Abdulai, J. and Ould-Khaoua, M. and Mackenzie, L.M. and Mohammed, A. (2008) *Neighbour coverage: a dynamic probabilistic route discovery for mobile ad hoc networks.* In: International Symposium on Performance Evaluation of Computer and Telecommunication Systems SPECTS 2008, 16-18 June 2008., Edinburgh, Scotland.

# Neighbour Coverage: A Dynamic Probabilistic Route Discovery for Mobile Ad Hoc Networks

Jamal-Deen Abdulai, Mohamed Ould-Khaoua, Lewis M. Mackenzie, Aminu Mohammed

*Abstract*—**Blind flooding is extensively use in ad hoc routing protocols for on-demand route discovery, where a mobile node blindly rebroadcasts received Route Request (RREQ) packets until a route to a particular destination is established. This can potentially lead to high channel contention, causing redundant retransmissions and thus excessive packet collisions in the network. Such a phenomenon induces what is known as broadcast storm problem, which has been shown to greatly increase the network communication overhead and end-to-end delay. In this paper, we show that the deleterious impact of such a problem can be reduced if measures are taken during the dissemination of RREQ packets. We propose a generic probabilistic method for route discovery, that is simple to implement and can significantly reduce the overhead associated with the dissemination of RREQs. Our analysis reveals that equipping AODV with probabilistic route discovery can result in significant reduction of routing control overhead while achieving good throughput.**

*Index Terms*— **Collision, Flooding, Forwarding Probability, MANETs, Network Connectivity, Reactive Routing, Overhead, Simulation,**

## I. INTRODUCTION

THERE has been a growing research activity on wireless mobile ad hoc networks (MANETs) over the past years due to their potential useful civilian and military applications. MANETs are formed dynamically by an autonomous system of mobile nodes that are connected via wireless links without using an existing fixed network infrastructure or centralized administration [1]. The nodes are free to move randomly and organize themselves arbitrarily; thus, the network's wireless topology may change rapidly and unpredictably. Nodes in MANETs act as end points and sometimes as routers to forward packets in a wireless multi-hop environment.

One of the fundamental challenges in the design of MANETs in a multi-hop environment is the design of dynamic routing protocol that can efficiently establish routes to deliver data packets between mobile nodes with minimum communication overhead while ensuring high throughput and low end-to-end delay.

Many routing protocols have been suggested for MANETs over the past few years [2-7]. In general, the routing protocols for MANETs fall into two categories [8] based on how route discovery process is initiated: proactive and reactive (or on-demand). Proactive routing protocols, such as DSDV [5] and OLSR [9], attempt to maintain consistent and up-to-date routing information from each node to every other node in the network. Each mobile node is required to periodically discover and maintain routes to every possible destination in the network. In the on-demand routing protocols, such as AODV [2] and DSR [3], routes are discovered only when they are needed. Each node maintains a route for a source-destination pair without the use of periodic routing table exchanges or full network topological view. Additionally, there are hybrid protocols that combine the features of both proactive and on-demand protocols. In such protocols, each node maintains routing information about its zone using proactive routing, but uses on-demand routing outside the zone [7]. The periodic routing information updates and updates due broken links that are inherent in proactive routing protocols can lead to a large routing control overhead in high mobility environments. Hence, these protocols surfer from excessive routing control overhead and therefore are not scalable in MANETs, which have limited bandwidth and whose topologies are highly dynamic.

In conventional on-demand routing protocols [2-4], a node that needs to discover a route to a particular destination, broadcasts a Route Request control packet (RREQ) to its immediate neighbours. Each mobile node blindly rebroadcast the received RREQ packet until a route is established. This method of route discovery is referred to as blind flooding. Since every mobile node is required to rebroadcast the received RREQ packet once. If the destination node is reached, the maximum number of rebroadcasts is about $N - 2$, where $N$ is the total of number of nodes in the Network. This can potentially lead to excessive redundant retransmissions and hence causing considerable collisions of packets in a contention-based channel, especially in dense wireless networks. Such a phenomenon induces what is known as broadcast storm problem, which has been shown to greatly increase network communication overhead and end-to-end

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delay [10, 11]. To reduce the deleterious impact of blind flooding, a number of broadcasting techniques have been suggested in [10-13].

Probabilistic broadcast schemes for MANETs have also been suggested in [10, 12, 14, 15]. In conventional probabilistic broadcast schemes, every mobile node rebroadcasts a packet based on a predetermined fixed forwarding probability *p*. Probabilistic broadcast schemes do not require global topological information on the network in order to make rebroadcast decisions. Thus these schemes are localized and can be used to effectively reduce the overhead associated with the dissemination of RREQ packets during route discovery. However, most probabilistic methods have focus on pure probabilistic scenarios [10-12] with relatively little investigations on the effects of such broadcast algorithms on specific applications such as route discovery.

This paper proposes a new probabilistic route discovery approach, called Dynamic Probabilistic Route Discovery (or DPR for short) which addresses the broadcast storm problem in existing on-demand routing protocols. In this approach, each node, upon receiving a broadcast packet, forwards the packet with probability *p* determined by the neighbourhood coverage and the local density of the node. The aim of this method is to keep the routing overhead low while achieving high reachability in order to ensure high overall network connectivity. We evaluate the new route discovery method using AODV. We have selected AODV in our present study as it is one of the early routing protocols proposed in the literature that has been widely investigated and analysed [2]. Our results reveal that equipping AODV with dynamic probabilistic route discovery method help to reduce the overall routing overhead while achieving comparable throughput with improved delivery latency when compare against the conventional AODV, especially in dense networks.

The rest of the paper is organised as follows. Section II presents related work on some route discovery techniques. Section III provides a brief overview of on-demand route discovery process in AODV. Section IV presents the new probabilistic route discovery method, DPR. Section V presents the simulation setup. Section VI conducts a performance evaluation of the new route discovery method. Finally, Section VII concludes this study and outlines some directions of future research work.

## II. RELATED WORK

The routing overhead associated with the dissemination of routing control packets such as RREQ packets can be quite huge, especially when the network density is high and the network topology frequently changes. Traditional on-demand routing protocols [2-4] produce a large amount of routing control traffic by blindly flooding the entire network with RREQ packets during route discovery. Recently, the issue of reducing the routing overhead associated with the route discovery and maintenance processes in on-demand routing protocols has attracted increasing attention.

Ko and Vaidya [6] have suggested Location Aided Routing (LAR) algorithm as an approach to mitigate the route discovery overhead by utilizing location aided information for mobile nodes. Such location information can be obtained using the global positioning system (GPS) receivers [16]. Castañeda and Das [17] have proposed the localisation of prior routing histories to localize the RREQ flood to a limited region of the network. The Routing On-demand Acyclic Multi-path (ROAM) [18] protocol mitigates the number of retransmissions of RREQ floods by using directed acyclic sub-graphs based upon the distance between the source and destination nodes. Nasipuri *et al.* [19] have suggested an on-demand routing method that employs the functionality of directional antenna systems. The use of directional antennas limits the direction and scope of the RREQ floods.

Other suggested solutions towards mitigating the RREQ floods involve the construction and maintenance of virtual backbones based on the physical topology of the network, and running the route discovery protocol over the backbone. [20-22]. Nodes on the backbone are privileged to forward RREQ packets during route discovery. The construction and maintenance of virtual backbone that guarantees total coverage of the entire network is either based on Connected Dominating Set (CDS) [20, 21] or Cluster based algorithms [22]. A CDS is a set of nodes such that every node in the network is either in the set or is the neighbour of a node in the set. In CDS-base routing, only the nodes in the dominating set are privileged to forward the RREQ packets. Undoubtedly, the efficiency of the CDS approach depends on the process of establishing and maintaining a CDS and the size of the corresponding sub-network. Unfortunately, the problem of finding a minimum CDS has been shown to be NP-complete [23]. In cluster base virtual backbone construction, the network topology is divided into several disjoint overlapping clusters. Each cluster elects one node as the cluster-head. The cluster-head of each cluster is responsible for forwarding RREQ packets on be half of its members. Cluster-heads communicate with each other by gateway nodes. A gateway is a node that has two or more cluster-heads as it neighbours.

Probabilistic routing approaches have also been proposed to help control the dissemination of the routing controls packets. Zhang and Agrawal [24] have described a probabilistic method for on-demand route discovery, where the probability to forward an RREQ packet is determine by the number of duplicate RREQ packets received at a node. In [25], the authors have proposed a probabilistic route discovery approach which utilizes the characteristics of both probabilistic and CDS based methods. The authors in [26] have suggested an on demand route discovery method that combines the functionality of probabilistic broadcasting and the area covered by the broadcast signal. The area covered by the broadcast signal is estimated by a GPS receiver or the signal strength at the receiving node. Azzedine et al. [27] have described analytical method of controlling the routing information advertisement in DSDV. The method uses probabilistic broadcast method and the frequency at which a node is allowed to send a packet.

Hass *et al.* [28] have proposed a gossip-based ad hoc route discovery approach. The authors have used a predefined probability value to decide whether or not to forward an RREQ packet. Some optimizations such as two-threshold scheme (i.e. use higher probability value for nodes with fewer neighbours) are introduced to prevent broadcast packets from quickly dying out and/or prevent nodes from transmitting excessive packets. In this approach, the forwarding node uses its local density (i.e. number of neighbours) to decide the forwarding probability to be used by neighbours. As a consequence, the forwarding probability at a node is predetermined by its predecessor.

## III. ON-DEMAND ROUTE DISCOVERY (AODV)

On-demand routing protocols [2-4] construct a path to a given destination only when it is required. They do not maintain topological information about the whole network, and thus there is no periodic exchange of routing information. Since the focus of our study is on the route discovery part of the protocol, we present a brief overview of the route discovery process in AODV in the remainder of this section.

When a source node **S** needs a route to some destination **D**, it broadcasts a RREQ packet to its immediate neighbours. Each neighbouring node rebroadcasts the received RREQ packet only once if it has no valid route to the destination. Each intermediate node that forwards the RREQ packet creates a reverse route pointing towards the source node **S**.

When the intended destination node **D** or an intermediate node with a valid route to the destination receives the RREQ packet, it replies by sending a route reply (RREP) packet. The RREP packet is unicast towards the source node **S** along the reverse path set-up by the forwarded RREQ packet. Each intermediate node that participates in forwarding the RREP packet creates a forward route pointing towards the destination **D**. The state created in each intermediate node along the path from **S** to **D** is a hop-by-hop state in which each node remembers only the next hop to destination nodes and not the entire route, as in DSR [3].

## IV. DYNAMIC PROBABILISTIC ROUTE DISCOVERY (DPR)

In traditional AODV, an intermediate node rebroadcasts all RREQ packets that are received for the first time. Assuming no intermediate node has a valid route to the destination and $N$ is the total number of nodes in the network, the number of possible rebroadcast in AODV is $N-1$. The basic probabilistic route discovery is simple. A source node sends an RREQ to its immediate neighbours with probability $p=1$. When an intermediate node first receives the RREQ packet, with probability $p<1$ it rebroadcasts the packet to its neighbours and with forwarding probability $1-p$ it simply drop the packet. Since the decision of each node to rebroadcast a packet is independent, the possible number of rebroadcasts is $p \times (N-1)$. We refer to this simple route discovery approach as Fixed Probabilistic Route Discovery, (FPR for short).

In a network of random distribution of mobile nodes as is MANET, there are regions of varying degrees of node density. Thus the need for an appropriate adjustment of the forwarding probability arises. Therefore, the FPR approach suffers unfair distribution of $p$, since every node is assign the same value of $p$ regardless of their local topological characteristics. It is critical to identify and categorise mobile nodes in the various regions of the network and appropriately adjust their forwarding probabilities. In this study, we propose a generic probabilistic route discovery algorithm that dynamically determines the forwarding probability of an RREQ taking into consideration the set of covered neighbours and the local density of the forwarding node.

### *A. Local Density*

To estimate the density of a region in the network, we use the local neighbourhood information of the region. A node is considered to be located at a dense region of the network if its number of neighbours is more than the average number of neighbours $\overline{n}$ in the network. The neighbourhood information is collected using a "hello" protocol to construct a 1-hop neighbour list at every node.

In the hello protocol, nodes exchange hello packets periodically. A node that receives a hello packet from its neighbour **U**, creates an entry for **U** in its neighbour table if it does not have one, else it updates the entry for **U**. If the node does not receive a hello packet from the neighbour **U** for some threshold amount of time, it times out and removes the entry for **U** from its neighbour table. A node considers all nodes in its neighbour table as its active neighbours and thus a link between them. The size of hello packets and the rate at which they are transmitted can drastically consume the communication bandwidth and thus degrade the overall network throughput. Also, there is often a trade off between the sending rate of hello packets and the accuracy of neighbourhood information. If the sending rate is high, then neighbourhood information at each node is accurate, but this introduces more congestion in the network. On the other hand, if the sending rate is low, then the congestion will be alleviated, but neighbourhood information will be inaccurate. Our algorithm uses small size of hello packets which contains only the identification number (4 bytes) and the sequence number (2 bytes) of the source. We have chosen a hello interval of 1.5seconds. To optimize the sending rate of hello packets, the RREQ packets also advertise the one-hop neighbourhood information, working as a hello packet. This event reschedules any pending hello packets.

### *B. Covered Nodes*

As described above, the goal of our protocol is to reduce the transmission redundancy incurred in disseminating the REEQ packet without degrading the overall network throughput. Our dynamic probabilistic route discovery allows each node to determine its forwarding probability according to the characteristic of its local density and the set of neighbours which are covered by the broadcast. When a node is ready to forward an RREQ packet, it appends its most recent neighbour list. Each node that receives the RREQ packet searches through the list to determine its set of neighbours that have been covered by the broadcast. The forwarding probability at a node is set low when relatively large percentage of its 1-hop neighbours are covered by the broadcast. Also, the probability is set high when small percentage of its neighbours is covered. We define covered neighbours as the neighbouring nodes of a broadcast source that have received the same broadcast packet from the previous sender.

### C. *Analytical Model*

In this section, we present the mathematical method of our probabilistic scheme. Let $A$ be the area of ad hoc network, $N$ be the number of mobiles nodes deployed in the network, and $R$ the signal transmission range. Let $\alpha$ be the fraction of the total network area covered by a mobile node.

$$\alpha = \frac{\pi R^2}{A} \tag{1}$$

The average number of neighbours $\overline{n}$ of the network can be obtained by using the following formula:

$$\overline{n} = (N-1)k\alpha \tag{2}$$

where $k$ is a constant, referred to as a connectivity parameter.

To validate equation (2), we have first conducted extensive simulations to determine the average number of 1-hop neighbours of various network densities. The simulation setup used for these investigations is defined in section V. Fig. 1 shows comparison between the simulation results and the analytical results. The figure shows that the average number of neighbours increases linearly with increasing network density. The best value of k in our scenario was found to be 1.18.

As discussed above, our route discovery method uses a node's local density information and its neighbour covered set to determine the forwarding probability of an RREQ. We introduce a simple equation that defines the relationship between the covered set, the local density and the forwarding probability. Let $n$ be the number of neighbours of a node $u$ and let $n_c$ be the number of nodes of $u$ that are covered by the broadcast. We define the forwarding probability at node $u$ as follows:

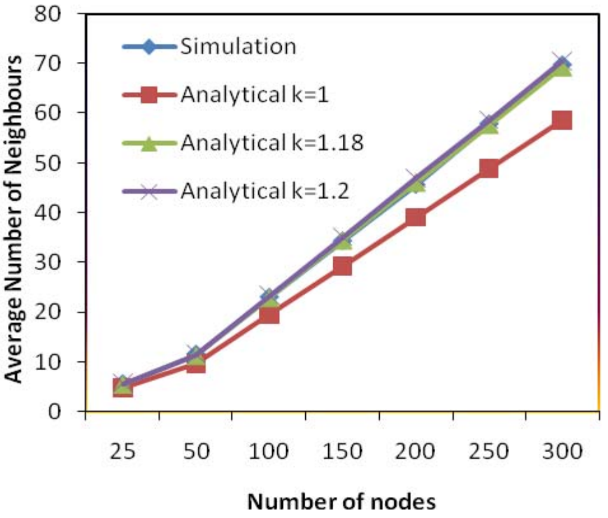

Fig. 1. Average number of neighbours vs. number of nodes in a 1000m x 1000m network topology area. Each node has a transmission range of 250m.
caption.

$$p_u = \begin{cases} \dfrac{n - n_c}{\overline{n}}; & n \le \overline{n} \\ \\ \dfrac{n - n_c}{n}; & n > \overline{n} \end{cases} \tag{3}$$

We have incorporated DPR and FPR in AODV as the base routing protocol. In what follows, we refer to such implementations of AODV as DPR-AODV and FPR-AODV. It is worth emphasising that our algorithms are applicable to other on-demand routing protocols [3, 4].

## V. SIMULATION SETUP

We have evaluated the performance of the new probabilistic route discovery method using ns-2 [29] packet level simulator (v.2.29). We have implemented the probabilistic route discovery methods by modifying the current AODV implementation in ns-2. We have compared our DPR-AODV and FPR-AODV algorithms with the traditional AODV. Our performance analysis is based on assumptions that have been widely used in the literature.

- All nodes participate fully in the routing protocol of the network. In particular each node participating in the network should also be willing to forward packets to other nodes in the network.
- Packets may be lost or corrupted in the wireless transmission medium during propagation. A node that receives a corrupted packet can detect and discards the packet.
- All mobile nodes are homogeneous (ie wireless transmission range and interface cards are the same).

The radio propagation model used in this study is the ns-2 default, which uses characteristic similar to a commercial radio interface, Lucent's WaveLAN card with a 2Mbps bit rate. The Distributed Coordination Function (DCF) of the IEEE 802.11 protocol is used as the MAC layer protocol. The mobility model is based on the random waypoint model in a field of 1000m x 1000m. In a random waypoint mobility model, each node at the start of the simulation remains stationary for a pause time seconds, then chooses a random destination and starts moving towards it with a randomly selected speed from a uniform distribution [0, max-speed]. After the node reaches its destination, it again stops for a pause-time interval and chooses a new destination and speed. This cycle repeats until the simulation terminates. The simulation is allowed to run for 900 seconds for each simulation scenario. To protect against transient or start-up data injecting bias into our results, we choose to skip the first 20 seconds of the simulation results. Other simulation parameters that have been used in our experiment are shown in Table 1.

Each data point represents an average of 30 different randomly generated mobility models with 95% confidence interval. We have evaluated the algorithms using the following performance metrics:

- Routing Overhead: the total number of RREQ packets transmitted during the simulation time. For packets sent over multiple hops, each transmission over one hop is counted as one transmission;
- End-to-end delay (or average delay): is the average time difference between the time a data packet is sent by the source node and the time it is successfully received by the destination node.
- Throughput: is defined total number of data packets received (bytes) at destinations in one second.
- Average Number of Collisions: The total number of packets dropped resulting from the collisions at the MAC layer.

## VI. PERFORMANCE RESULTS

This section evaluates the performance of DPR-AODV, and FPR-AODV, using AODV as the base routing protocol. The main focus is to reduce the routing overhead in the route discovery phase, therefore reducing the contention in the network and decreasing the probability of packet collisions. As a result, average delay can also be reduced, and the available bandwidth can be used more efficiently.

The evaluation of the three algorithms is conducted on different network conditions. First, the impact of network density on the performance of the protocols under question is assessed. We vary the network density by increasing the number nodes (i.e. 25, 50, 100, … , 300) deployed in a fixed square topology area of 1000m x 1000m. For each topology, 10 source-destination connections and a packet generation rate of 4 packets/sec have been used. The second part of the simulation studies investigates the effects of offered load on the performance of the algorithms. We vary the traffic injection rate by increasing the number of source-destination pairs (i.e. 1, 5, 10, … , 35), with each source node sending packets at the rate of 4packets/sec. In order to strike a balance between node mobility and its impact on the results, a 100 node model and a maximum node speed of 5m/sec with 0 pause times have been employed.

### A. Routing Overhead

The three route discovery algorithms impose vastly different amounts of overheads when the network density is increase. Fig. 2 demonstrates that DPR-AODV can significantly mitigate the routing overhead incur during the route discovery process, especially in dense networks. At low and medium dense networks, the overhead is reduced by about 56% in DPR-AODV when compared with the conventional AODV. Under the same network conditions, the overhead is reduced by about 30% when FPR-AODV is compared with the AODV. At moderately high dense networks, DPR-AODV demonstrates superior performance over the FPR-AODV and conventional AODV by further reducing the overhead by about 68%.

The effects of offered load on the performance of the algorithms in terms of routing overhead are shown in Fig. 3. Again, the DPR-AODV incurred lower routing overhead than AODV and its fixed probabilistic variant for various offered load. DPR-AODV achieves around 60% reduction of overhead when 1 connection is used and about 68% when 35 connections are used.

### B. Average Collision Rate

Fig. 4 shows the effects of network density on the performance to the algorithms in terms of average number of MAC collisions per unit simulation time. Since data and control packets share the same physical channel, the collision probability is high when the dissemination of RREQ packet is not appropriately controlled. Compared with the traditional AODV, the DPR-AODV protocol incurs lower average packet collision rate by achieving about 74% reduction of packet collision rate when the number of nodes deployed in 1000m x 1000m is 300.

Fig. 5 depicts the average collision rates of the three protocols when the offered load is varied from 1 to 35 source-destination connections. As expected, the DPR-AODV demonstrates significant reduction of packet collision for various offered loads. Compared with the AODV, DPR-AODV achieves around 76% reduction and FPR-AODV can achieve about 44% reduction of average collision rate when the offered load is 35 connections.

### C. Throughput

Fig. 6 shows achieved throughput with increasing network density. The figure shows that, although DPR-AODV can significantly reduce the routing control overhead and packet collisions as demonstrated in Fig. 2 and Fig. 4 , it is still can achieve comparable performance levels in terms of throughput when compared with the conventional AODV for various network densities. We can observe from the figure that the effects of network density on the performance of the protocols in terms of throughput is less insignificant when the traffic density is 10 connections; each generating at 4packets/sec.

In Fig 7, we measure the throughput of all the protocols for various offered loads ranging from 1 to 35 source-destination connections. The throughputs achieved by all the protocols are similar, especially when the offered load is between 1 and 25 connections. We observed that the throughputs for all the protocols saturates at offered load 15. However, at offered load 30, DPR-AODV achieved better throughput of about 9% (i.e. 13Kbytes/sec) when compared with the traditional AODV.

### D. End to End Delay

Fig. 8 measures the end-to-end delay of data packets that have been received at the destinations. When network density increases, more RREQ packets fail to reach the destinations due to high probability of packet collisions and channel contention cause by excessive redundant retransmissions of route request packets. Therefore the waiting time of data packets in the interface queues increases. The significant reduction of routing overhead translates to better end-to-end delay in dense networks. Compared with the traditional AODV, the DPR-AODV can reduce latency in dense networks by 46%. The figure also demonstrates the effects of poor network connectivity on delivery latency when the density is low. The poor performance of DRP-AODV in low density networks is due to the fact that large number of the RREQ packets sent failed to reach their destinations, therefore forcing more data packets to queue for longer times.

Fig. 9 shows the effects of the offered load on average delay. All protocols show comparable results with increasing offered load. However, DPR-AODV shows that it can achieve better delay under high offered load.

**Table 1.** SIMULATION PARAMETERS

| Simulation Parameter | Value |
|---|---|
| Simulator | NS-2 (v.2.29) |
| Transmitter range | 250 meters |
| Bandwidth | 2 Mbps |
| Interface queue length | 50 |
| Traffic type | CBR |
| Packet size | 512 bytes |
| Packet Rate | 4 packets/sec |
| Number of traffic flows | 1, 5, 10, …, 35 |
| Simulation time | 900 sec |
| Number of trials | 30 |
| Topology size | 1000m x 1000 m |
| Number of nodes | 25, 50, …, 300 |
| max-speed | 5m/sec |

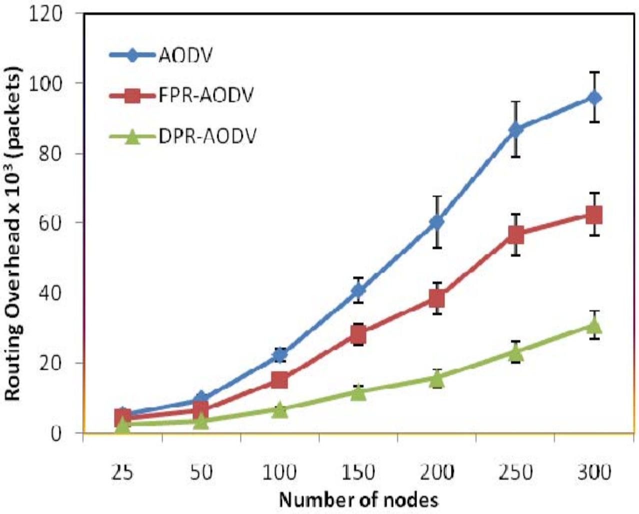

Fig. 2. Routing Overhead vs. network density with maximum node speed of 5 m/sec. Traffic pattern consist 4packets/sec, 512 bytes packet size and 10 source destination connections.

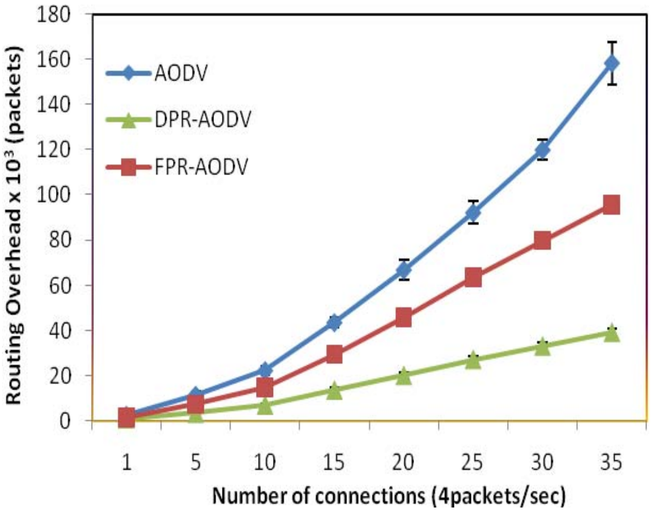

Fig. 3. Routing Overhead vs. traffic rate for 100 nodes in a 1000m x 1000m with maximum node speed of 5 m/sec.

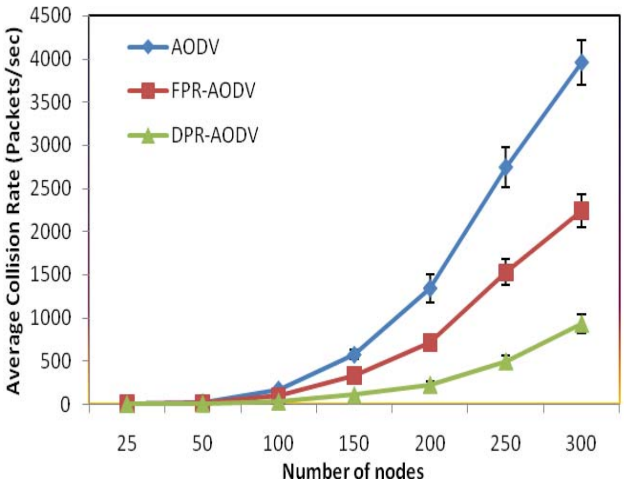

Fig. 4. The average MAC collisions vs. network density with maximum node speed of 5 m/sec. Traffic density is 4packets/sec, 512 byes and 10 source destination connections.

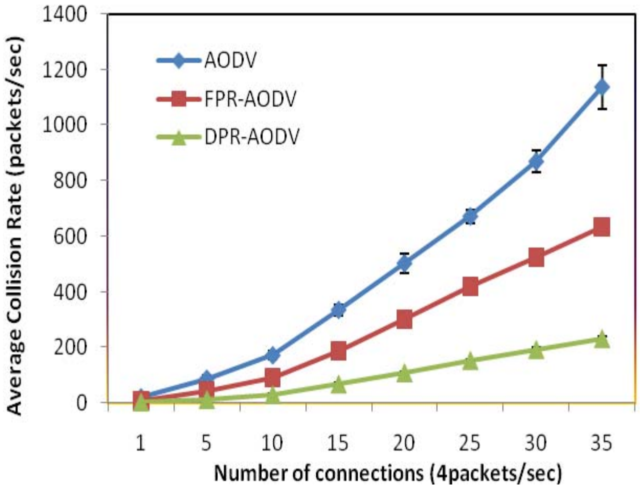

Fig. 5. The average MAC collisions vs. traffic rate for 100 nodes in a 1000m x 1000m with maximum node speed of 5 m/sec.

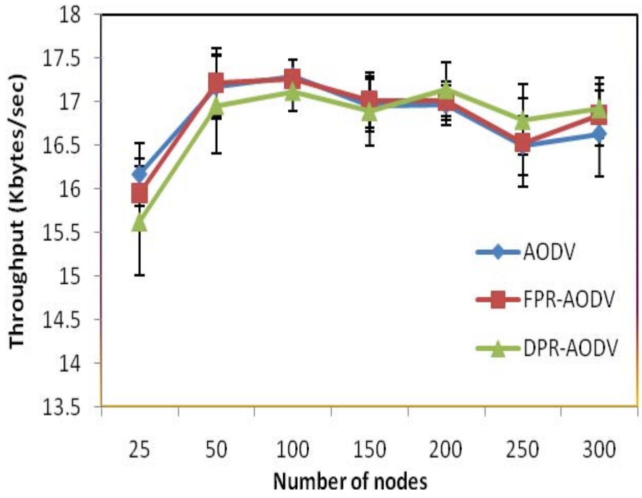

Fig. 6. Throughput vs. network density with maximum node speed of 5 m/sec. Traffic density is 4packets/sec, 512 byes and 10 source destination connections.

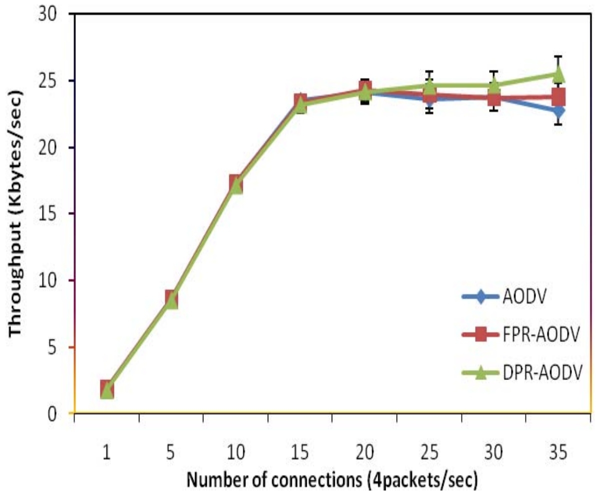

Fig. 7. Throughput vs. traffic rate for 100 nodes in a 1000m x 1000m with maximum node speed of 5 m/sec.

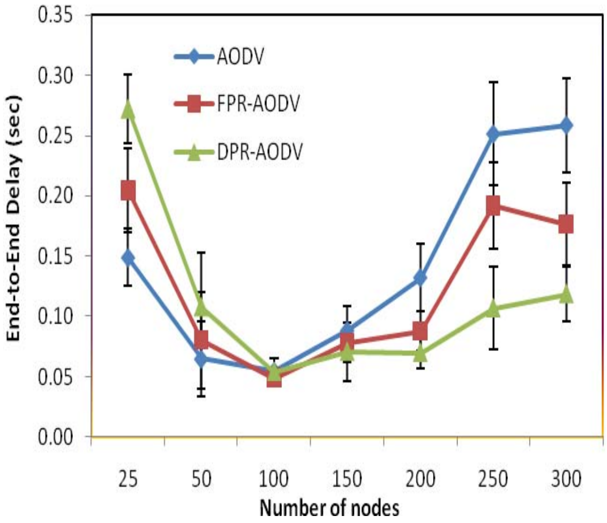

Fig. 8. End-to-end delay vs. network density with maximum node speed of 5 m/sec. Traffic density is 4packets/sec, 512 byes and 10 source destination connections.

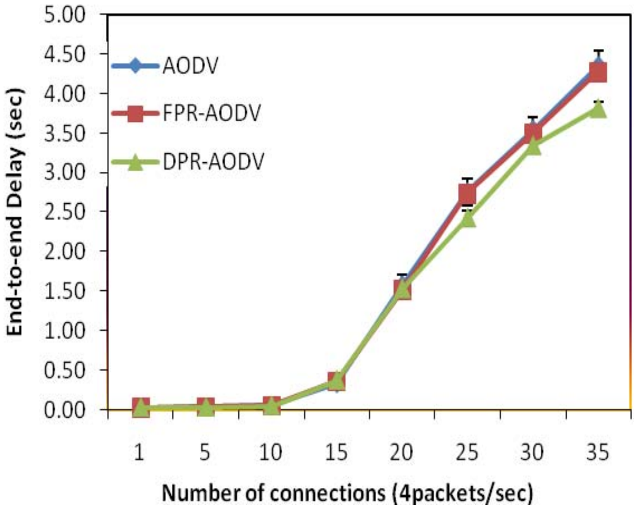

Fig. 9. End-to-end delay vs. traffic rate for 100 nodes in a 1000m x 1000m with maximum node speed of 5 m/sec.

## VII. CONCLUSION

This paper has proposed and evaluated the performance of dynamic probabilistic route discovery using AODV as the base routing protocol, which traditionally uses the blind flooding. The AODV routing protocol implementation in ns-2 has been modified to incorporate our probabilistic route discovery algorithms. The forwarding probability is determined taking into account the local density and covered set of neighbours of the sending node. In order to reduce the routing overhead without degrading the network throughput, especially in dense networks, the forwarding probability of nodes located in sparse areas is set high while it is set low at nodes located in dense areas. Compared with AODV and FPR-AODV, results obtained from the extensive simulations have revealed that our DPR-AODV generates a much lower routing overhead, especially in dense networks, thus significantly reducing the number of MAC collisions.

As a continuation of this research in the future, we plan to further explore the performance of the probabilistic route discovery in proactive routing protocols such as OLSR. Secondly, we plan to refine our analytic model for probabilistic route discovery approaches in order to facilitate the exploration of the optimal adaptation strategy.

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