 the nodes hops away may degrade the throughput greatly [12]. Hence, in this case the route of A→E→F→D is better than that of A→B→C→D. Another important parameter considered here is power budget, which is the total power loss when transmitting a packet from the source node to the destination node [13]. 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.

As shown in Fig. 1, in ad hoc networks using directional antennas, the interference from the nodes hops away may be eliminated when the route A→E→F→D is selected instead of the route A→B→C→D, since the transmit beam of A→E does not overlap with the receive beam of D→F. In the proposed routing protocol, if the angle between A→B and A→D is less than a threshold γ while the angle between D→C and D→A is also less than the threshold γ, they overlap and hence interfere with each other. In our simulations a sharp beam with a beamwidth of $2\beta = 40$ degrees is used by all nodes to transmit packets. Therefore, we have

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

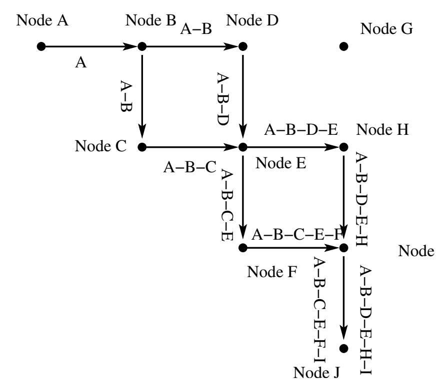

Fig. 2. DSR-based directional route discovery process.

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

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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 from node F to node A has a same procedure of calculating the DOAs and the overlap count.

Note that in the original DSR, since all the duplicated RREQs are discarded, it is unlikely to find the best route to 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 kind of situation, 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 hence 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. For the sake of avoiding excessive overhead, a threshold is set in the destination node. When the number of the 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 10, which is big enough to find the best route in our scenarios.

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 [13] PowerBudget $= \sum_{i=1}^{N-1} PL_{i,i+1}$, where $PL_{i,i+1}$ is the power loss between node i and node $i+1$.

In the directional routing protocol, 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 DSR route table of each node, along with the value of overlap count. Therefore, according to the information of hop count, power budget, overlap count, the receiving nodes first compare them with the corresponding information in their route table and then update their information for the source node or create new routes to the source node in the route tables. In the unicast of RREP to the source node, the intermediate node or the source node may update its route table for the destination. Specifically, a route with the smallest hop count has the highest priority to be selected. 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.

III. Performance Results

In this section the performance of the proposed DSR-based directional routing protocol is investigated by using our real-time QualNet-based 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. In the physical layer, the receiver sensitivity is -93.0 dBm, the IEEE 802.11b data-rate is 2 Mbps and the noise factor is 10.0. The directional antenna model employed in our simulations is capable of forming a sharp beam with a beamwidth of $2\beta = 40$ degrees, 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 retransmission limit is 0 or 2. For simplicity, there is no fading in our simulation and free space is selected as the path loss model.

The directional MAC protocol employed in our simulations is briefly described as follows. In the route set-up stage, node i will broadcast RREQs omnidirectionally to its neighbor nodes, i. e. 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-transmitting 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.

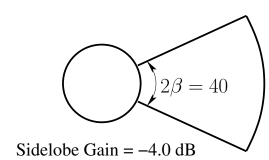

Fig. 3. Directional antenna model employed in our simulations.

The performance of the DSR-based directional routing protocol is investigated for a network consisting of 24 nodes as depicted in Fig. 4. We set the initial transmit power for every node at 10.5 dBm. It is possible that route $1 \to 2 \to 3 \to 6 \to 7 \to 9 \to 10$ is selected when using the original DSR routing protocol. By invoking the DSR-based directional routing protocol, route $1 \to 2 \to 5 \to 6 \to 8 \to 9 \to 10$ will be selected as best route in accordance with the metrics described in Section II. As shown in Fig. 5, the directional routing scheme can significantly improve the performance of the DSR routing protocol. Note that in route $1 \to 2 \to 5 \to 6 \to 8 \to 9 \to 10$, 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 that when node i is directionally communicating with node $i+1$, node i can not receive data from node $i-1$. This kind of packet loss happens frequently when

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the input bit rate is higher than 600Kbps. 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 directional antennal model and its beam is overlapped with that of node 1, an interference with 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 dB 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 model and its beam is overlapped with that of node 1. The SINR at node 7 is reduced from 26.26 dB to 12.31 dB. Furthermore, node 10 is interfered by the signal from node 3 or node 7 when node 10 is receiving data from node 9. The SINR at node 10 is reduced from 26.73 dB to 12.09 dB or from 26.73 dB 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 350Kbps. Since free space is selected as the path loss model and the path loss factor α is 2.0, we have $PL_{i,j} = 20\log(\frac{4\pi d_{i,j}}{\lambda})$, where λ denotes the wavelength and $d_{i,j}$ is the distance between node i and j. In the case where node i is transmitting DATA to node $i+1$ while node j is receiving DATA from node $j-1$, if node i and node j's beams are overlapped, the interference from node i to node j is $P_I = P_T + 15.56 - PL_{i,j}$, while the signal power from node $j-1$ to node j is $P_R = P_T + 15.56 - PL_{(j-1),j}$. Hence the Signal to Interference-and-Noise Ratio (SINR) at node j is less than $20\log(\frac{d_{i,j}}{d_{(j-1),j}})$. In the case of $d_{i,j} = 5 \cdot d_{(j-1),j}$, which means node i is 5 hops away from node j, the SINR at node j is less than 14.0 dB. Therefore, nodes that are multiple hops away will cause interference and disrupt communications.

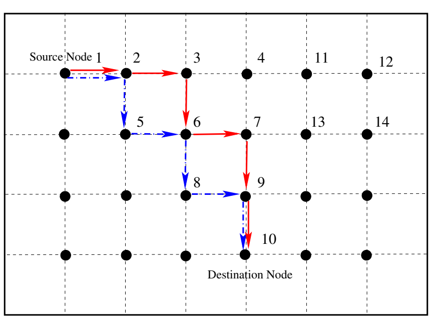

Fig. 4. Arbitrary ad hoc network: Scenario A. Route $1 \rightarrow 2 \rightarrow 3 \rightarrow 6 \rightarrow 7 \rightarrow 9 \rightarrow 10$ is randomly selected when using the original DSR routing protocol. By contrast, when invoking the proposed directional routing protocol, route $1 \rightarrow 2 \rightarrow 5 \rightarrow 6 \rightarrow 8 \rightarrow 9 \rightarrow 10$ will be set up, where there is no overlap.

In Fig. 6, schemes A and B of the proposed directional routing protocol are studied comparatively. In this scenario

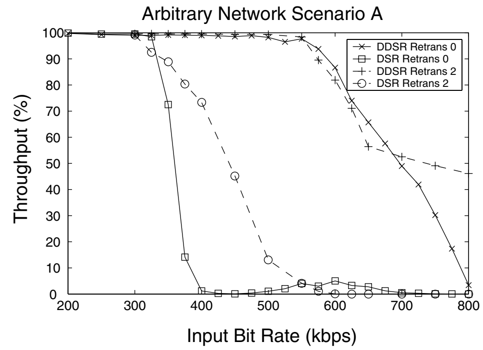

Fig. 5. Arbitrary ad hoc network: Scenario A. In the case of transmit power being 10.5, the DSR-based directional routing protocol outperforms the original DSR routing protocol significantly.

B, the transmit power is 12.5 dBm. Recall that in scheme A, the route with smaller overlap count has higher priority over the power budget. Therefore, as shown in Fig. 7, route $1 \rightarrow 5 \rightarrow 6 \rightarrow 4 \rightarrow 11 \rightarrow 14$ is selected when using scheme A. By contrast, route $1 \rightarrow 2 \rightarrow 3 \rightarrow 4 \rightarrow 11 \rightarrow 14$ 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 $1 \rightarrow 5 \rightarrow 6 \rightarrow 4 \rightarrow 11 \rightarrow 14$, scheme A achieves a much better performance than scheme B, although the total power loss of route $1 \rightarrow 2 \rightarrow 3 \rightarrow 4 \rightarrow 11 \rightarrow 14$ is smaller than the former. Specifically, in route $1 \rightarrow 2 \rightarrow 3 \rightarrow 4 \rightarrow 11 \rightarrow 14$, when node 4 is receiving data from node 3, its SINR will be reduced from 28.82 dBm to 8.99 dBm if it is interfered by the signal from node 1 to node 2. By contrast, in route $1 \rightarrow 5 \rightarrow 6 \rightarrow 4 \rightarrow 11 \rightarrow 14$, 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 $1 \rightarrow 2 \rightarrow 3 \rightarrow 4 \rightarrow 11 \rightarrow 14$. The packet loss caused by the interference from nodes hops away occurs frequently when input bit rate is higher than 350Kbps and consequently degrades the throughput performance significantly.

Finally, the performance of the proposed directional routing protocol is investigated in a random ad hoc network as seen in Fig. 8. The results in Fig. 9 demonstrate that the DSR-based directional routing protocol is capable of greatly improving the performance of random ad hoc networks.

IV. Conclusions

In this paper we have proposed an DSR-based directional routing protocol, in order to enhance the performance of ad hoc networks using directional antennas. The proposed directional routing protocol avoids interference from nodes hops away by exploiting the directionality of the beams. Arbitrary networks and random networks have been studied in our simulations. The results show considerable performance gains of the directional routing protocol over the DSR routing protocol, which is designed for transmission of real-time data such as voice and video. Finally, we should point out that the novelty of this paper is that in the proposed routing protocol, the overlap count

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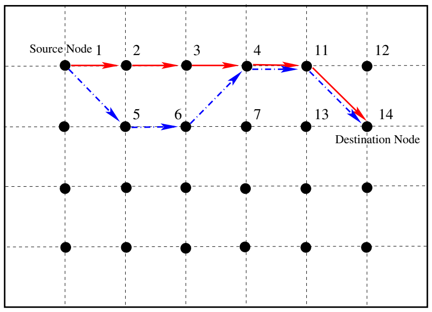

Fig. 6. Arbitrary ad hoc network: Scenario B. In scheme A the route with smaller overlap count has higher priority over the power budget, while in scheme B the route with smaller power budget has higher priority.

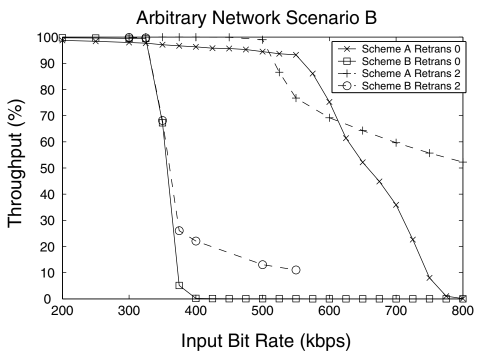

Fig. 7. Arbitrary ad hoc network: Scenario B. Scheme A achieves a much better performance than scheme B, since there is no overlap and hence no interference from nodes hops away in the route of scheme A.

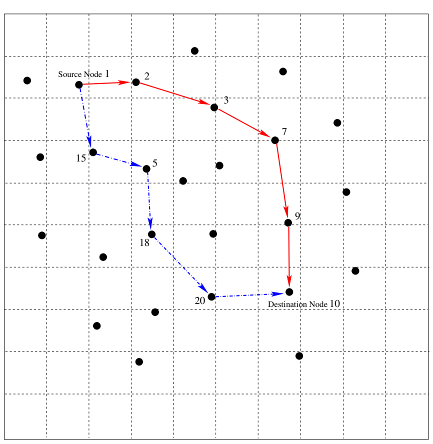

Fig. 8. Random ad hoc network. Route $1 \rightarrow 2 \rightarrow 3 \rightarrow 7 \rightarrow 9 \rightarrow 10$ is randomly selected when using the original DSR routing protocol. By contrast, when invoking the proposed directional routing protocol, route $1 \rightarrow 15 \rightarrow 5 \rightarrow 18 \rightarrow 20 \rightarrow 10$ will be set up.

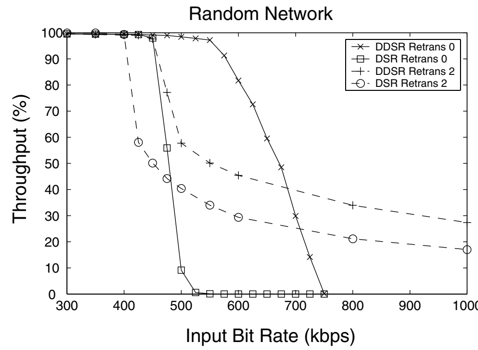

Fig. 9. Random ad hoc network. Similarly as in arbitrary ad hoc networks, the proposed DSR-based directional routing protocol is capable of achieving considerable performance gains over the traditional DSR routing protocol.

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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