UNIVERSITY
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GLASGOW

Probabilistic Route Discovery for Wireless Mobile Ad Hoc Networks (MANETs)

A Thesis Submitted

by

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for

The Degree of Doctor of Philosophy

to

The Faculty of Information and Mathematical Sciences

University of Glasgow

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Abstract

Mobile wireless *ad hoc* networks (MANETs) have become of increasing interest in view of their promise to extend connectivity beyond traditional fixed infrastructure networks. In MANETs, the task of routing is distributed among network nodes which act as both end points and routers in a wireless multi-hop network environment.

To discover a route to a specific destination node, existing on-demand routing protocols employ a broadcast scheme referred to as *simple flooding* whereby a route request packet (RREQ) originating from a source node is blindly disseminated to the rest of the network nodes. This can lead to excessive redundant retransmissions, causing high channel contention and packet collisions in the network, a phenomenon called a *broadcast storm*.

To reduce the deleterious impact of flooding RREQ packets, a number of route discovery algorithms have been suggested over the past few years based on, for example, location, zoning or clustering. Most such approaches however involve considerably increased complexity requiring additional hardware or the maintenance of complex state information. This research argues that such requirements can be largely alleviated without sacrificing performance gains through the use of probabilistic broadcast methods, where an intermediate node rebroadcasts RREQ packets based on some suitable *forwarding probability* rather than in the traditional deterministic manner.

Although several probabilistic broadcast algorithms have been suggested for MANETs in the past, most of these have focused on “pure” broadcast scenarios with relatively little investigation of the performance impact on specific applications such as route discovery. As a consequence, there has been so far very little study of the performance of probabilistic route discovery applied to the well-established MANET routing protocols. In an effort to fill this gap, the first part of this thesis evaluates the performance of the routing protocols Ad hoc On demand Distance Vector (AODV) and Dynamic Source Routing (DSR) augmented with probabilistic route discovery, taking into account parameters such as network density, traffic density and nodal mobility. The results reveal encouraging benefits in overall routing control overhead but also show that network operating conditions have a critical impact on the optimality of the forwarding probabilities.

In most existing probabilistic broadcast algorithms, including the one used here for preliminary investigations, each forwarding node is allowed to rebroadcast a received packet with a fixed forwarding probability regardless of its relative location with respect to the locations of the source and destination pairs. However, in a route discovery operation, if the location of the destination node is known, the dissemination of the RREQ packets can be directed towards this location. Motivated by this, the second part of the research proposes a probabilistic route discovery approach that aims to reduce further the routing overhead by limiting the dissemination of the RREQ packets towards the anticipated location of the destination. This approach combines elements of the fixed probabilistic and flooding-based route discovery approaches. The results indicate that in a relatively dense network, these combined effects can reduce the routing overhead very significantly when compared with that of the fixed probabilistic route discovery.

Typically in a MANET there are regions of varying node density. Under such conditions, fixed probabilistic route discovery can suffer from a degree of inflexibility, since every node is assigned the same forwarding probability regardless of local conditions. Ideally, the forwarding probability should be high for a node located in a sparse region of the network while relatively lower for a node located in a denser region of the network. As a result, it can be helpful to identify and categorise mobile nodes in the various regions of the network and appropriately adjust their forwarding probabilities. To this end the research examines probabilistic route discovery methods that dynamically adjust the forwarding probability at a node, based on local node density, which is estimated using number of neighbours as a parameter. Results from this study return significantly superior performance measures compared with fixed probabilistic variants.

Although the probabilistic route discovery methods suggested above can significantly reduce the routing control overhead without degrading the overall network throughput, there remains the problem of how to select efficiently forwarding probabilities that will optimize the performance of a broadcast under any given conditions. In an attempt to address this issue, the final part of this thesis proposes and evaluates the feasibility of a node estimating its own forwarding probability dynamically based on locally collected information. The technique examined involves each node piggybacking a list of its 1-hop neighbours in its transmitted RREQ packets. Based on this list, relay nodes can determine the number of neighbours that have been already covered by a broadcast and thus compute the forwarding probabilities most suited to individual circumstances.

To my Mother

To my wife and my two sons

To all my brothers and sisters

For their endless support, encouragement and love

Acknowledgements

I would like to express my deepest gratitude to my supervisors Prof. Mohamed Ould-Khaoua and Dr. Lewis M. Mackenzie for their support and guidance throughout this research. Their suggestions, criticisms and frequent encouragements have been pivotal in improving my thesis. They have been a constant source of inspiration, motivation and knowledge, all along this journey.

I must also express my sincere gratitude to my colleagues and staff members in the Department of Computing Science at the University of Glasgow, in particular the ENDS group for their constructive and insightful comments during my presentations. I would especially like to thank the colleagues I have collaborated and co-authored research papers with. In no particular order, these are Aminu Mohammed and Sara Al-Homoud.

I am greatly indebted to the Government of Ghana GETFUND programme, in particular the Faculty of Applied Sciences at the University for Development Studies, for financial support and for granting me a scholarship to pursue my further studies at doctoral level.

Finally I present my profound thanks to my family: my mother, sisters and brothers whose support and endless love have always been with me in the course of my studies in the UK. Above all I would like to seize this opportunity to express my dearest gratitude to my wife and two sons, Nabeweya, Waheeb and Zakariya whose unconditional love, support, motivation and patience have made the completion of this thesis possible.

Viva committee: Prof. Joe Sventek, Prof. Mike Woodward and Dr. Karen V Renaud

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Abbreviations

ACK	Acknowledgement
AP	Access Point
AODV	Ad hoc On-demand Distance Vector
BSS	Basic Service Set
CSMA/CA	Carrier Sense Multiple Access with Collision Avoidance
CBR	Constant Bit Rate
CTS	Clear To Send
DARPA	Defence Advanced Research Projects Agency
DCF	Distributed Coordination Function
DLAR	Dynamic Load Aware Routing
DSDV	Destination-Sequenced Distance Vector
DSR	Dynamic Source routing
ID	Identification
ESS	Extended Service Set
IEEE	Institute of Electrical and Electronics Engineers
MAC	Medium Access Control
MANET	Mobile Ad hoc Network
OLSR	Optimized Link State Routing
OSI	Open Systems Interconnection
PDA	Personal Data Assistance
PCF	Point Coordination Function
RFC	Request For Comments
RTS	Request To Send
SHARP	Sharp Hybrid Adaptive Routing Protocol
Wi-Fi	Wireless-Fidelity
WLANs	Wireless Local Area Networks
WiMAX	Worldwide Interoperability for Microwave Access

Chapter 1

Introduction

Wireless communication is currently one of the fastest growing technologies worldwide due to recent advances in mobile computing devices and wireless technology. Mobile devices such as laptops, personal digital assistants (PDAs), and mobile phones have become lightweight and portable enough to be conveniently carried by mobile users.

Wireless communication networks have a number of advantages over their traditional wired counterparts. In principle, wireless networks allow anywhere/anytime connectivity. They can be deployed in areas without a pre-existing wired-communication infrastructure or where it is difficult to lay cables. For example, in many places, historic preservation laws make it difficult to carry out cable installation in old buildings. In addition, the installation of a wireless network is much cheaper than a wired infrastructure making wireless networks an attractive option, especially in less developed world regions. Further, wireless networks provide a flexible and instantaneous communication setup. For instance, mobile users can turn on their laptops and PDAs and immediately connect to the Internet at public places such as airports, university campuses and coffee shops. Conference attendees can have wireless access to the Internet and can even share presentation files with other attendees.

The wireless communication industry has several segments such as cellular telephony, satellite-based communication, wireless local area networks (WLANs) and worldwide interoperability for microwave access (WiMAX). The de facto adoption of the IEEE 802.11 standard [1] has fuelled the development of WLANs by ensuring interoperability of wireless transmission technologies among various vendors thereby aiding the technology's market penetration. This standard defines the specifications of the first two layers of the Open System Interconnection (OSI) protocol stack [2] and operates in the unallocated ISM frequency band (i.e. 2.4 GHz or 5 GHz) of the electromagnetic spectrum.

The IEEE 802.11 standard [1] defines two major wireless networks for WLANs depending on the underlying configurations: *infrastructure-based* and *infrastructureless*-based (or *ad hoc*) networks. The infrastructure-based WLANs require special nodes (i.e. hosts or terminal in the network) called access points (APs), which are connected via existing wired LANs. The APs are used to coordinate communication between the *mobile nodes* (i.e. mobile hosts or terminals in the network such as laptops and PDAs) and wired networks. This configuration is used to provide services for so-called Wi-Fi hotspots [3], i.e., to provide wireless internet access at airports, conferences and other public places. The set of mobile nodes that are associated with a particular AP is called the Basic Service Set (BSS) [4]. To extend the Wi-Fi coverage area, a number of BSSs can be connected together by means of a Distribution System (i.e. a backbone network). The later configuration is referred to as the Extended Service Set (ESS) in the IEEE 802.11 nomenclature [1]. All APs in an ESS are given the same *service set identifier*, which serves as a network "name" for the network users. Figure 1-1 shows a typical example of an infrastructure-based WLAN. Here, the ESS is the union of the two BSSs (assuming that both APs are configured to be part of the same ESS). In contrast to a wired LAN, mobile nodes in an ESS are not physically constrained by cables and may communicate with each other, even though they may be in different BSSs, and they may move between BSSs in a seamless hand-off process.

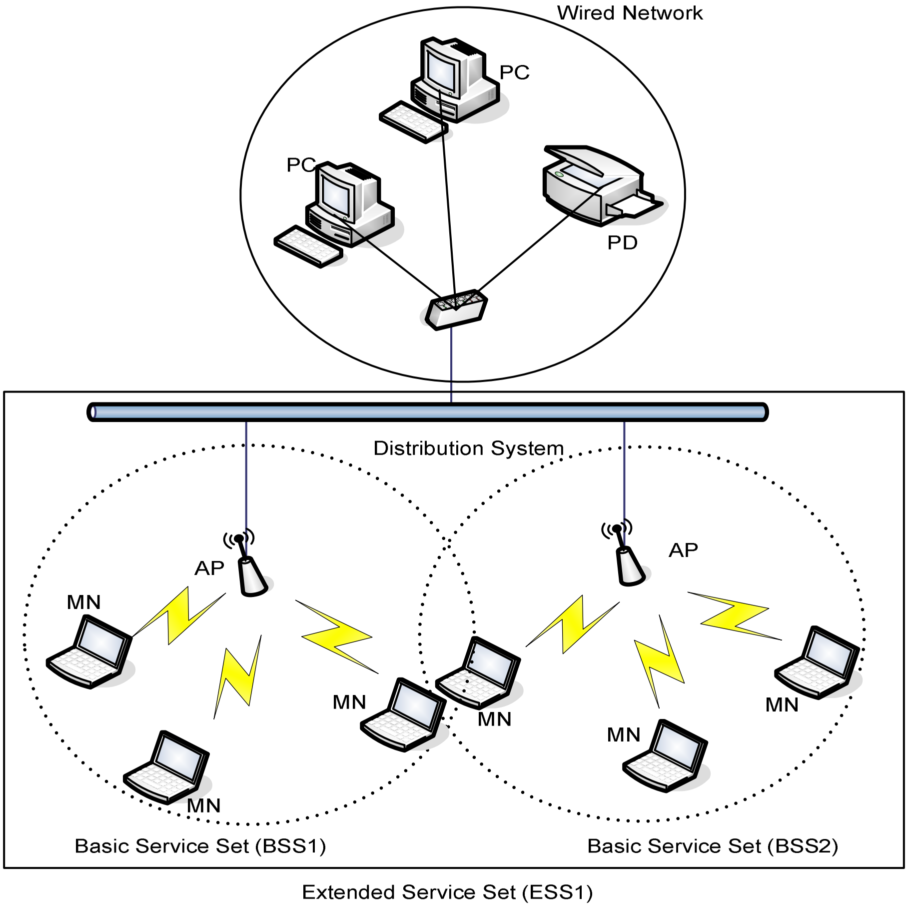


Figure 1.1. An Infrastructure-based wireless LAN consisting of wireless access points (APs) and mobile nodes (MN), personal computers (PCs) and a network printer (PD).

The cost and difficulty associated with the deployment of infrastructure-based WLANs may not be acceptable for dynamic environments such as battlefields, disaster sites, and temporary conference meetings where people and/or vehicles need to be temporarily interconnected [4]. Such environments are often without a pre-existing communications infrastructure, or the cost of deploying such an infrastructure may be prohibitive. In these cases, infrastructureless or ad hoc WLANs provide an efficient alternative solution. The ad hoc WLANs do not need any fixed infrastructure and require only the mobile nodes to cooperate in a peer-to-peer fashion to form an Independent Basic Service Set (IBSS) [5] in order to exchange data. However, this configuration of the IEEE 802.11 standard is limited to single-hop communication which is only applicable to mobile nodes within a mutual transmission radius. But, as the processing power and transceiver capabilities of mobile nodes have increased, it has became feasible to increase the communication range of IBSS using the mobile nodes themselves as forwarding agents and relying on the upper layers of the protocol stack for multi-hop paths. This requires the implementation of routing mechanisms at each mobile node so that it can forward packets towards intended destinations [6-9]. By acting as routers, mobile nodes may form the backbone of a spontaneous network that extends the range of the ad hoc WLAN beyond the transmission radius of the source. This later configuration of ad hoc WLANs is popularly referred to as a Mobile Wireless Ad Hoc Network (or MANET for short) [10, 11]. Figure 1.2 shows a typical example of a MANET. Suppose node **D** is outside the range of node **A**'s transmission range (the dotted circle around node **A**) and node **A** is outside the range of node **D**'s transmission range. Therefore, these two nodes cannot directly communicate with each other. If nodes **A** and **D** wish to exchange a packet, nodes **B** and **C** act as routers and forward the packet on behalf of **A** and **D**, since **B** and **C** are intermediate nodes that are within the transmission range of **A** and **D**.

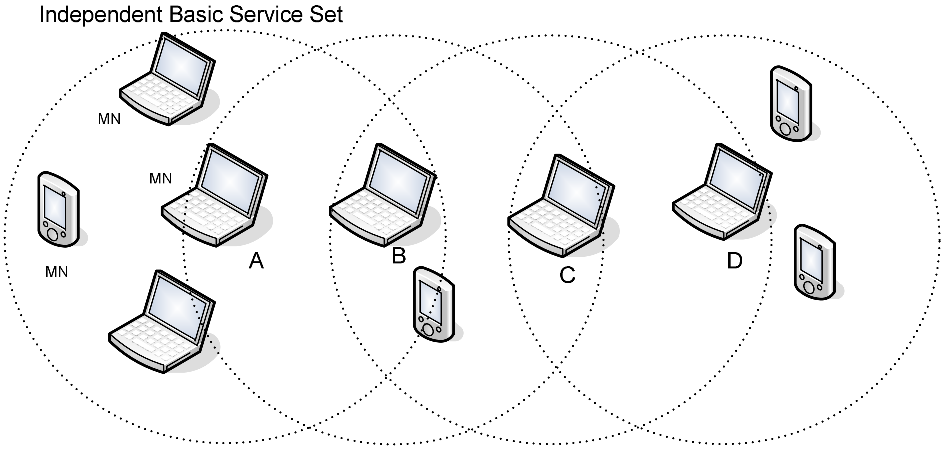


Figure 1.2. A scenario for a Mobile Wireless Ad Hoc Network (MANET).

1.1 Characteristics of MANETs

MANETs are self-organizing and adaptive in that the topology of a formed network can change on-the-fly without the intervention of a system administrator [4, 11]. Although MANETs share many of the properties of the traditional wired networks, they possess certain unique characteristics which derive from the inherent nature of their wireless communication medium and the distributed function of their medium access mechanisms. The issues involved may be categorised as follows.

***Wireless Channel*:** The wireless communication medium (or channel) is susceptible to a variety of transmission impediments such as path loss, interference and blockage [12, 13]. These factors restrict the range, data rate and reliability of the wireless transmission. A signal is considered successfully received at a node if the measured signal to interference and noise ratio (SINR) is large enough to be decoded. Typically, the transmitted signal has a direct-path component between the transmitter and receiver [12]. Other components of the transmitted signal referred to as multi-path components are signals reflected, diffracted or scattered by the environment, and arrive at the receiver shifted in amplitude, frequency and phase with respect to the direct-path component [12].

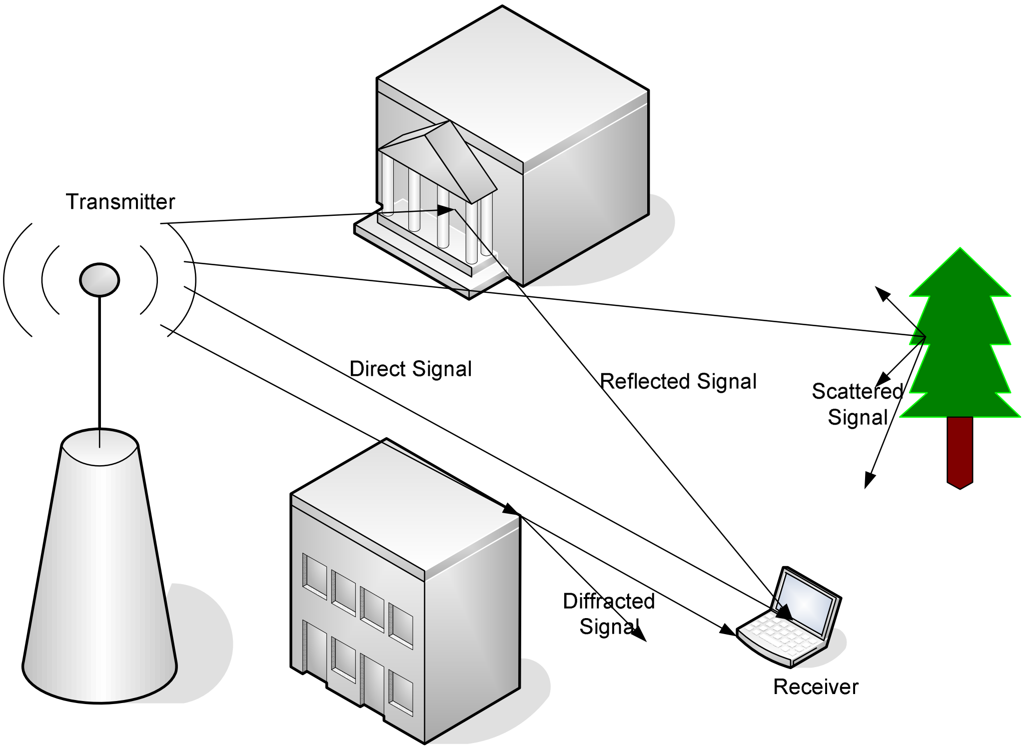


Figure 1.3. Multipath components of a transmitted signal

Path Loss of a signal**:** can be expressed as the ratio of the power of the transmitted signal to that of the received signal at the receiver on a given path [14, 15]. Estimation of path loss is critical in designing and deploying of 802.11 networks, since it measures the effects of the terrain and the carrier frequency used on signal propagation. Several path loss models have been suggested for 802.11 networks [4, 15]. The free space propagation model is the simplest path loss model which assumes the existence of a direct-path signal between the transmitter and the receiver, with no atmospheric attenuation of multi-path components. Another popular wireless signal propagation model is the two-ray ground model [16] which assumes that the signal reaches the receiver through two paths, one a line-of-sight path, and another the path through which the reflected or refracted and scattered wave is received.

Fading: One of the major problems that plague radio frequency networks is multi-path fading [4]. This refers to the rapid fluctuations in signal strength when received at the receiver, and it is usually caused by propagation mechanisms, notably, reflection, refraction or diffraction of the transmitted signal. For example, most mobile nodes operating on 802.11 are equipped with omni-directional antennas which radiate radio frequency energy in all directions. Signals spread outwards from the transmitting antenna and are reflected, refracted or diffracted by obstacles within the transmission radius [14, 15]. The signal received at the receiver is the sum of all the different components. The combined signal at the receiver may give a net superposition of 0 (i.e. if different components of the signal arrived 180^0 out of phase), in which case the receiver would not be able to decode the signal.

Interference: Transmission over the wireless communication medium is susceptible to interference from different sources. Two main forms of signal interference are adjacent channel interference and co-channel interference [17, 18]. In adjacent channel interference, the signals in nearby frequencies have components outside their allocated frequency ranges, and these components may interfere with on-going transmissions in the adjacent frequencies. This interference can be avoided by carefully introducing guard bands between the allocated frequency ranges. Co-channel interference is one of the major problems in MANETs, and is due to other nearby (e.g.) communication systems using the same transmission frequency [13]. The MAC layer of the 802.11 standard [19, 20] is carefully designed to reduce co-channel interference by dynamically coordinating access to the wireless channel among mobile nodes. Other approaches to reducing radio interference at the physical layer include the use of directional antennas which radiate radio signals in particular directions [17, 18, 21].

Taking the above transmission impediments into account, and for isotropic transceivers, three signal ranges may be identified [22] as shown in Figure 1.3. These are from the sender’s perspective:

Transmission Range (Rt): The range within which a transmitted packet can be successfully received by the intended receiver. Within this range, the SINR is large enough for the frame to be decoded by the receiver. The *Rt* depends mainly on the transmission power, the radio propagation prosperities and the sensitivity of the receiver hardware.

Carrier Sensing Range (Rc): The range within which nodes are able to sense the transmitted signal, even though correct frame reception may not be available. This range is used by the transmitting node to distinguish between busy and idle channels. A mobile node reports the channel state as busy if its 802.11 clear channel assessment mechanism senses energy above a threshold that is determined by antenna sensitivity. The *Rc* is typically larger than the transmission range, usually twice as large as the transmission range when the highest transmit power level is applied as depicted in Figure 1.3. However, a large *Rc* reduces spatial reuse (i.e. allowing concurrent communication between different source-destination pairs which are “reasonably” far from each other using either the same time slot or frequency band) [23] and affects the aggregate throughput because any potential transmitters, which sense a busy channel, are required to keep silent [24].

Interference Range (Ri): The range within which the intended receiver may be subject to interference from other transmission sources, thereby causing the rate of transmission errors to be higher than desired. This range is not fixed and largely depends on the transmitter-receiver distance and the receiver-interfering node distance.

It is mostly assumed that the transmission range is lower than the carrier sensing range and the interference range, i.e. $Rt < Rc$ and $Rt < Ri$ [20]. The authors in [22] have demonstrated that the ranges should be related to one another with $Rt \leq Rc \leq Rt + Ri$ in order to maximise the aggregate network throughput for a uniformly distributed network topology.

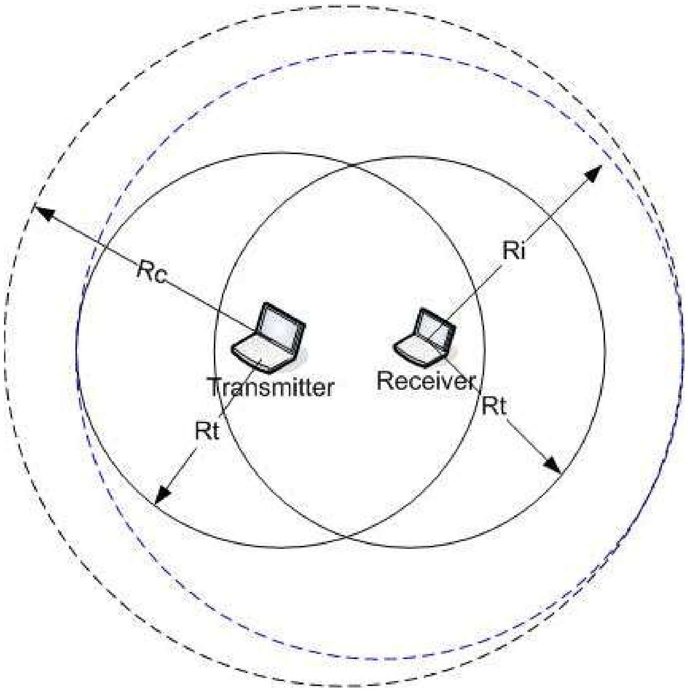


Figure 1.3. The transmission, interference and carrier sense ranges of two communication nodes.

Any communication protocol for MANETs should contend with the issue of interference in the wireless shared medium. When two or more nodes transmit a packet to a common neighbour at the same time, the common node will not receive any of these packets. In such a case, *collision* is said to have occurred at the common node [25].

***Mobility*:** The network topology in MANETs can be highly dynamic due to the movement of nodes; thus an ongoing communication session suffers frequent path breaks. The frequent path breaks in a MANET can be due to the movement of nodes in the network. Also, it can be due to the ability of nodes to leave or join the network at any time. This can be due to individual random mobility, group mobility, motion along pre-planned routes etc [26, 27]. Establishing and maintaining network connectivity in such a mobile environment will require periodic exchange of network information, leading to a possible increase in communication overhead. As a consequence, routing protocols for MANETs must be able to perform efficient and effective mobility management [28].

***Bandwidth*:** Abundant communication bandwidth is available in wired networks due to the advent of fibre optic cables [29] and exploitation of wavelength division multiplexing technologies [30]. However, the available radio frequency bandwidth of the wireless channel in MANETs is significantly lower compared to their wired counterparts [31]. Since the wireless channel is shared by the nodes located within the same transmission range, the bandwidth available per wireless channel depends on the number of nodes and the traffic they each inject into the network. As a result, only a fraction of the total bandwidth is available for each node. Also, the limited bandwidth availability imposes a constraint on routing protocols when maintaining topological information. Due to the frequent changes in the network topology, maintaining consistent topological information at all nodes results in significant communication overhead which, in turn, leads to inefficient utilisation of the limited channel bandwidth [31]. Therefore, the design of any routing protocol should take account of this constraint by minimizing the overhead as much as possible.

Limited Resources: Most ad hoc network nodes such as PDAs, laptops and sensors suffer from constrained resources compared to their wired counterparts. These resources include limited energy, computational power and memory [32, 33].

Energy: Nodes in a MANET depend on batteries for their energy source. However, since a battery's lifetime is limited, the power resource is at a premium. But wireless signal transmission, reception, retransmission, and beaconing operations all consume battery power. An overview of several approaches to power conservation through energy-aware mechanisms is included in [32, 33]. Energy efficiency in mobile nodes can be achieved through improvement in various levels, including the communication terminal (i.e. processors, BUS, PCMCIA, form factor etc.), protocols (i.e. broadcast and unicast protocols), and application layers (browsing, FTP, streaming etc.). For example, the power management feature in 802.11 cards allows two modes of operation, the active mode and power save mode [34]. During the active mode, the wireless card is always ready to transmit or receive frames in accordance with the specifications of the 802.11 medium access control protocols. In the power save mode, nodes are temporarily put to sleep and are awakened only in scheduled time intervals for short durations.

Computational power: The computing components used in a mobile node, such as processors, memory and I/O devices, usually have low capacity and limited processing power. Therefore, algorithms for communication protocols need to be lightweight in terms of computational and storage requirements [35].

1.2 Applications of MANETs

There are a number of possible application areas for MANETs. These can range from simple civil and commercial applications to complicated high-risk emergency services and battlefield operations [4, 33, 36]. Below are some significant examples including civil, emergency and military domains; the interested reader can refer to [33] for further details and other examples.

Civil and Commercial Applications: Two emerging wireless network scenarios that are soon likely to become part of the daily routines are vehicular communication in an urban environment, and personal area networking. In the vehicular communication scenario, short range wireless communication will be used within the car for monitoring and controlling the vehicle’s mechanical components. Another application scenario is for communication with other vehicles on the road. Potential applications include road safety messages, coordinated navigation and other peer-to-peer interactions.

Personal area networks (PANs) are formed between various mobile (and immobile) devices mainly in an ad-hoc manner. For example, on a University campus, students can form small workgroups to exchange files and to share presentations, results etc. At conferences, participants can connect their laptops or PDAs to share files and other network services. In an amusement park, groups of young visitors can interconnect to play network games. Their parents can network to exchange photo shots and video clips. But PANs will become more useful when connected to a larger network. Used in this way, PANs can be seen as extensions of the telecom network or Internet. Closely related to this is the concept of ubiquitous/pervasive computing where people, whether transparently or not, will be in close and dynamic interaction with devices in their environment.

Emergency Services: MANETs can be very useful in emergency search and rescue operations, such as in environments where the conventional infrastructure-based communication facilities are destroyed due to natural calamities such as earthquakes, or simply do not exist. Immediate deployment of MANETs in these scenarios can assist rapid activity coordination. For instance, police squad vehicles and fire brigades can remain connected and exchange information more quickly if they can cooperate to form ad hoc networks. The major factors that favour MANETs for such tasks are their self-configuration capability with minimal overhead, independent of a fixed or centralized infrastructure, the freedom and flexibility of mobility, and the unavailability of conventional communication infrastructures.

Battlefield Operations: In future battlefield operations, autonomous agents such as unmanned ground vehicles and unmanned airborne vehicles will be projected to the front line for intelligence, surveillance, enemy antiaircraft suppression, damage assessment and other tactical operations. It is envisaged that these agents, acting as mobile nodes, will organise into groups of small unmanned ground, sea and airborne vehicles in order to provide fast wireless communication, perhaps participating in complex missions involving several such groups. Examples of such activities might include: coordinated aerial sweep of large urban/suburban areas, reconnaissance of enemy positions in the battlefield etc [36].

1.3 Routing in MANETs

Providing efficient routing protocols is one of the most significant challenges in MANETs and is critical for the basic operations of the network [37, 38]. In MANETs, a route consists of an ordered set of intermediate nodes that transport a packet across a network from source to destination by forwarding it from one node to the next. The unique characteristics of MANETs, such as those discussed in Section 1.2, make routing in MANETs a challenging task. Firstly, the mobility of nodes results in a highly dynamic network with rapid topological changes causing frequent route failures. Secondly, the underlying wireless channel, working as a shared medium, provides a much lower and more variable bandwidth to communicating nodes than in wired networks. As a result, an effective routing protocol for a MANET environment has to dynamically adapt to changing network topology, and should be designed to be bandwidth-efficient by reducing the routing control overhead so that as much as possible of the channel bandwidth is available for the actual data communication.

Significant research has been devoted to developing routing protocols for MANETs [6-9]. These protocols can be can be classified into three main categories based on the route discovery and routing information update mechanisms employed: *proactive* (or *table driven*), *reactive* (*or on-demand driven*) and *hybrid*.

***Proactive routing protocols*:** such as those described in [6, 9] attempt to maintain consistent and up-to-date routing information (routes) from each node to every other node in the network. Topology updates are propagated throughout the network in order to maintain a consistent view of the network. Keeping routes for all destinations has the advantage that communication with arbitrary destinations experiences minimal initial delay. Furthermore, a route could be immediately selected from the route table. However, these protocols have the disadvantage of generating additional control traffic that is needed to continually update stale route entries [37, 39]. Especially in highly mobile environments, communication overhead incurred to implement a proactive algorithm can be prohibitively costly [37]. Typical and well-known examples of proactive routing protocols are destination-sequence distance vector (DSDV) [6] and optimized link state routing (OLSR) [9].

***Reactive routing protocols*:** such as those proposed in [7, 8] establish routes only when they are needed. When a source node requires a route to a destination, it initiates a route discovery process by flooding the entire network with a *route request* (RREQ) packet. Once a route has been established by receiving a *route reply* (RREP) packet at the source node, some form of route maintenance procedure is used to maintain it, until either the destination becomes inaccessible or the route is no longer desired. These protocols use less bandwidth for maintaining the routing tables at every node compared to proactive routing protocols by avoiding unnecessary periodic updates of routing information. However, route discovery latency can be greatly increased, leading to long packet delays before a communication can start. Ad hoc on-demand distance vector (AODV) [7] and dynamic source routing (DSR) [8] are well-known examples of reactive routing protocols.

Hybrid routing: A hybrid routing protocol [40-42] attempts to combine the best features of proactive and reactive algorithms. It often consists of the two classical routing protocols: proactive and reactive. Hybrid protocols divide the network into areas called zones which could be overlapping or non-overlapping depending on the zone creation and management algorithm employed by a particular hybrid protocol. The proactive routing protocol operates inside the zones, and is responsible for establishing and maintaining routes to the destinations located within the zones. On the other hand, the reactive protocol is responsible for establishing and maintaining routes to destinations that are located outside the zones. The zone-based routing protocol (ZRP) [40] and sharp hybrid adaptive routing protocol (SHARP) [42] are well-known examples of hybrid routing protocols.

1.4 Broadcasting in MANETs

Broadcasting is a fundamental operation in MANETs whereby a source node sends the same packet to all the nodes in the network. In multi-hop MANETs where all the nodes may not be within the transmission range of the source, intermediate nodes may need to assist in the broadcast operation by retransmitting the packet to other remote nodes in the network. In traditional broadcast settings, the dissemination of packets often uses up valuable network resources such as node power and bandwidth. Hence, it is important to carefully choose the intermediate nodes so as to avoid redundancy in the dissemination process.

Broadcasting at the physical layer can be based on two transmission models; the *one-to-all model and* the *one-to-one model*. In the one-to-all model, transmission by each node can reach all nodes that are within its transmission radius, while in the one-to-one model, each transmission is directed toward only one neighbour (using narrow beam directional antennas or separate frequencies for each node) [43, 44]. However, broadcasting has been studied in the literature mainly for the one-to-all model [43, 45]. This is primarily because most of the current mobile devices have omni-directional antenna implementation where the communication signal is propagated to and received from all directions.

Broadcasting at the network layer has many important uses and several MANET protocols assume the availability of an underlying broadcast service [7, 8, 46, 47]. Applications that rely on broadcasting include paging a particular node or information dissemination to the whole network (e.g. alarm signal). Moreover, broadcasting is the backbone of most network layer protocols, providing important network management control and route establishment functionality. For instance, routing protocols such as AODV [7], DSR [8] and ZRP [40] each use a broadcast technique or a derivative of it to establish routes. Other routing protocols, such as the temporally-ordered routing algorithm (TORA) [48], use broadcast techniques to disseminate error packets for broken links to the entire network. Broadcasting is also often used as a building block for multicast protocols [47].

Several broadcast approaches have been suggested in the literature including probabilistic, counter-based, location-based and neighbour-knowledge-based approaches [49, 50]. In the case of probabilistic approaches, a node rebroadcasts the received packets according to a certain probability. In counter-based approaches, a node rebroadcasts a packet only when the number of duplicate packets received at the node is less than a certain counter-threshold value. The location-based approaches reduce the number of forwarding nodes by exploiting the geographic information of the network using location information aided devices such as GPS receivers. In neighbour-knowledge-based approaches, periodic exchange of neighbourhood information among nodes in the network is used to reduce the redundant transmission of broadcast packets.

1.5 Related Work

Finding a route between a given pair of nodes in MANETs is an expensive operation in terms of both bandwidth utilization and packet latency. Moreover, establishing a route via proactive or reactive routing protocol requires some exchange of routing control packets. In particular, the overhead associated with the exchange of the control packets can be quite high in MANETs, especially in environments where the network topology frequently and rapidly changes. Most routing protocols such as those described in [7, 8, 40, 51] typically use a simplistic form of broadcasting called *simple flooding* for routing tasks such as route discovery and topology dissemination. However, this method can potentially lead to excessive redundant retransmissions, channel contention and packet collisions in the network. Such a phenomenon induces what is known as the *broadcast storm problem* [49], which has been shown to greatly degrade network throughput data delivery latency.

Recently there has been substantial work devoted to mitigating the communication overhead associated with broadcasting for route discovery and maintenance processes in MANETs [28, 52, 53]. However, most of the proposed solutions suffer from a number of disadvantages. Below is a summary of some of the existing solutions with a brief description of their drawbacks.

Location-based routing algorithms [53, 54]:

In location-based routing algorithms, such as those suggested in [53, 54], location aided information services are used at mobile nodes to limit the direction and scope of the dissemination of routing control packets in the network. A location aided information service that provides the location of a destination is the key component of systems that use location-based routing algorithms. Every node learns the locations of its immediate neighbours by exchanging “hello” packets [41, 55]. But to learn the locations of potential distant nodes, the help of a location service is required. In traditional cellular networks, there are dedicated locations servers (with well-know addresses) that maintain location information about the network. However in MANETs, such a centralised approach is not viable since the topology is dynamic and unpredictable.

An alternative to a centralized dedicated location service is the use of Global Position System (GPS) receivers [56] or some other indirect localization technique. In this case each mobile node is assumed to be equipped with a GPS receiver for location information. However, in reality position information provided by GPS includes some amount of error, which is the difference between GPS-calculated coordinates and the actual coordinates. For example, the NAVSTAR Global Positioning System has positional horizontal accuracy of about 100m at the 95% probability level [57] and Differential GPS offers accuracies of a few meters [56].

Location-Aided Routing (LAR) [53] is an optimisation of reactive routing protocols to mitigate the overhead of simple flooding. LAR assumes that each node knows its location, but does not employ any special location service to obtain the locations of other nodes. Instead, destination location information obtained from prior route discovery is used as an estimate of a destination’s location. Based on the estimated location of a destination, a source node can limit its route search to a defined zone in the network. The Distance Routing Effect Algorithm for Mobility (DREAM) [28] is an optimisation of proactive routing protocols to reduce the overhead associated with the exchange of routing tables. In DREAM, every node proactively maintains a location table that stores location information about each other node in the network. However, it attempts to reduce the overhead associated with the update of location information by exploiting the distance and mobility effects of the network topology. Distant nodes are less privileged to receive frequent location updates compared to closer ones, which use distance effects for the limited dissemination of channel state updates. Also, each node generates updated information about its location according to its rate of mobility. Fast moving nodes generate updates more often than slow moving nodes. DREAM forwards data packets in a form similar to the route search in LAR.

A performance evaluation of location aided routing algorithms in vehicular ad hoc networks has been presented in [54], whereas an overview of location based protocols has been included in [58, 59]. Castañeda and Das [60] have proposed an optimisation of reactive routing protocols by utilizing prior route histories to limit the query flood to a region in the neighbourhood of the prior routes. The protocol maintains a set of nodes which include all the nodes on the last valid route between specific source-destination pairs. In subsequent route discoveries, only such nodes are privileged to propagate the query floods. The disadvantage of this method is that the route histories become stale quickly in a highly dynamic environment.

***Zone-based routing algorithms [40, 41, 55, 61]*:**

The zone-based routing framework [40, 41] exploits the concept of protocol hybridization to reduce the overhead associated with the dissemination of routing control packets. It attempts to balance the trade-off between proactive dissemination and reactive discovery of routing information. While proactive routing protocols can provide low latency through frequent dissemination of routing information, they entail high routing overhead and scale poorly with increasing network density [37]. In contrast, reactive routing protocols can achieve low routing overhead, but may suffer increased latency due to on-demand route discovery and route maintenance [62].

ZRP [40] was the first zone-based hybrid routing protocol with both proactive and reactive routing components. ZRP defines a zone around each node consisting of its *k*-hop neighbourhood. Routing within a zone (i.e. intra-zone routing) is performed using a proactive routing protocol and routing between nodes in different zones (i.e. inter-zone routing) is performed by a reactive routing protocol. To reduce the overhead associated with simple flooding during inter-zone routing, “bordercasting” is used. In bordercasting, the route request packets are propagated by multicasting them directly to the peripheral nodes of the zone. Recent ZRP protocols such as those described in [41, 55, 61] adopt a multi-level routing zone structure around each node. In this case, the frequency of link state information updates is low for inner-zones and high for outer-zones.

SHARP [42] is similar to ZRP in terms of protocol hybridization, but it operates under the assumption of the presence of hot spot nodes (i.e. nodes that have significant incoming data) in a MANET. A proactive zone is defined around each hot spot node. Nodes within the proactive zone maintain routes proactively only to the central node. The nodes that are in the proactive zone use the proactive component to establish routes. However, the performance of a zone based routing protocol is closely related to the dynamics and size of the network and the parameters for zone construction [41]. In addition, each node is required to use different routing protocols for different zones in the network. This is a disadvantage for mobile nodes as state information has to be kept for each routing protocol. In a recent work on the ZRP framework [61], it has been argued that using a uniform zone radius throughout the whole network is inefficient since each node is assigned the same zone radius regardless of its local topological characteristics. Instead, having independent zone radii allows each node to automatically configure its optimal zone radius in a distributive manner. However, in the Independent Zone Radii (IZR) protocol [61], each node has to know which nodes have a demand for its link state updates by exchanging additional control packets.

Backbone-based Routing Algorithms [63-65]:

Other suggested solutions towards mitigating the routing overhead associated with route discovery algorithms is through the use of virtual backbones constructed and maintained on the physical topology of the network [63-65]. The route discovery protocol is run over a virtual backbone in which only the nodes in the backbone are privileged to forward the RREQ packets. The construction and maintenance of a virtual backbone which guarantees a total coverage of the entire network is the primary application of Connected Dominating Sets (CDS) algorithms [58] and/or cluster based algorithms [65].

A CDS of a network is defined as 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 [58, 59]. In routing, only the nodes that are in the connected dominating set are privileged to forward the RREQ packets. Undoubtedly, the efficiency of the CDS approach depends on the process of establishing and maintaining the CDS and the size of the corresponding sub-network. If the size of the CDS is large, the system would incur large communication overhead. On the other hand, if the size is small the system would suffer from poor reachability. Therefore, it is crucial to determine a minimum CDS that can balance the trade off between the communication overhead and the reachability [58, 59]. Unfortunately, the problem of finding a minimum CDS for most graphs (e.g. a MANET) has been shown to be NP-complete [66] even when complete network topology information is available.

A wide range of heuristic algorithms have been suggested to construct a Minimum Connected Dominating Set (MCDS) [58, 59, 67] for a network with randomly distributed nodes. For example, Guha and Khulla [68] have proposed two heuristic methods for constructing the MCDS of a connected network with bounded performance guarantees. Das *et al.* [69] have presented distributed implementations of the two heuristic algorithms. Many CDS based algorithms in the literature [70] have been motivated by one or other of these two heuristics. However, the construction and maintenance of an efficient MCDS requires the exchange of a large amount of topology information, extending to much more than 1-hop neighbourhood information. For example in [67], an MCDS is constructed for RREQ dissemination, but each node is required to know its 3-hops neighbourhood information. This is achieved through periodic exchange of “hello” packets with a very large payload in order to exchange two-hop/three-hop neighbourhood lists.

In the cluster routing approach [71, 72], a virtual backbone is constructed by dividing the network topology into several overlapping clusters. Each cluster elects one node as the cluster-head. The cluster-head in each cluster is responsible for forwarding RREQ packets on behalf of its members. Cluster-heads communicate with each other through gateway nodes. A gateway is a node that has two or more cluster-heads as it neighbours. However, organising a MANET into stable clusters is crucial to avoiding the prohibitive overhead associated with cluster-head changes [73]. Moreover, node mobility in MANETs may still cause frequent failures of the wireless links. As a consequence, clustering algorithms designed for MANETs must be able to handle node mobility. For example, in the (α, t)-cluster approach [74], only neighbouring nodes that fulfil a certain probability of path availability bound are clustered. As such, clustering is more dominant in low mobility networks. Clustering algorithms often suffer from significant time complexity [75] and large communication overhead due to establishing and maintaining clusters, especially in high mobility environments.

1.6 Motivations

As mentioned above, broadcasting is an important network service for routing protocols in MANETs. In the case of on-demand routing protocols, broadcasting is used to disseminate the RREQ packets to the entire network for route discovery. Improving the broadcast service used for on-demand route discovery is crucial to provide good network performance and scalability. The core problem in broadcasting is how to minimize the number of nodes that rebroadcast the RREQ packets while maintaining a high degree of reachability (i.e. the percentage of nodes that receive a RREQ packet) in order to discover routes to the destination. Broadcasting a large number of RREQ packets may guarantee a high chance of discovering routes to destinations. However, this method of discovering destinations may result in an inefficient utilisation of limited system resources such as the communication bandwidth and battery power [49, 50]. Therefore, a route discovery technique that can guarantee an efficient utilisation of these limited system resources while achieving acceptable levels of other important performance metrics such as throughput and end-to-end delay is highly desirable.

As stated in Section 1.5, there has been significant research conducted on reducing the overhead associated with the route discovery process in routing protocols [53, 76]. Most of the proposed algorithms have considered using additional hardware devices such as location aided devices [53, 54], or require global or near-global network topological information [63, 64] in order to control the routing overhead. One promising solution to alleviating the communication overhead associated with route discovery is to provide an efficient probabilistic route discovery algorithm that aims to reduce the number of nodes forwarding the RREQ packets while still guaranteeing that destinations are reached.

In the traditional probabilistic broadcast approach, each intermediate node is allowed to rebroadcast a packet based on a predetermined fixed forwarding probability. Indeed, probabilistic broadcast algorithms have recently received considerable attention [49, 50, 77-80] as they are simple to implement and do not require special additional hardware as do location-based algorithms. Furthermore, probabilistic broadcast methods require little or no topological information in order to make rebroadcast decisions [49, 81]. As a result, the effects of node mobility on probabilistic methods are limited and they can be used to effectively reduce the overhead associated with the dissemination of RREQ packets during route discovery.

Most probabilistic broadcast approaches that have been proposed in the literature [49, 50, 81] have considered a fixed forwarding probability at each intermediate node. This could lead to most nodes not receiving the broadcast packet when the forwarding probability is set too low or more redundant transmissions if the probability is set too high, as discussed in [77, 78]. One of the causes for this stems from the fact that every node in the network has the same probability of rebroadcast, regardless of its local topological characteristics, such as neighbouring node density. In a dense network, multiple nodes may share similar transmission coverage. Therefore, if some nodes, randomly, do not forward the broadcast packet, these could save resources without degrading the delivery effectiveness. On the other hand, in a sparse network, there is much less shared coverage; thus some nodes might not receive the broadcast packet unless the rebroadcast probability is set high enough. Consequently, the rebroadcast probability should be set differently from one node to another according to their local topological characteristics.

In addition, most probabilistic broadcast approaches [49, 50, 78, 81] have focused on optimizing ‘pure’ probabilistic broadcasting with comparatively little attention to applications in practical areas such as route discovery. Very recently, there have been a few attempts towards the application of probabilistic broadcast in on-demand route discovery. In [77], an intermediate node is allowed to forward an RREQ packet based on a probability value which is determined by the number of duplicate RREQ packets received at the node.

However, the number of duplicate RREQ packets received at a node does not necessarily correspond to the exact number of neighbours of a given node, since some of its neighbours may have failed to rebroadcast the RREQ packet according to their local rebroadcast probability. In an attempt to define a more realistic rebroadcast decision, the authors of [77] have extended their work in [80] to incorporate a CDS algorithm where different forwarding probabilities are assigned to dominating nodes (i.e. nodes in the CDS) and non-dominating nodes (i.e. nodes outside the CDS). However, the construction and maintenance of MCDS has been shown to be NP-complete [66] and as such routing protocols that are built on CDS based algorithms do not scale well.

Haas *et al.*[82] have suggested a gossip-based ad hoc routing approach using an AODV implementation. In this approach, each node forwards a received RREQ packet with a predefined fixed forwarding probability. Some optimisations, such as the two probability thresholds scheme of which one is set to flooding (i.e. forwarding probability = 1), are introduced to prevent the propagation of the broadcast packet from quickly dying out. Again, the number of duplicate packets received at a node is used to determine whether to flood the RREQ packet or to forward it with a fixed probability.

In this research new probabilistic broadcast algorithms for efficient route discovery in MANETs have been proposed and evaluated. These algorithms aim to utilise up-to-date local topological characteristics of intermediate nodes to appropriately determine the forwarding probability at each node. The algorithms are simple to implement because they do not require global topological information in order to determine the forwarding probability. Moreover, they do not require the use of location aided devices as LAR [53].

1.7 Contributions

Although a few attempts have been made to implement probabilistic broadcast algorithms for route discovery in MANETs [77, 82], to the best of my knowledge, most of these studies have not considered the impact of important network operating conditions in a MANET, including node mobility, network density and offered load, to assess the performance of probabilistic route discovery over a wide range of forwarding probabilities.

As part of the preliminary investigations for this research, the performance of fixed probabilistic route discovery in two well-known reactive routing protocols, AODV [7] and DSR [8], is assessed. In this approach the forwarding probability is the same at all the network nodes. AODV and DSR have been chosen for this study as they are among the most widely investigated and analysed routing protocols proposed in the literature [7, 8, 37, 62]. Extensive simulation experiments are conducted over a wide range of forwarding probabilities and varying network operating conditions, as characterised by node mobility, network density and offered load. Simulation results show that appropriate use of the forwarding probability for the dissemination of RREQ can significantly reduce the overhead associated with the route discovery process while maintaining other important performance characteristics of the network such as throughput and end-to-end delay.

In the case of fixed probabilistic route discovery, the received RREQ packet is retransmitted with a fixed forwarding probability at a mobile node regardless of its local geographical characteristics, e.g. relative geographic locations between source and destination node pairs. A new probabilistic route discovery approach is introduced which is aimed at further reducing the routing overhead by localising the dissemination of RREQ packets to a limited region in the network where the destination is expected to be located. This is achieved by combining the functionalities of simple flooding and fixed probabilistic based route discovery algorithms. This study reveals that the combined effects of the two approaches can drastically reduce routing overhead, packet collision rate and end-to-end packet delay while achieving competitive levels of network throughput when compared with AODV and its fixed probabilistic counterparts.

Nodes in MANETs are often randomly distributed over a given topology area. As a result, it is critical to identify dense and sparse regions of the network so that appropriate forwarding probabilities can be assigned to each node in these regions. To reduce congestion levels by avoiding unnecessary retransmissions of RREQ packets in a dense network, it is appropriate to assign a low forwarding probability in this network. On the other hand, to improve the network connectivity in a sparse network, the forwarding probability should be set high. To achieve this, a new adjusted probabilistic route discovery algorithm is suggested. The algorithm dynamically adjusts the forwarding probability at each node based on its local density. In this study, the local density of a node is estimated using its number of 1-hop neighbours, which is obtained by periodic exchange of “hello” packets among neighbouring nodes. Extensive simulation results have reveal that this dynamic probabilistic method achieves lower routing overhead than fixed probabilistic route discovery while maintaining comparable performance in other important performance characteristics of the network such as throughput and end-to-end delay.

Although the probabilistic route discovery methods suggested above can significantly reduce the routing control overhead without degrading the overall network throughput, they still face the problem of how to set the initial forwarding probability that optimises the performance of the routing protocols in terms of improved network throughput and savings in terms of routing overhead and packet collisions. Also, the forwarding probability at a node is determined only by the neighbour density irrespective of whether all the neighbours have received the broadcast packet. As the fourth contribution of this thesis, a new probabilistic route discovery technique which allows a node to compute its own forwarding probability according to its local neighbour density and its covered neighbour set (i.e. the neighbours which have been covered by a given received RREQ packet) is proposed. Simulation results reveal that this technique outperforms the fixed and adjusted probabilistic route discovery techniques in most considered performance metrics such as routing overhead, collision rate and end-to-end delay while maintaining comparable performance in other important performance characteristics of the network such as throughput.

1.8 Thesis Statement

Traditional on-demand route discovery methods employ simple flooding, where a mobile node blindly rebroadcasts received RREQ packets in search of a path to the destination node. This method can potentially lead to the *broadcast storm problem*, which has been shown to greatly degrade network performance.

A number of performance evaluation studies have demonstrated that the broadcast storm problem associated with route discovery operations can be reduced (e.g. the location-based, zone-based and backbone-based routing protocols) [41, 53]. However, most of the proposed route discovery solutions have been evaluated under the assumption of full knowledge of the geographic locations of nodes or of the entire network topology which requires additional hardware devices (e.g. GPS receivers) and/or frequent exchange of global topology information among network nodes.

This thesis will justify the following key claims:

T1. An efficient route discovery algorithm can be developed that can avoid the use of GPS receivers and global topology information while exhibiting competitive system performance (e.g. network throughput) with lower routing overhead, collision rate and end-to-end delay. This is achieved by allowing each node to rebroadcast a received route request (RREQ) packet with a fixed forwarding probability. The present study is among the very few that have been reported in the literature which analyses the impact of different fixed forwarding probabilities on the performance of probabilistic route discovery in two well-known routing protocols, AODV [7] and DSR [8], over a number of important system parameters; namely network density, node mobility and traffic load.

T2. A probabilistic route discovery approach can be developed which can further reduce the route discovery overhead by exploiting the functionalities of both simple flooding (which guarantees high reachability) and the fixed probability (which guarantees a reduction in routing overhead) approaches. This is achieved by making use of routing history at forwarding nodes to identify regions of the network that require simple flooding for route discovery and the regions that requires fixed probabilistic route discovery.

T3. The performance of the probabilistic route discovery approach can be significantly improved if appropriate measures are taken to exploit the random distribution of mobile nodes in MANETs, where there are regions of varying degrees of node density. For example in a dense network, the retransmissions redundancy is relatively high and can degrade the overall performance of the network. On the other hand in a sparse network, the connectivity of the network is relatively. Therefore, to achieve a fine balance between improving the network connectivity and the retransmissions redundancy, the forwarding probability should be set dynamically to reflect the local topological characteristics of a given node; e.g. whether the node is located in a sparse or dense network. Simulation results have shown that using neighbourhood information at a node to dynamically set the forwarding probability can significantly reduce the routing overhead, packet collisions and end-to-end packet delay, while improving network throughput for most considered network operating conditions.

1.9 Outline of the Thesis

The rest of the thesis is organised as follows:

Chapter 2 provides background information that is required for the understanding of the subsequent chapters. It presents brief descriptions of the principles and operations of the protocols in the first three layers of the OSI model that are required in this study. The chapter also justifies the use of simulation as a means of evaluating the suggested route discovery solutions and outlines the list of assumptions and mobility models used in this research.

Chapter 3 conducts an extensive performance analysis of fixed probabilistic route discovery in two on-demand routing protocols, AODV and DSR. It also investigates the performance merits of a wide range of forwarding probabilities and how they affect network performance for different network densities, node mobility and traffic load.

Chapter 4 proposes and evaluates a new route discovery method that combines the best features of probabilistic broadcast and simple flooding based route discovery approaches.

Chapter 5 presents a new adjusted probabilistic route discovery technique which dynamically adjusts the forwarding probability at a node according to the local neighbour density of forwarding node.

Chapter 6 presents a performance analysis of a new dynamic probabilistic route discovery technique, which aims at further reducing the number of forwarding nodes by allowing each node to mathematically compute its own forwarding probability according to the proportion of its local neighbour density and the covered neighbour set of the forwarding node.

Finally, chapter 7 summarises the results obtained in this research and outlines some possible directions for future work.

Chapter 2

2.1 Preliminaries

The main objective of this chapter is to provide background information that is required for the understanding of subsequent chapters. As such, the chapter is organised as follows. Section 2.2 of the chapter describes the communication mechanisms of MANETs based on the layered OSI reference model [83]. Section 2.3 presents an overview of broadcasting and routing protocols in MANETs that will be used in subsequent chapters. Section 2.4 includes descriptions of the mobility model that is used in this study to simulate node mobility. Section 2.5 presents a brief description of the network simulator (Ns-2). Section 2.6 outlines the common simulation assumptions which apply throughout this study. Section 2.7 provides a justification of the method used for the study while Section 2.8 outlines the metrics used for performance evaluation of the proposed algorithms. Finally, Section 2.9 provides a summary of the chapter.

2.2 MANETs and OSI Reference Model

The International Organization for Standardization (ISO) proposed the Open System Interconnection (OSI) reference model [83] in the early 1980s, which was primarily designed to enable multi-vendor computers to interact and communicate. The layered OSI architecture presents a general framework for building modular systems (see Figure 2.1). It divides the network functionalities, which are involved in provisioning end-to-end data transmission, into hierarchical layers containing sub-tasks (sub-functions). OSI defines seven layers in a hierarchy that goes from physical to application layers. Today, OSI is still a reference model, often used to describe and outline the different levels of networking protocols and their relationships with each other. The communication mechanisms of a MANET are mainly associated with the protocols operating at layers 1 to 3 of the OSI reference model. The higher layers are active only in the source and destination nodes.

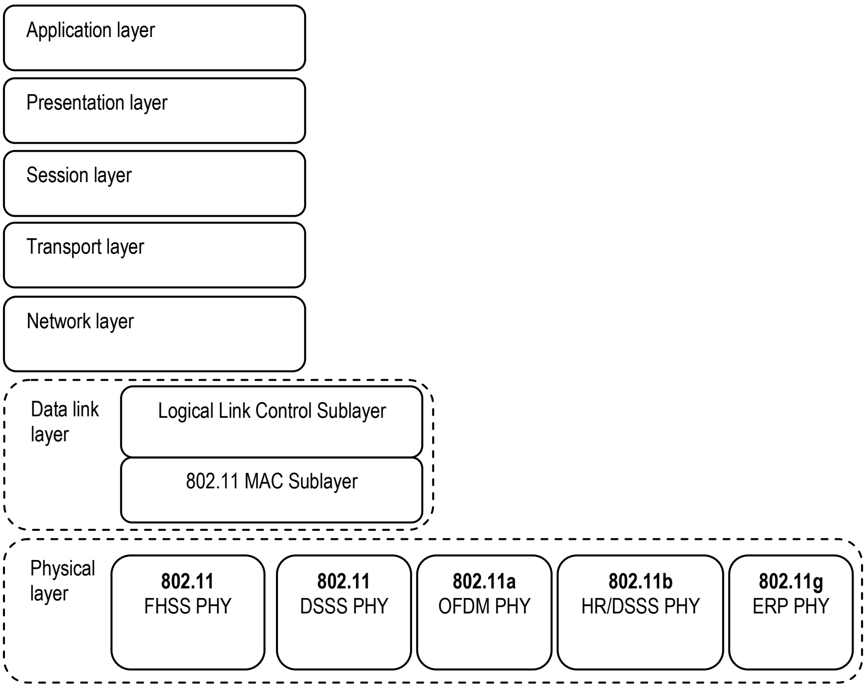


Figure 2.1. The OSI reference model and its relationship with MANET (802.11) protocols.

2.2.1 Physical Layer

The physical layer (PHY) of the 802.11 standard [1, 84] serves as an interface between the MAC sublayer and the wireless medium where frames are transmitted and received. It provides mechanisms for sensing the wireless channel and indicating to the MAC sublayer when a signal is detected or when the channel is idle. This mechanism is known as clear channel assessment (CCA). As shown in Figure 2.2, the physical layer is divided into two sublayers: the Physical Layer Convergence Protocol (PLCP) sublayer and the Physical Medium Dependent (PMD) sublayer. The PLCP abstracts the functionalities such as channel status that the physical layer has to offer to the MAC sublayer while PMD handles signal encoding, decoding, and modulation.

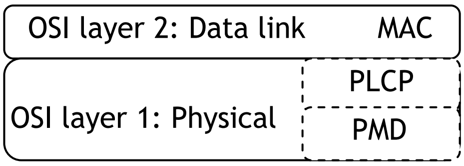


Figure 2.2. The logical structure of the physical layer.

Three PHY standards of 802.11 were initially defined in 1997 [85]. The first two, the frequency-hopping spread-spectrum (FHSS) and the direct-sequence spread-spectrum (DSSS), utilise the radio frequency (RF) band of the electromagnetic spectrum, and the third standard uses the infrared band (IR). The 802.11 (FHSS) standard utilises a set of narrow channels for data transmission. The system “hops” through all the channels in a predetermined sequence. For example, the 2.4 GHz frequency band is divided into 70 channels of 1 MHz each. Every 20 to 400 milliseconds the transmission "hops" to a new channel following a predetermined cyclic pattern. The system operates at 1 Mbps data rate using a 2-level Gaussian frequency shift keying modulation scheme (2GFSK) [85, 86] and 2 Mbps using a 4-level GFSK [85, 86].

In the 802.11 (DSSS) standard, the data stream is spread over a larger frequency band by applying a chipping sequence [85, 87]. The 802.11 (DSSS) operates in the 2.4 GHz radio frequency band, at data rates of 1 Mbps using a differential binary phase shift keying (DBPSK) [85, 87] modulation scheme and 2 Mbps using a differential quadrature phase shift keying (DQPSK) modulation scheme [85, 88].

The third physical layer specification of the 802.11 standard is based on infra red (IR), which can support data rates up to 4Mbps. However, the modulation techniques for RF links such as those used in DSSS, FHSS and DBPSK, are extremely difficult to employ in wireless IR links due to the difficulty of collecting signal power in a single electromagnetic mode [89]. As a consequence, IR systems employ intensity modulation with direct detection such as pulse position modulation (PPM) [90] and on-off keying (OOK) [90]. Generally, RF is preferred to IR due to its flexibility, support for mobility and ability to penetrate walls and opaque objects [4].

Recent advances in the technology of chipsets and the RF signal encoding and modulation techniques of 802.11 operating devices have added additional physical layers: 802.11a PHY, 802.11b PHY and 802.11g PHY [1, 85].

The 802.11a PHY standard uses an orthogonal frequency division multiplexing (OFDM) [85, 91] modulation scheme to support operations of up to 54Mbps data rate in the 5GHz band. Using OFDM, the wideband modulation is subdivided into many sub-carriers, each of which has a narrow bandwidth in comparison to the coherence bandwidth of a typical indoor environment. But this lacks backward compatibility with the original 802.11 standards. The 802.11b PHY standard is an extension of 802.11 (DSSS) which supports 1 Mbps, 2Mbps, 5.4 Mbps and 11 Mbps data rates using an enhanced chipping sequence algorithm known as complementary code keying (CCK) [92] for signal modulation. 802.11g offers data rates comparable to 802.11a and provides backward compatibility support to 802.11 (DSSS) and 802.11b while still operating in the ISM band (i.e. 2.4 GHz). But the 802.11g physical layer specification uses the OFDM [85, 91], the modulation scheme used in 802.11a to obtain higher data rates.

The 802.11n PHY standard [85, 93] is the latest offering from the IEEE standard committee tasked with the provisioning of more robust, secure and high data rate wireless communication systems. The data rate is envisaged to reach 100 Mbps net throughput, after subtracting all the overhead for protocol management features. The 802.11n standard is built upon previous 802.11 standards, especially 802.11a, by incorporating Multiple-In/Multiple-Out (MIMO) antennas [94]. Prior to 802.11n, 802.11 devices had a single antenna or two antennas in a diversity configuration, but one of the requirements is that the “best” antenna be selected. However, in MIMO, each RF chain is capable of simultaneous reception or transmission at more than one antenna. The simultaneous reception and processing of a chain of RF signals at various antennas of a node has the benefit of resolving multipath fading, and can improve the quality of the received signals.

2.2.2 Data Link Layer

The data link layer (DLL) performs several important functions such as error control, flow control, addressing, framing, and communication medium access control [83]. The DLL consists of two sublayers (Figure 2.1): the logical link control sublayer (LLC), which is responsible for error control and flow control, and the medium access control sublayer, which takes care of addressing, framing, and medium access control. Since nodes in MANETs share the same communication channel, collisions may occur if there is more than one node transmitting at the same time. As a consequence, the medium access control (MAC) sublayer is tasked to efficiently control access to the shared channel among nodes in a MANET.

The major challenge of the MAC sublayer is the hidden terminal problem [95]. In the case of the hidden terminal problem, a packet collision happens at the intended receiver if there is transmission from a hidden terminal. As shown in Figure 2.3, when node **A** transmits a frame to node **B**, node **C** (a hidden terminal) is not aware of the transmission due to its distance from node **A**. If node **C** simultaneously transmits a frame to node **B**, a collision occurs at node **B**.

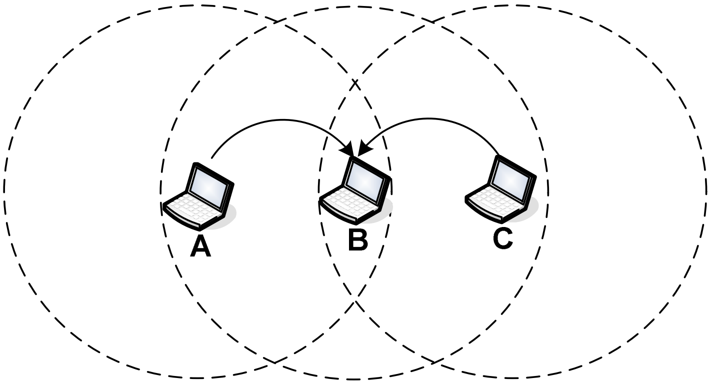


Figure 2.3. Example of the hidden terminal problem in a MANET (C is hidden from A) collision.

Many MAC protocols [1, 21, 25] have been proposed to mitigate the adverse effects of the hidden terminal problem through collision avoidance. Most collision avoidance schemes (such as the carrier sense multiple access with collision avoidance (CSMA/CA) [1] employed by the distributed coordination function (DCF) component of the MAC sublayer of the IEEE 802.11 standard) are sender-initiated, including an exchange of channel reservation control frames between the communicating nodes prior to data transmission. In this case, all the neighbouring nodes of a given communicating node need to be informed that the channel will be occupied for a time period. As shown in Figure 2.4, node **A**, wishing to transmit a data frame to node **B**, first broadcasts an RTS (request-to-send) frame containing the length of the data and the address of node **B**. Upon receiving the RTS, node **B** responds by broadcasting a CTS (clear to send) frame containing the length of the data and address of node **A.** Any node overhearing either of these two control frames remains silent for the entire transmission period. This silent period is known as virtual carrier sense.

Overhearing an RTS or CTS from neighbouring nodes can inhibit one node from transmitting to other nodes outside the communication range. For example, in Figure 2.4, the communication between nodes **A** and **B** will inhibit node **D** from initiating communication with node **C**. This problem is known as the exposed terminal problem. This problem can potentially lead to inefficient utilisation of the communication channel. One of the suggested solutions to mitigate the exposed terminal problem is the use of smart antennas or directional antennas [17, 21] where the propagation of CTS, RTS and DATA frames are directed towards the intended nodes (Figure 2.5).

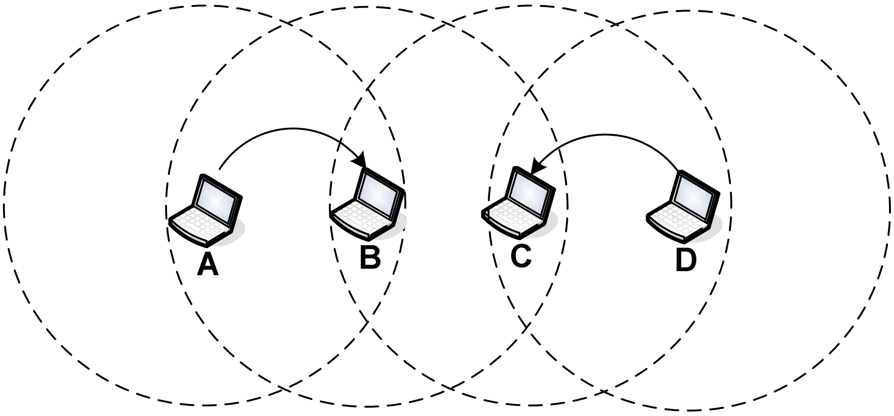


Figure 2.4. An example of the exposed terminal problem in a MANET (C is exposed to B).

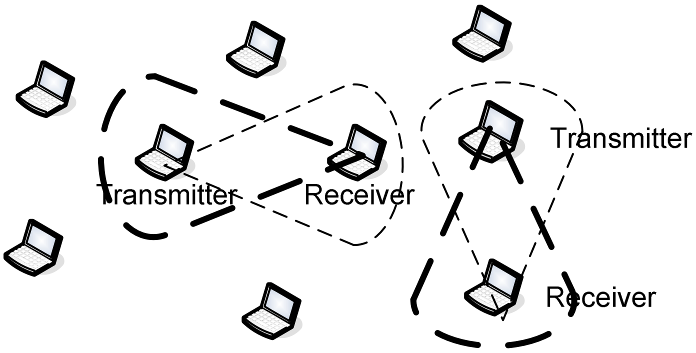


Figure 2.5. An ad hoc network with directional antennas.

2.2.3 Network layer

The Network layer provides end-to-end transmission service. This includes the exchange of routing information, finding a feasible route to a destination, repairing broken links and providing efficient utilization of the available communication bandwidth [83]. One of the most important properties of MANETs is the mobility associated with the nodes. However, the mobility of nodes results in frequent route breaks, packet collisions, transient loops, stale routing information and difficulty in resource reservation [37]. As a consequence, a good routing protocol should be able to solve the above issues with a low communication overhead.

Due to the bandwidth and battery life limitations in MANETs, the use of a routing protocol with a low communication overhead is critical to the overall system performance. The routing control packets exchanged for finding a new route and maintaining existing routes should be minimised. The control packets consume the limited bandwidth and can also cause collisions with data packets, especially when the network is scaled in terms of number of nodes [35]. Therefore, an efficient routing protocol that can cope with high network density while using a small number of routing control packets is highly desirable. In Section 2.3, I will discuss in more depth the issues that arise at the network layer in MANETs, notably broadcasting and routing protocols.

2.2.4 Transport Layer

The main objectives of transport layer protocols include setting up and maintaining end-to-end connections, reliable end-to-end delivery of data packets, flow control, and congestion control [83, 96, 97]. The two most important protocols in the transport layer are: Transmission Control Protocol (TCP) [96] and User Datagram Protocol (UDP) [97].

TCP [96, 98] provides reliable, in-order delivery of a stream of bytes making it suitable for applications like file transfer and email. The protocol is optimized for reliability of delivery rather than timely delivery. As a consequence, TCP can sometimes incur significant delays while waiting for out-of-order packets (usually called segments) or retransmissions of lost segments, and it is not particularly suitable for real time applications such as voice over IP (VoIP).

UDP [97] allows communicating nodes to exchange short messages, also known as datagrams. The protocol does not guarantee delivery reliability and ordering of datagrams in the way that TCP does. Datagrams may arrive out of order, be duplicated or go missing without notice. Avoiding the overhead of checking whether every packet actually arrives makes UDP faster and more efficient, at least for applications that do not require guaranteed delivery, such as broadcasting, video streaming and VoIP.

Initially, when a TCP connection is initiated between source and destination, TCP enters a slow-start phase [96, 98]. In this phase, the congestion window (i.e. the number of segments transmitted per acknowledgment received) is increased for every received acknowledgment (ACK). The window size is increased by the number of segments acknowledged. This behaviour effectively doubles the window size each round trip time. Therefore, there is an exponential increase in the congestion window. This happens until either an ACK is not received for some segments or a predetermined threshold value is reached. Once the threshold is reached, the window size increases by one for every round-trip time. This phase is known as the congestion avoidance phase where progression of window size is linear. The increase continues until a loss is perceived. On detecting a loss, the source node infers congestion and evokes the congestion control algorithm by reducing the window size. Using the congestion control mechanism, TCP has been shown to perform well in wired networks [98].

In wireless networks, e.g. MANETs, TCP is faced with performance degradation due to its inability to differentiate packet loss due to congestion from the loss due to frequent route breaks, the presence of stale routing information, a high channel error rate and frequent network partitions. Ahuja *et al.* [99] conducted the first evaluation of TCP performance under different routing protocols over MANETs. Details of proposed modifications of TCP over MANETs have been presented in [100].

The three upper layers (session, presentation and application) will not be discussed in this thesis, since this research focuses on the protocols operating within the first four layers of the OSI reference model; the interested reader may refer to [4] for more details on these layers.

2.3 Broadcasting and Routing in MANETs

Broadcasting in MANETs is not only a legitimate candidate for unicast routing protocols [7, 8] in mobile scenarios, but also is an integral part of a number of other, multicast routing protocols [101]. *Simple flooding* is the simplest form of broadcasting where the source node broadcasts a packet to its neighbouring nodes [123]. Each neighbouring node receiving the broadcast packet for the first time rebroadcasts it. As a result, the broadcast propagates outwards from the source node, eventually terminating when every node has received and transmitted the broadcast packet exactly once.

Simple flooding ensures the full coverage of the entire network, i.e. the broadcast packet is guaranteed to be sent to every node in the network, provided the network is static and connected and the MAC layer of the communication channel is error-free during the broadcast process [43]. However, in moderate to large sized dense networks, simple flooding may incur far more transmissions than necessary for the broadcast packet to reach every node. Figure 2.6 shows a sample network with 5 nodes. When node ***v*** broadcasts a packet, nodes ***u***, ***w*** and ***x*** receive the packet. ***u***, ***w*** and ***x*** then forward the packet and lastly ***y*** also broadcasts the packet. Clearly, there is a great deal of broadcast redundancy as a result of simple flooding in this case. Transmitting the broadcast packet only by nodes ***v*** and ***u*** is enough for the broadcast operation. When the size of the network (i.e. number of nodes) increases and the network becomes denser, more transmission redundancy will be introduced and these transmissions are likely to trigger considerable transmission collision and contention that would eventually cause a considerable degradation in network performance. This phenomenon of broadcasting induces what is often referred to in the literature as the broadcast storm problem [49].

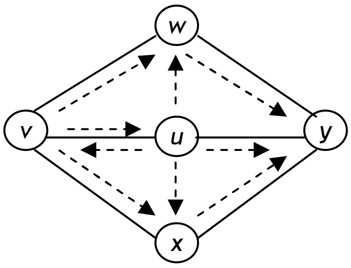


Figure 2.6. Example of a mobile ad hoc network of five nodes with redundant transmissions.

2.3.1 Broadcast Algorithms in MANETs

The broadcast storm problem [49, 50] can be avoided by reducing the number of nodes that forward the broadcast packet. Ni *et al.* [49] have classified several proposed broadcast algorithms in two categories: *probabilistic* and *deterministic*. William and Camp [43] have compared the performance of several proposed broadcast approaches including the probabilistic, counter-based, area-based, neighbour-designated and cluster-based. The following sections provide a brief description of each these approaches.

2.3.1.1 Counter-Based Methods [49]

In a counter based technique, when a node receives a broadcast packet, it initiates a random assessment delay (RAD) and counts the number of received duplicate packets. When the RAD expires, the node rebroadcasts the packet only if the counter does not exceed a threshold value C. If the counter exceeds the threshold after expiration of RAD, the node assumes all its neighbours have received the same packet, and refrains from forwarding the packet. The predefined counter threshold C is the key parameter in this technique. Ni *et al.* [49] have demonstrated that broadcast redundancy associated with simple flooding can be reduced while maintaining comparable reachability in a network of 100 nodes, each with 500m transmission range placed on an area between 1500m x 1500m and 5500m x 5500m by using a counter based scheme with the value of C set to 3 or 4.

2.3.1.2 Area-Based Methods [49]

Area based methods allow a node to forward a broadcast packet based on the additional coverage area. The additional coverage area is determined by a distance-based scheme or location-based scheme. For example, if the node receiving the packet is located a few meters away from the sender, the additional area covered by forwarding the packet is quite low [49]. At the other extreme, if the node receiving the packet is located at the boundary of the sender's transmission range, then a rebroadcast would reach a significant additional area, 61%, as suggested in [50].

Using a distance based scheme [49], a node compares the distance between itself and each neighbouring node that has previously forwarded a given packet. Upon reception of a previously unseen packet, a random assessment delay (or RAD for short) is initiated and redundant packets are cached. When the RAD expires, the locations of all the sender nodes are examined to see if any node is closer than a threshold distance value. If true, the node does not rebroadcast. Therefore, a node using the distance-based scheme requires the knowledge of the geographic locations of its neighbours in order to make a rebroadcast decision. A physical layer parameter such as the signal strength at a node can be used to gauge the distance to the source of a received packet. Alternatively, if a GPS receiver is available, nodes could include their location information in each packet transmitted. The distance-based scheme succeeds in reaching a large part of the network but does not economise the number of broadcast packets. This is because a node may have received a broadcast packet many times, but will still rebroadcast the packet if none of the transmission distances are below a given distance threshold.

Using a location based scheme [49, 50], each node is expected to know its own position relative to the position of the sender using a geolocation technique such as GPS. Whenever a node originates or forwards a broadcast packet it adds its own location to the header of the packet. When a neighbouring node initially receives the packet, it notes the location of the sender and calculates the additional coverage area obtainable if it were to rebroadcast. If the additional area is less than a threshold value, the node will not rebroadcast, and all future receptions of the same packet will be ignored. Otherwise, the node assigns a RAD before delivery. If the node receives a redundant packet during the RAD, it recalculates the additional coverage area and compares that value to the threshold. The comparison of the area calculation and threshold occurs for all redundant broadcasts received until the packet reaches either the scheduled send time or is dropped.

2.3.1.3 Neighbour Knowledge Based Methods [43, 49, 102, 103]

Neighbour knowledge based schemes [43, 49, 102] maintain state information about their neighbourhood via periodic exchange of “hello” packets, which is used in the decision to rebroadcast. The objective is to predetermine a small subset of nodes for broadcasting a packet such that every node in the network receives it. Often this subset is called the forwarding set. Below are brief descriptions of the various neighbour-knowledge-based schemes.

Forwarding Neighbours Schemes **[103]:**

In forwarding neighbours schemes, the forwarding status of each node is determined by its neighbours. Specifically, the sender proactively selects a subset of its 1-hop neighbours as forwarding nodes. The forwarding nodes are selected using a connected dominating set (CDS) algorithm and the identifiers (IDs) of the selected forwarding nodes are piggybacked on the broadcast packet as the forwarder list. Each designated forward node in turn designates its own list of forward nodes before forwarding the broadcast packet. The Dominant Pruning algorithm [104] is a typical example of the forwarding neighbours schemes. Ideally, the number of forwarding nodes should be minimised to decrease the number of redundant transmissions. However, the optimal solution is NP-complete and requires that nodes know the entire topology of the network.

Self Pruning Schemes **[45, 47, 104]:**

For broadcasting based on a self pruning scheme [45, 47, 104], each node may determine its own status as a forward node or non-forward node, after the first copy of a broadcast packet is received or after several copies of the broadcast packet are received. For example the authors of [45] have suggested that each node must have at least 2-hop neighbourhood information which is collected via a periodic exchange of “hello” packets among neighbouring nodes. A node piggybacks its list of known 1-hop neighbours in the headers of “hello” packets and broadcast packets and each node that receives the packet construct a list of its 2-hop and 1-hop neighbours that will covered by the broadcast. If the receiving node will not reach additional nodes, it refrains from broadcasting; otherwise it rebroadcasts the packet.

***Scalable Broadcast Algorithm (SBA)* [102]:**

This algorithm requires that all nodes have knowledge of their neighbours within a two hop radius [102]. This neighbour information coupled with the identity of the node from which a packet is received allows a receiving node to determine if it would reach additional nodes by forwarding the broadcast packet. 2-hop neighbour information is achievable via a periodic exchange of “hello” packets; each “hello” packet contains the node’s identifier and the list of known neighbours. After a node receives a “hello” packet from all its neighbours, it has 2-hop topology information centred at itself.

***Multipoint Relaying Algorithm* [105]:**

In multipoint relaying [105], each node selects a small subset of its 1-hop neighbours as Multipoint Relays (MPRs) sufficient to cover its 2-hop neighbourhood (see Figure 2.9). When a broadcast packet is transmitted by a node, only the MPRs of a given node are allowed to forward the packet and only their MPRs forward the packet and so on. Using some heuristics, each node is able to locally compute its own MPRs based on the availability of its neighbourhood topology information. The neighbourhood topology information is obtained via a periodic exchange of “hello” packets among neighbouring nodes. Each “hello” packet contains the sender’s ID and its list of neighbours.

2.3.1.4 Cluster-Based Methods [74, 75]

In cluster-based broadcast methods, the network is partitioned into several groups of clusters forming a simple backbone infrastructure. Each cluster has one cluster head that dominates all other members in the cluster, e.g. is responsible for forwarding packets and selecting forwarding nodes on behalf of the cluster. Two or more overlapping clusters are connected by gateway nodes. Although clustering can be desirable in MANETs, the overhead associated with the formation and maintenance of clusters is non-trivial in most cases [74]. Therefore, the total number of transmissions (i.e. number of forwarding nodes) is generally used as the cost criterion for broadcasting. Cluster heads and gateway nodes of a given MANET together form a connected dominating set [58]. The problem of finding the minimum number of forwarding nodes that forms the minimum connected dominating set is well known to be NP-complete [66].

2.3.1.5 Probabilistic Based Methods [49, 50, 106]

Probabilistic broadcasting is one of the simplest and most efficient broadcast techniques that have been suggested [49] in the literature. In this approach, each intermediate node rebroadcasts received packets only with a predetermined forwarding probability. Clearly, the appropriate choice of the forwarding probability determines the effectiveness of this technique as discussed in Section 1.6. To determine an appropriate forwarding probability, Sasson *et al.* [81] have suggested the use of random graphs [66] and percolation theory [107] in MANETs. The authors have claimed that there exists a probability value $P_c < 1$, such that by using P_c as a forwarding probability, almost all nodes can receive a broadcast packet, while there is not much improvement on reachability for $p > P_c$. Since P_c is different in various MANET topologies, and there is no existing mathematical method for estimating P_c, many probabilistic approaches use a predefined value for P_c.

The advantage of probabilistic broadcasting over the other proposed broadcast methods [43, 49, 102, 103] is its simplicity. However, studies [49, 81] have shown that although probabilistic broadcast schemes can significantly reduce the degrading effects of the broadcast storm problem [49], they suffer from poor reachability, especially in a sparse network topology. But the authors in [106] have argued that the poor reachability exhibited by the probabilistic broadcast algorithms in [49, 81] is due to assigning the same forwarding probability at every node in the network.

Cartigny and Simplot [79] have described a probabilistic scheme where the forwarding probability p is computed from the local density n (i.e. the number of neighbours of the node considering retransmission). The authors have also introduced a fixed value parameter k to achieve high reachability. This broadcast scheme has a drawback of being locally uniform. This is because each node in the network determines its forwarding probability based on the fixed efficiency parameter *k* which is not globally optimal.

Zhang and Agrawal [26] have described a dynamic probabilistic scheme using a combination of probabilistic and counter-based approaches. In this approach, the forwarding probability at a node is set based on the number of duplicate packets received at the node. But the value of a packet counter at a node does not necessarily correspond to the exact number of neighbours of the node, since some of its neighbours may have suppressed their rebroadcasts according to their local rebroadcast probability.

In [106], the network topology is logically partitioned into sparse and dense regions using the local neighbourhood information. Each node located in a sparse region is assigned a high forwarding probability whereas the nodes located in the dense regions are assigned low forwarding probability.

2.3.2 Reactive Routing Mechanisms in MANETs

The design of routing protocols in MANETs must deal with a number of considerable challenges due to the constraints and unique characteristics of MANETs. As explained in Chapter 1, the two main categories of routing protocols for MANETs are proactive and reactive routing protocols. However, due to high overhead associated with the proactive routing protocols, only reactive routing protocols have been considered in this research. The rest of the section describes the main functionality of some of the traditional reactive routing protocols for MANETs that have been widely investigated and analysed, namely AODV [7] and DSR [8].

2.3.2.1 Ad hoc On-demand Distance Vector (AODV) routing

AODV is a reactive routing protocol that establishes a route to a destination on an on-demand basis, i.e. a route is established only when it is required by a source node for transmitting data packets. This is beneficial to mobile environments such as MANETs since fully up-to-date knowledge of all routes from every node implies large communication overhead. The routing mechanism of AODV consists of two processes; *route discovery* and *route maintenance*.

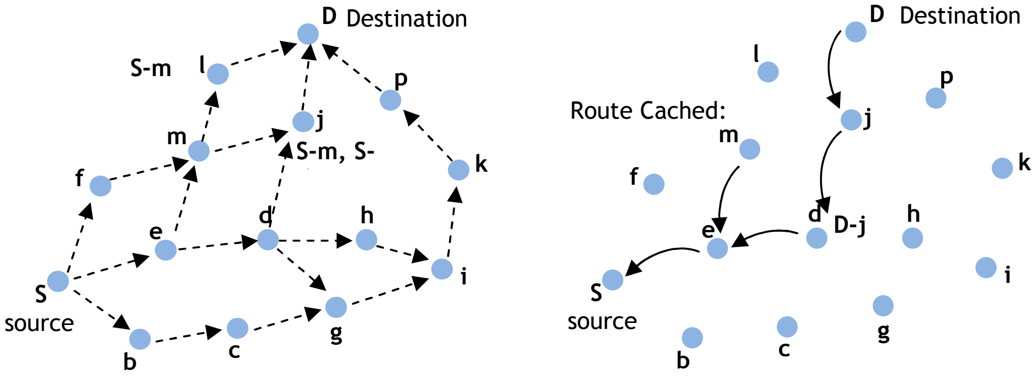
When a source node needs to send data, but does not already have a valid route to the destination, it initiates a route discovery process in order to locate the destination. A route request (RREQ) packet is disseminated throughout the entire network via simple flooding [7]. The RREQ packet contains the following main fields: source identifier, destination identifier, source sequence number, destination sequence number (created by the destination to be included along with any route information it sends to requesting nodes), broadcast identifier and time-to-live. The destination sequence number is used by AODV to ensure that routes are loop-free and contain the most recent route information [6, 7].

Each intermediate node that forwards an RREQ packet creates a reverse route back to the source node by imprinting the next hop information in its routing table. Once the RREQ packet reaches the destination or an intermediate node with a valid route, the destination or intermediate node responds by unicasting a route reply (RREP) packet to the source node using the reverse route. The validity of a route at the intermediate nodes is determined by comparing its sequence number with the destination sequence number. Each node that participates in forwarding the RREP packet back to the source creates a forward route to the destination by imprinting the next hop information in the routing table. Nodes along the path from source to destination are not required to have knowledge of which nodes are forming the path other than the next hop nodes to the source and destination.

The next phase of the routing mechanism is the route maintenance process. After the route discovery process and as long as the discovered route is used, the intermediate nodes along the active route maintain an up-to-date list of their 1-hop neighbours by means of a periodic exchange of “hello” packets. Also, when the route becomes inactive, i.e. no data is sent over it, a timer is activated, after the expiration of which the route is considered stale and expires. If the routing agent (i.e. AODV) at a node becomes aware of a link breakage for an active route, a Route Error (RERR) packet is generated at the point of breakage. This is then disseminated to the appropriate nodes participating in the route's formation and those nodes actively using the route. The nodes affected by the invalid route mark it for expiration since it is no longer useful. In this fashion, the RERR packet propagates to the source node which can then initiate a new route discovery phase.

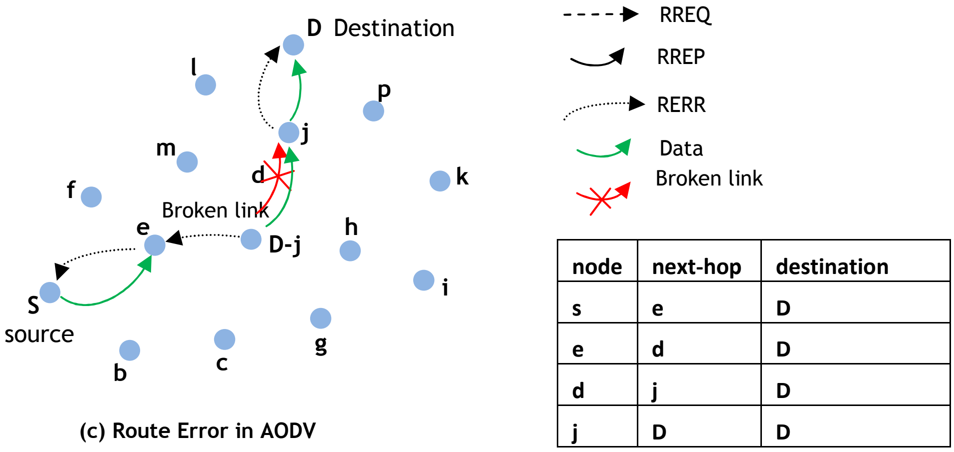
Consider the example depicted in Figures 2.7 (a-c). In Figure 2.7a, the source node ***S*** initiates a route discovery process by originating an RREQ to be flooded in the network in search of destination node ***D***, assuming the RREQ contains the destination sequence number 3 and the source identification ***S***. When nodes ***b***, ***e*** and ***f*** receive the RREQ packet, they check their routing tables to determine the next hop (i.e. route) to the destination. If they don't have a valid route to the destination, they each forward it to their neighbours; ***c***, ***d*** and ***m***. Assume ***c*** and ***m*** have routes to the destination node, node ***D*** through routes ***c-g-i-k-p-D*** and ***m-l-D*** respectively. If the destination sequence number at the intermediate node ***m*** is 4 and is 1 at node ***c***, then only node ***m*** is allowed to unicast an RREP along the route to the source node ***S***. This is because ***c*** has an older route to node ***D*** compared to the route available to node ***S***, while node ***m*** has a more recent route to the destination ***D*** compared to the route available to node ***S***. If the RREQ packet eventually reaches the destination through the route ***e-d-j-D*** or any other alternative route then the destination node ***D*** unicasts an RREP along the reverse route to ***S***. In this case the source node may receive multiple RREP packets. All the intermediate nodes receiving an RREP update their routes with the latest destination sequence number. They also update the routing information if it leads to the shortest route between the source and the destination nodes.

Figure 2.7 (c) shows the maintenance process due to a broken link. When a link breaks, which is determined by absence of "hello" packets or link acknowledgement, the source and destination nodes are notified. For example, when the link between node ***d*** and ***j*** is broken, both nodes originate RERR packets to inform the source, the intermediate nodes along the path and the destination node about the link break. The nodes delete the corresponding entries from their routing tables. The source node reinitiates the route discovery process with a new RREQ packet containing a new broadcast identification and the previous destination sequence number.



(a) Route request dissemination in AODV

(b) Route Reply in AODV



(c) Route Error in AODV

node	next-hop	destination
s	e	D
e	d	D
d	j	D
j	D	D

Path established between S and D

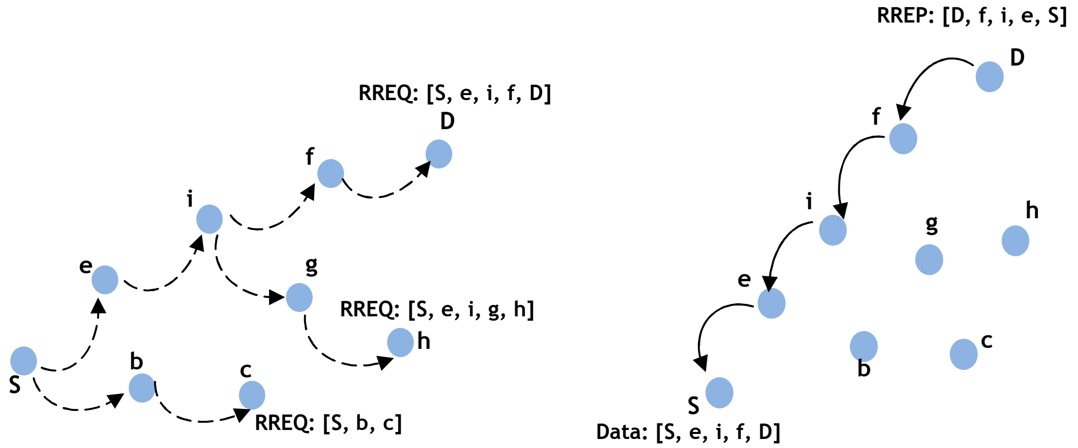
Figure 2.7. Illustration of the route discovery and route maintenance processes in AODV.

2.3.2.2 Dynamic Source Routing (DSR)

DSR [8] is characterised by source routing rather than next hop routing as in AODV, where each packet to be routed carries in its header a complete ordered list of nodes through which the packet must pass. The key advantage of source routing is that the intermediate nodes do not need to maintain up-to-date routing information in order to route the data packets towards the destination since the packets themselves already contain all the routing decisions. This fact, coupled with the on-demand nature of the protocol, eliminates the need for periodic route advertisement and neighbour detection packets present in other protocols [6, 9]. The routing mechanism of the DSR protocol consists of two phases: route discovery and route maintenance.

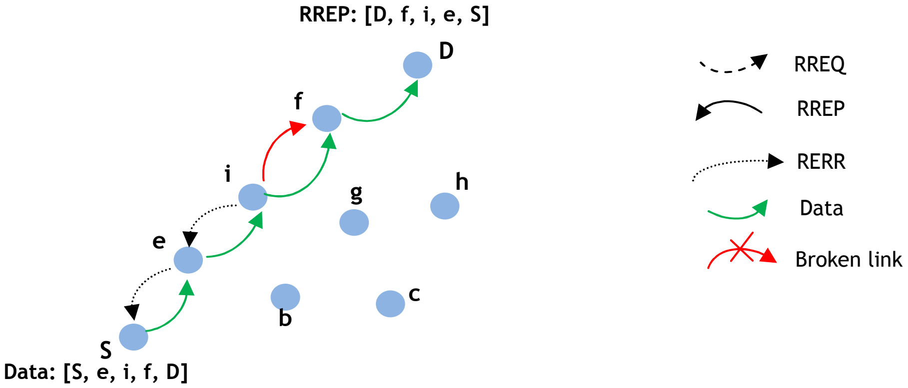
When a node using a DSR routing agent attempts to send a data packet to a destination for which it does not already know the route, it initiates a route discovery process to determine such a route. The route discovery works by disseminating RREQ packets (see Figure 2.8a) in the network using simple flooding, i.e. each node receiving an RREQ packet rebroadcasts it, unless it is the destination or it has a valid route to the destination in its route cache. Such a node replies to the request with an RREP packet that is routed back to the source node. The propagated RREQ packets build up the route traversed so far. The RREP packet is unicast back to the source node by traversing this path backward (see Figure 2.8b). The route carried by the RREP packet is cached at the source node for future use. Following the route discovery process, each data packet flowing from source to destination contains the complete route to the destination.

Route maintenance is responsible for detecting changes in the network topology that affect the used routes. Whenever a link failure occurs (detected by the failure of an attempted data transmission over a link, for example), an RERR packet is transmitted back to the source node from the node where the link breakage has occurred (see Figure 2.8c). The transmitted RERR packet erases all the entries in the route caches along the path that contains the broken link. The source node must reinitiate the route discovery process, if this route is still needed and no alternate route is found in the cache.



(a) Route request dissemination in DSR

(b) Route Reply in DSR



(c) Route Reply in DSR

Figure 2.8. Illustration of the route discovery process in DSR.

2.4 Mobility Model

Mobile nodes in a MANET often move from one location to another, but finding ways to model these movements is often not obvious. In order to thoroughly evaluate communication protocols for MANETs such as AODV, it is necessary to develop and use mobility models that realistically capture the movements of mobile nodes that eventually utilise the given protocol.

Currently, there are two groups of mobility models used for the evaluations of protocols proposed for MANETs: traces and synthetic models [108]. Traces are mobility patterns that are observed in real life systems. They provide accurate information, especially when they involve a large number of participants and appropriately long observation periods. Unfortunately, privacy issues, including the confidentiality of certain data, may prohibit the collection and distribution of such statistics. Furthermore, new environments like MANETs are not easily modelled if traces have not yet been created. In this situation synthetic models are often used. Synthetic mobility models such as the *random waypoint* model [109] attempt to represent the behaviours of mobile nodes without the use of traces. Recently, other mobility models which account for different motion patterns have been suggested. For instance, the community based mobility model [110] models human mobility within communities and among different communities, the Manhattan mobility model [27] models vehicular mobility on structured roads in a city, and the Group mobility model [26] models a motion pattern similar to military combat zones, e.g. the motion of a military infantry commander and his/her battalion.

The random waypoint mobility model [109] is one of the most popular mobility models in MANETs research and is itself the focal point of most research activity [26, 27, 111]. The model defines a collection of nodes which are placed randomly within a confined simulation space. Then, each node selects a random destination inside the simulation area and travels towards it at a certain speed, s. Once it has reached its destination, the node pauses for some time, t, before it chooses another random destination and repeats the process. The node speed, s, of each node is specified according to a uniform distribution with $s \in (0 \ldots V \max)$, where $V \max$ is the maximum speed parameter. Pause time is a constant t seconds.

It should be noted that the random waypoint mobility model is the most popular of the “entity” mobility models [26, 27], where each node's motion is independent to that of others. Its popularity may be attributed to its ease of implementation and intuitive appeal in view of the lack of widely employed MANET testbeds where mobility patterns could be traced and then used in simulations. Other proposed mobility models include “group” mobility models [26], where the movements of nodes may be correlated, such as the motion of vehicles on the highway.

2.5 The Network Simulator

Simulation has proven to be a valuable tool in many research areas where analytical methods aren’t applicable and experimentation isn’t feasible.

Researchers generally use simulation to analyze system performance prior to physical design or to compare multiple alternatives over a range of system conditions. In recent years, several *discrete-event* network simulation tools have been suggested for performance analysis in MANETs [113-115]. Commonly used network simulators include Ns-2 [113], GloMoSim [114], QualNet [116] and OPNET [117]. For example, a survey [115] has shown that 114 out of 151 MobiHoc papers published (75.5%) between 2000 and 2005 used simulation for performance analysis. Some of the network simulators such as Ns-2 and GloMosim have been developed as University research projects and are available for free download, while others such as QualNet (the commercial successor of GloMoSim) are available for a fee. Figure 2.9 shows simulation usage results of the MobiHoc authors that did identify simulation as being used for the period 2000-2005 [115].

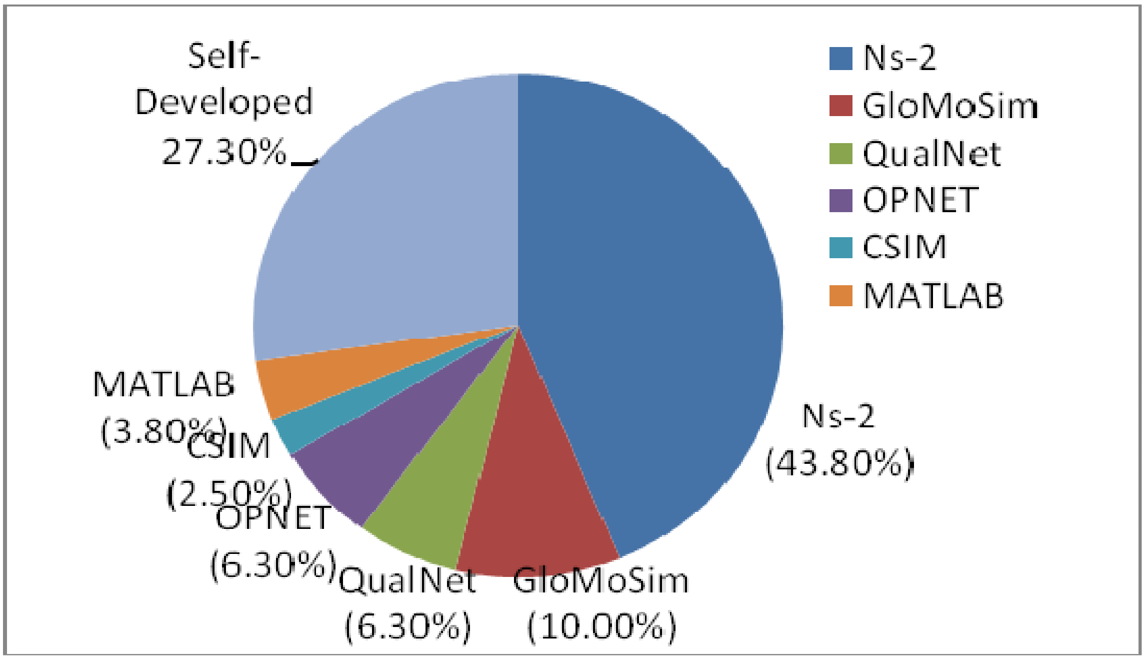


Figure 2.9. Simulator usage from MobiHoc survey for 2000-2005.

The Ns-2 [113] is one of the most popular discrete event network simulation tools and its architecture is organized according to the OSI reference model [83]. Although it was originally designed for wired networks, Ns-2 has been extended for simulating wireless networks, including wireless LANs, mobile ad hoc networks (MANETs), and sensor networks. It is a popular and powerful network simulation tool, and the number of users has increased greatly over the last decade [115]. For example, 35 of the 80 simulation-based MANET papers published in the 2000-2005 ACM MobiHoc proceedings (i.e. about 43.8%) used Ns-2 [115]. This is due to the fact that it is freely available, open source and includes detailed simulations of important operations of such networks [111]. The development efforts of the simulator have been supported by DARPA and NSF [118].

The Ns-2 simulator includes radio propagation models that support propagation delay, capture effects, and carrier sense [4, 119]. The radio models use characteristics similar to the commercial Lucent WaveLAN technology with a nominal bit rate of 2Mb/s and a nominal range of 250 meters with an omni-directional antenna. The radio propagation models in NS-2 include the free space propagation model, the two-ray ground reflection model and the shadowing propagation model [119].

Ns-2 [113] implements the standard IEEE 802.11 Distributed Coordination Function (DCF) MAC protocol [1, 84] described in Section 2.2.2. In this standard the transmission of each unicast data packet is preceded by an RTS/CTS control packet exchange between communicating nodes to reduce the probability of collisions due to hidden terminals [95]. Each correctly received unicast data packet should be followed by an Acknowledgment (ACK) to the sender; otherwise the sender retransmits the packet a limited number of times (e.g. 7 times) until this ACK is received [84]. Broadcast packets such as RREQ packets, on the other hand, are not preceded by an RTS/CTS exchange nor acknowledged by their recipients, but they are sent only when the transmission medium is sensed as idle.

2.6 Assumptions

The subsequent chapters will report results from extensive simulation experiments that have been conducted to evaluate the performance of the proposed route discovery approaches in MANETs. The following assumptions, which have been widely adopted in the literature [6, 7, 37, 39, 43, 62, 106] have been used throughout this research.

- Each mobile node has sufficient power to function throughout the simulation time. At no time does a mobile node run out of power or malfunction because of lack of power. In addition, the wireless transceivers are active at all times.

- The number of nodes in a given topology remains fixed throughout the simulation time. Note that network partitioning may still be evident during simulation and so the network may not be connected at all times.

- Transmissions may interfere with each other (i.e. affect each other if they occur in close proximity); however a node will always successfully decode a transmission provided it is within transmission range of the source and there is no interfering transmission.

- All mobile nodes are homogeneous, i.e. all nodes are equipped with IEEE 802.11 transceivers with the same nominal transmission range.

- 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.

- A route discovery process can be initiated by any source node which has a data packet to be transmitted.

It is worth noting that other assumptions will be stated in the following chapters when appropriate.

2.7 Justification of Method of Study

In this research, extensive simulations are conducted to explore performance-related issues of probabilistic route discovery in MANETs. This section briefly discusses the choice of simulation as the proper method of study for the purpose of this dissertation, justifies the adoption of Ns-2 as the preferred simulator, and further provides information on the techniques used to reduce the opportunity of simulation errors.

After some consideration, simulation has been chosen as the method of study in this research. Notably, when this research work was undertaken, analytical models with respect to multi-hop MANETs were considerably coarse in nature [126], which made them unsuitable for the purpose of studying probabilistic route discovery with a reasonable degree of accuracy. In addition, since the range of this study involves the use of a large number of mobile nodes, even a moderate deployment of nodes as an experimental test-bed could involve substantial and expensive costs. Simulation was therefore chosen since it provides a reasonable trade-off between the accuracy of observation involved in a test-bed implementation and the insight and completeness of understanding provided by analytical model.

To conduct performance analysis of the proposed solutions in this thesis, the popular Ns-2 (v.2.29) simulator [113] has been extensively used. Ns-2 was chosen primarily because it is a proven simulation tool utilised in many previous studies on MANETs [115] and has been validated and verified in [112, 125]. While extending the simulator to evaluate the proposed protocols, special care was taken to ensure that the algorithms implemented would function as designed.

Before gathering the simulation results presented this thesis, the validation of the simplest protocol in the thesis was first carried out in two ways. The AODV implementation of the Ns-2 simulator was extended to include fixed probabilistic route discovery, in which an intermediate node is allowed to forward a received RREQ packet based on a fixed probability $p \leq 1$. The first validation was conducted using the Ns-2 “validation test suite”, which compares the simulation results produced by the own extended executable with some reference simulation results.

The second validation test consisted of running the modified fixed probabilistic version of AODV over a 5 non-mobile chain topology on a 1000m x 1000m area. Each node has a transmission range of 250m, and the distance between two successive nodes was between 180m and 200m as shown in Figure 2.10. The choice of distance between two successive nodes was to reduce the exposed node problem and also to ensure that a node could communicate with only its 1-hop neighbour. Constant bit rate (CBR) data traffic of 4packets/sec connecting node 0 to node 4 was used. The forwarding probability at the intermediate nodes 1 and 3 was set at $p = 1$(i.e. simple flooding AODV) and the probability at node 2 was varied in order to regulate the dissemination of the RREQ packet towards the destination node 4. The aim of this validation test was to achieve 100% delivery success when the probability at node 2 is $p = 1$ and 0% delivery success when the probability at node 2 is $p = 0$. On another simulation run, the forwarding probability was set as a low as $p = 0.05$. A total of 487 packets out of 796 transmitted were received at node 4 representing 61%. 24% packets were dropped because of route unavailability and 15% were dropped because of no buffer space in the interface queue (IFQ).

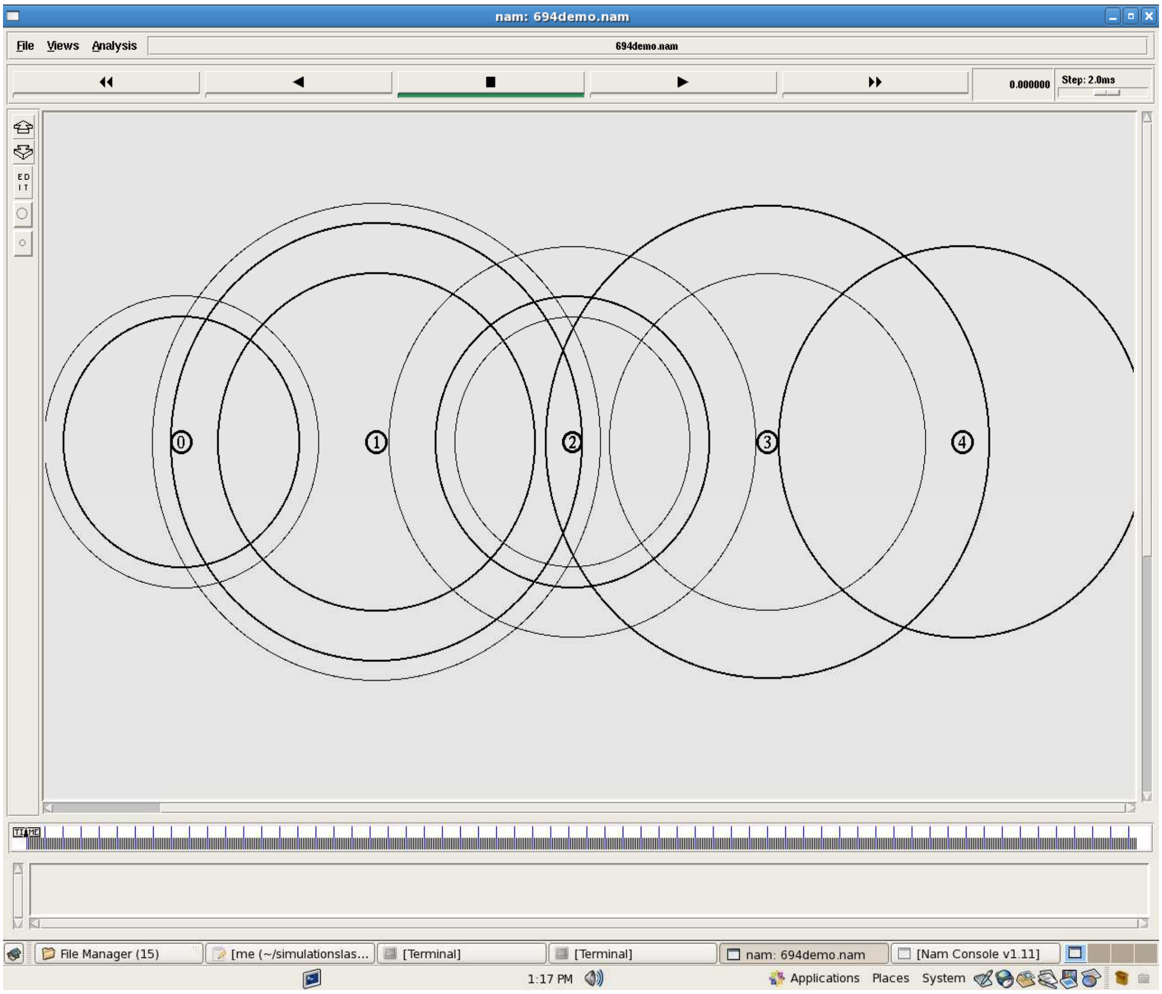


Figure 2.10. A screen short of wireless network visualisation representing a 5 node chain topology for the validation of the fixed probabilistic AODV implementation in the Ns-2.

2.8 Performance Metrics

The performance of routing protocols is largely dependent on the efficiency of the route discovery method used [37]. In this research, the new route discovery approaches are incorporated in some existing routing protocols and their performance are measured using the following performance metrics. These performance metrics have been widely used in the literature [37, 38]:

- ***Routing overhead***: the total number of RREQ packets generated and transmitted during the entire simulation time period. For packets sent over multiple hops, each transmission over one hop is counted as one transmission.

- ***Route discovery delay:*** the elapsed time between the first broadcast of an RREQ packet and the received route reply.

- ***End-to-end delay:*** the average delay a data packet experiences to cross from source to destination. This delay includes all possible delays caused by buffering during route discovery delay, queuing at the interface queues and retransmission delays at the MAC, propagation and transfer times.

- ***Network connectivity success ratio***: The ratio of the number of route reply packets received over the number of route request packets transmitted at the source node(s). This metric measures the success rate of establishing paths.

- ***Collisions Rate***: the total number of RREQ packets dropped by the MAC layer as a result of collisions per unit simulation time.

- ***Normalised Throughput:*** the ratio of the number of data packets successfully received at the destinations per unit simulation time over the theoretical throughput (i.e. the number of data packets generated per second).

2.9 Summary

In this chapter, the characteristics of MANETs is discussed and their implementation according to the OSI reference model, focusing in particular on the physical, data link, network and transport layers. The chapter has also reviewed various broadcast algorithms that have been proposed for MANETs including simple flooding as well as probabilistic, counter-based, knowledge based, distance based and location based methods.

This chapter provides background information on two routing protocols, AODV and DSR that are used in the implementation of the new route discovery techniques proposed in this research. It has also briefly described the Ns-2 simulator that is used to conduct the performance evaluation of the routing protocols and briefly discussed the choice of simulation as a tool of study in this research. Finally, the chapter has listed some assumptions that apply throughout the dissertation.

In describing the various routing protocols in the above sections, it has been assumed that simple flooding is used for route discovery processes. However, each of the broadcast techniques discussed in Section 2.2.1 can be used to reduce the overhead associated with the route discovery process.

By recognising the fact that route discovery is intended to search for the destination node only, there is more room for improvement in terms of the dissemination of RREQ packets, since the flooded RREQ packets need not reach every node in the network. Probabilistic broadcast algorithms can be used to reduce the dissemination of RREQ packets while maintaining important network system performance such as network throughput and end-to-end delay.

The next chapter will examine a probabilistic broadcast algorithm for route discovery processes where each forwarding node rebroadcasts an RREQ packet with a fixed probability. The chapter will also present a performance analysis of the probabilistic route discovery over a wide range of fixed probability values, taking into consideration the effects of a number of important system parameters in MANETs including node density, traffic load and node mobility. The main objective of this investigation is to identify and highlight the performance limitations of this broadcast technique for route discovery. The subsequent chapters will propose more efficient probabilistic route discovery techniques that can overcome these limitations.

Chapter 3

Performance Analysis of Fixed Probabilistic Route Discovery

3.1 Introduction

In traditional on-demand routing protocols, e.g. AODV [7] and DSR [8], route request (RREQ) packets are disseminated throughout the entire network in search of a particular destination. In particular, each node forwards a received RREQ packet once until a destination is reached. This method of route discovery is known as simple flooding [49]. However, in on-demand routing protocols, once a route to a destination has been established, all the intermediate nodes along the route adhere to the forwarding responsibilities of data packets. Therefore some of the RREQ packet transmissions associated with a route discovery is redundant. As a consequence, the number of retransmissions of RREQ packets during the route discovery process can seriously affect the performance of the routing protocol in terms of communication overhead and end-to-end delay [37, 39].

To reduce the communication overhead associated with the dissemination of broadcast packets in "pure" broadcast scenarios while still maintaining an acceptable level of reachability, probabilistic approaches have been proposed in the literature as an alternative to simple flooding [49, 81, 106, 121]. In the probabilistic schemes, upon receiving a broadcast packet for the first time, a node forwards the packet with a pre-determined forwarding probability p and drops the packet with the probability 1-p, as shown in Figure 3.1. Every forwarding node is assigned the same forwarding probability p and when $p = 1$ the probabilistic scheme reduces to simple flooding.

The effects of network density and nodal mobility on probabilistic flooding in a pure broadcast scenario have been analysed over a wide range of forwarding probabilities [106]. The authors have shown that probabilistic broadcast algorithms can achieve improvements in terms of saved rebroadcast in high mobility and dense networks. However, to the best of my knowledge, there has not been a study that evaluates the performance impact of probabilistic broadcast on practical applications such as route discovery over a wide range of forwarding probabilities and varying network operating conditions, notably, network density, node mobility, traffic load and network size.

Motivated by the above observations, the main objective of this chapter is to conduct an extensive performance analysis by means of Ns-2 [113] simulations of probabilistic route discovery in two popular on-demand routing protocols, namely AODV [7] and DSR [8]. In the case of probabilistic route discovery, each received RREQ packet is forwarded once with the forwarding probability p (see Figure 3.1). The performance analysis is conducted over a range of forwarding probabilities from 0.1 to 1 in steps of 0.1. This simulation study is the first evaluation to be reported in the literature and will help to provide insight into the potential performance discrepancies of the two routing protocols and, more significantly, to outline the relative performance of the various forwarding probabilities under varying network operating conditions. The performance analysis is conducted using the most widely used performance metrics: throughput, delivery ratio, network connectivity, end-to-end delay, routing overhead and collision rate.

The remainder of this chapter is organised as follows: Section 3.2 describes the simulation model and the system parameters. Section 3.3 analyses the effects of network operating conditions on the performance of fixed probabilistic route discovery in both AODV and DSR. Finally, section 3.4 concludes the chapter.

Algorithm: Fixed Probabilistic Route Discovery

```
Upon receiving a RREQ packet rq at a node
If RREQ is receved for the first time
        set rebroadcast probability to $p = P_c$

EndIf

Generate a random number Rnd over the range [0,1]
If $Rnd \leq p$
        broadcast the RREQ packet
Else
        drop the packet
```

Figure 3.1. An outline of the algorithmic framework for probabilistic route discovery

3.2 Simulation Model and System Parameters

The NS-2 simulation model consists of two sets of scenario files; topology scenario files and traffic generation pattern files. The topology scenario files define the simulation area and the mobility model of randomly distributed mobile nodes over the simulation time period. On the other hand, the traffic pattern files define the characteristics of data communications, notably, data packet size, packet type, packet transmission rate and the number of traffic flows. In all scenarios, each node is assumed to be equipped with a wireless transceiver operating on 802.11 wireless standards [1]. The physical radio frequency characteristics of each wireless transceiver such as the antenna gain, transmit power and signal to noise and interference ratio, are chosen to mimic the commercial Lucent WaveLAN technology [122] with a nominal bit rate of 2Mb/sec and a nominal transmission range of 250 meters with an omni-directional antenna. The propagation model used is the Ns-2 [113] default which combines both a free space propagation model and a two-ray ground reflection propagation model [119].

The simulation scenarios consist of three different settings, each specifically designed to assess the impact of a particular network operating condition on the performance of probabilistic route discovery. First, the impact of network density or size is assessed by varying the number of mobile nodes placed on an area of fixed size 1000m x 1000m. The second simulation scenario investigates the effects of node mobility on the performance of probabilistic route discovery by varying the maximum speed of a fixed number of mobile nodes placed on a fixed area of 1000m x 1000m. The last simulation scenario evaluates the performance impact of traffic offered load on the algorithms by providing a different number of traffic flows (i.e. source-destination connections) for a fixed number of nodes placed on a 1000m x 1000m topology area.

Each node participating in the network is transmitting within the 250m transmission range and each simulation runs for a period of 900sec. It is worth noting that the above settings could represent a MANET scenario in real life; e.g. a University campus, festive location or battlefield. Note that the number of mobile nodes could be larger than the one presented in these scenarios and the operational time could be longer; the values chosen are to keep the simulation running time manageable while still generating enough traces for analysis. Flows of Constant Bit Rate (CBR) unicast data packets, each with size 512 bytes and sending rate of 4 packets/sec have been used as it was important to challenge the routing protocols with identical offered loads and environmental conditions in order to enable direct and fair comparison among the various forwarding probabilities as well as the routing protocols. The forwarding probabilities in this chapter have been varied from 0.1 to 1.0, with 0.1 increments per simulation trial, and each data point for each forwarding probability represents an average of 30 randomly generated topology scenario files.

In this study, mobile nodes move according to the widely used random waypoint mobility model [109, 115], where each node at the beginning of the simulation remains stationary for *pause time* seconds, then chooses a random destination and starts moving towards it with a speed selected from a uniform distribution $[0,\ V_{\max}]$. After the node reaches its destination, it again stands still for a pause time interval $t\,\text{sec}$ and picks up a new random destination and speed. This cycle repeats until the simulation terminates. The maximum speed $V_{\max}$ is varied for each simulation scenario from 1m/sec to 25m/sec and pause times of 0 seconds are considered to allow constant mobility. Other simulation parameters used in this research study have been widely adopted in existing performance evaluation studies of MANETs [37, 39], and are summarised below in Table 3.1.

Each randomly generated topology represents an experimental trial. Different numbers of trials were first considered and it was observed that the means of 20, 25 and 30 trials are within the same confidence interval of 95% confidence level. Thus the statistics have been collected using a 95% confidence level over 30 randomly generated topologies which have been found to have the lowest relative error compared with the 20 and 25 topologies. The error bars in the graphs represent the upper and lower confidence limits from the means and in most cases they have been found to be quite small. For the sake of clarity and tidiness, the error bars have not been included in some of the graphs.

Table 3.1. System parameters, mobility model and protocol standards used in the simulation experiments

Simulation Parameter	Value
Simulator	NS-2 (v.2.29)
Transmitter range	250 meters
Bandwidth	2 Mbps
Interface queue length	50packets
Traffic type	CBR
Packet size	512 bytes
Simulation time	900 sec
Number of trials	30
Topology size	1000m x 1000m
Number of nodes	25, 50, 75, . . . , 225
Maximum speed	1m/sec 5m/s, 10m/sec, ... , 25m/s

3.3 Analysis of Fixed Probabilistic Route Discovery Using AODV (FP-AODV) and DSR (FP-DSR)

This section conducts a performance comparison analysis of the fixed probabilistic route discovery technique in both AODV [7] and DSR [8]. The current AODV and DSR implementations of the Ns-2(2.29) simulator [113], which are implemented according to the RFC-AODV [7] and RFC-DSR [8] respectively, have been modified in order to implement the fixed probabilistic route discovery. In what follows, such implementations of AODV and DSR are referred to as FP-AODV and FP-DSR. In each of the modified routing protocols, a route discovery process is initiated when the source node needs to send a data packet, but does not have a valid route to the destination, or when an active route to the destination is broken.

3.3.1 Effects of Network Density

This section presents the performance impact of network density on FP-AODV and FP-DSR over different forwarding probabilities. The network density has been varied by deploying 100 and 150 nodes over a fixed area of 1000m x 1000m for different forwarding probabilities. Each node in the network moves with a speed randomly chosen between 0 and 20m/sec. 10 identical random source-destination connections (i.e. traffic flows), each generating 4 data packets per second, have been used. The packet size is 512 bytes. In the figures presented below, the x-axis represents the variations of forwarding probabilities, while the y-axis represents the results of the performance metric of interest.

Collision Rate:

Figure 3.2 shows the effects of network density on the performance of FP-AODV and FP-DSR in terms of average collision rate. As previously stated in Section 3.1, if the forwarding probability is set to 1 then the probabilistic route discovery algorithm is reduced to the traditional route discovery by simple flooding, which is commonly used in traditional on-demand routing algorithms such as AODV.

As expected, the collision rate for a given network size (i.e. a given number of nodes) decreases almost linearly with decreasing forwarding probabilities. This is due to the fact that decreasing the forwarding probability reduces the chances of two or more nodes in the same transmission range transmitting at the same time, leading to a possible reduction in the number of collisions. For example in Figure 3.2, when the forwarding probability is reduced from p = 1 (i.e. simple flooding) to p = 0.7, the collision rate in FP-AODV for both the 100 and 150 node networks is reduced by approximately 88% and 93% respectively, while in FP-DSR the collision rate is reduced by as much as 119% for a 100 node network and approximately 70% for a 150 node network.

Figure 3.2 also reveals that for a given forwarding probability, the number of packet collisions incurred by the two routing protocols increases as the number of nodes increases. As can be seen in Figure 3.2, the collision rate of FP-AODV is increased by a factor of 3 when the number of nodes is increased from 100 to 150 nodes and the forwarding probability is $p=1$. In the FP-DSR, the average collision rate at $p=1$ is increased by a factor 6 with similar changes in network density as above. At a relatively low network density (e.g. 100 nodes), FP-DSR outperforms FP-AODV. This is due to the aggressive use of route caching in FP-DSR which helps to reduce the number of RREQ packets generated and transmitted. Although the number of RREQ packets generated and transmitted in FP-DSR is relatively low (See Figure 3.3 below), when compared against that of FP-AODV in a relatively large size networks (e.g. 150 nodes), the average collision rate of the routing protocols are comparable.

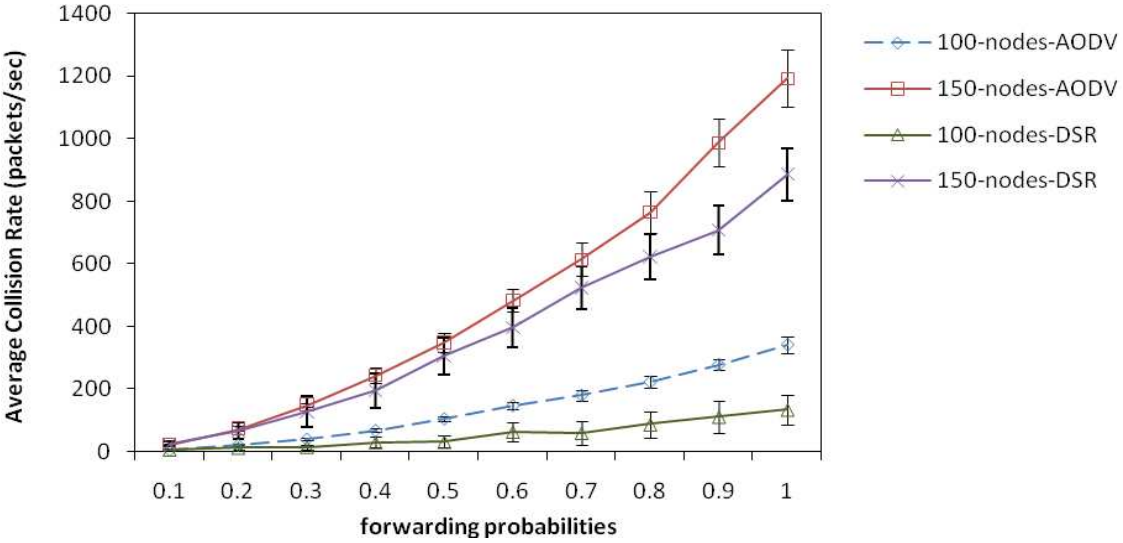


Figure 3.2. Average Collisions rate vs. forwarding probabilities for 100-node and 150-node networks.

Routing Overhead:

Figure 3.3 shows the routing overhead incurred by FP-AODV and FP-DSR versus forwarding probabilities for different network densities. The routing overhead in this study represents the number of RREQ packets generated and disseminated throughout the network. The figure reveals that for a given network density, the routing overhead incurred by each of the routing protocols decreases almost linearly as the forwarding probability decreases. For example, when the probability is reduced from $p=1$ to $p=0.7$, the routing overhead in FP-AODV is reduced by approximately 54% for the 100 nodes network and 60% for the 150 nodes network. For a similar reduction of the forwarding probability in FP-DSR, the routing overhead is slightly reduced by approximately 7% in the 100 nodes network and about 27% in the 150 nodes network. This is because when the forwarding probability is decreased, the number of redundant retransmissions of RREQ packets is reduced; redundant retransmission occurs when an intermediate node forwards an RREQ packet that has been received by all its immediate neighbours.

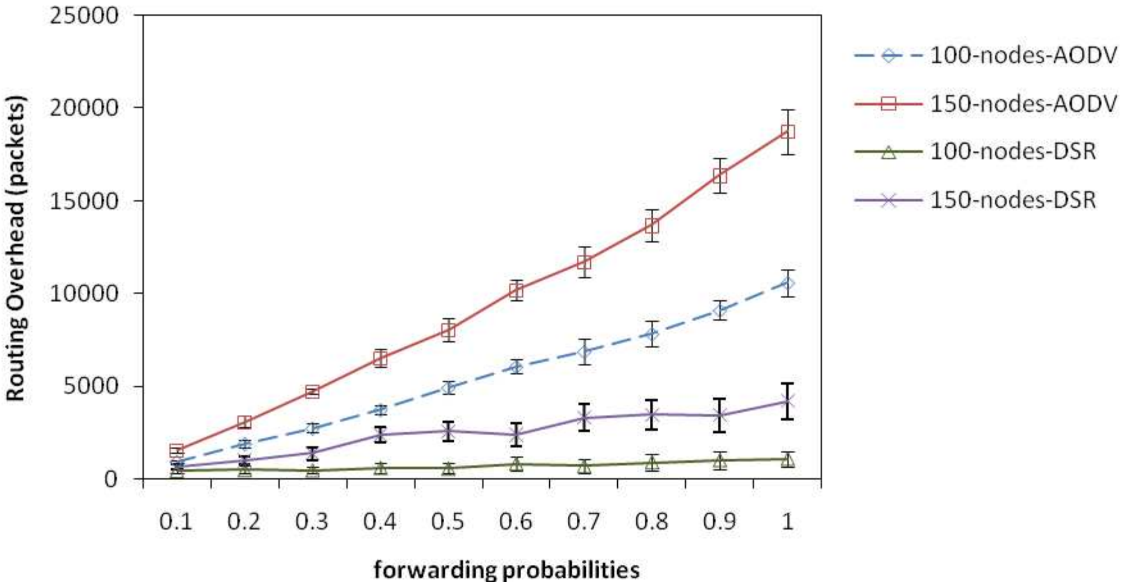


Figure 3.3. Routing overhead vs. forwarding probabilities for 100-node and 150-node network.

Connectivity Success Ratio:

Connectivity Success ratio measures the percentage of route discovery processes that succeed in finding a route. In a moderate to large sized networks, broadcast redundancy contributes to excessive network congestion which increases the chances of packet collisions and contention for the communication channel, and as a consequence, the connectivity success ratio of the network is reduced.

As can be seen in Figure 3.4, the connectivity success ratio of FP-AODV is relatively low for both high and low forwarding probabilities (e.g. p < 4 and p > 7) respectively. For p < 4, fewer than optimal number of nodes is allowed to forward the RREQ packets, thereby preventing some of the RREQ packets from reaching their destinations. On the hand, for p > 7, more than optimal number of nodes in the network are allowed to forward the RREQ packets, as a consequence, the channel contention and packet collisions are increased thereby reducing the capacity of the available bandwidth for the data communication. The connectivity success ratio in FP-DSR drops sharply in relatively dense network (e.g. 150 nodes). This is due to the path accumulation on the RREQ packets which increases the size of the packets. As a consequence, the probability of packet collision in the network is increased.

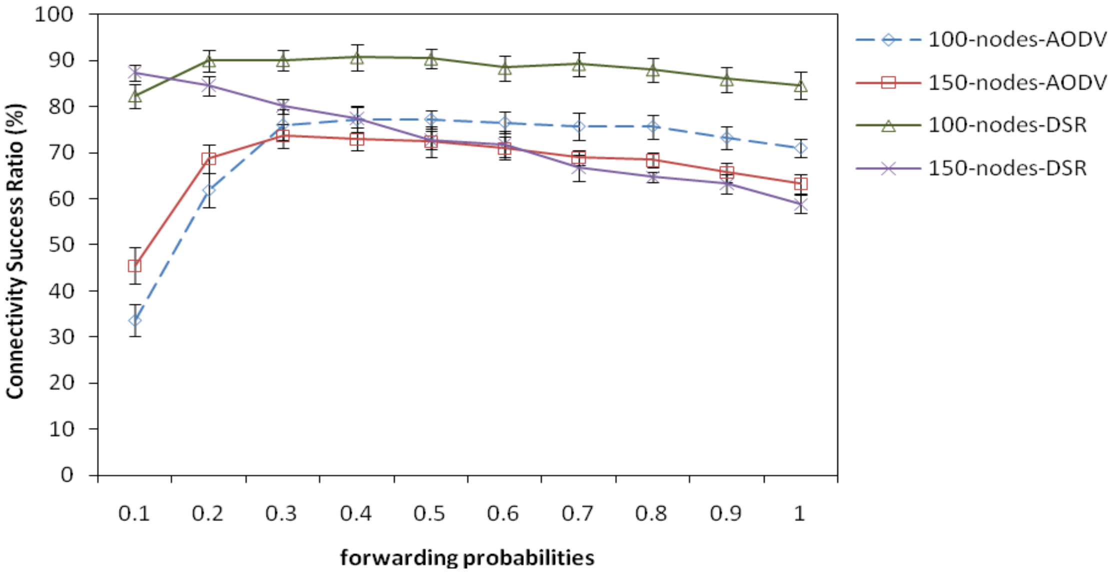


Figure 3.4. Network connectivity vs. forwarding probabilities for 100-node and 150-node networks.

Normalised Network Throughput:

In Figure 3.5, the normalised network throughput of FP-AODV and FP-DSR is plotted against forwarding probabilities for different network sizes of 100 and 150 nodes placed in a topology area of 1000m x 1000m.

The results in Figure 3.5 shows that for FP-AODV, the normalised aggregate throughput in both topology scenarios (i.e. 100 and 150 nodes networks) increases as the forwarding probability increases from 0.1 to 0.6. On the other hand, the throughput decreases as the forwarding probability increases from 0.7 to 1.0. The normalised throughput in FP-DSR for each of the network densities decreases as the forwarding probability increases from 0.1 to 1. The results in Figure 3.5 also show that at low forwarding probability normalised throughput of FP-AODV is relatively lower compared with that of FP-DSR. However, in a dense network the FP-AODV outperforms the FP-DSR when the forwarding probability is set high, particularly in a dense network.

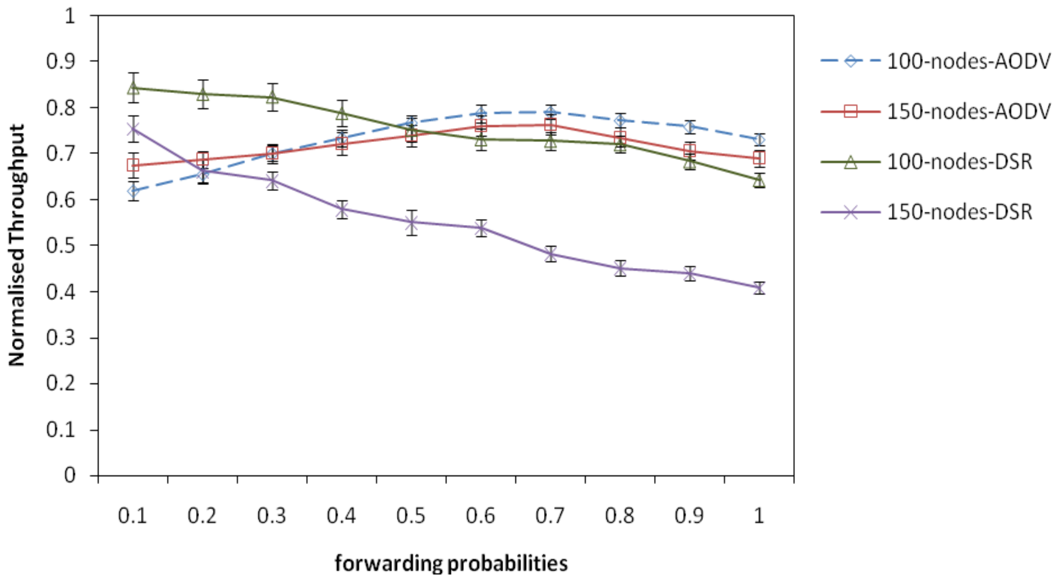


Figure 3.5. Throughput vs. forwarding probabilities for 100-node and 150-node networks.

End-to-End Delay:

In Figure 3.6, the results of FP-AODV and FP-DSR in terms of the *average* end-to-end packet delay are plotted against forwarding probabilities; please note that the terms “end-to-end delay”, “average delay” and “latency” will be used interchangeably in this thesis, and that they are defined as the average time difference between when a unicast data packet was initially sent by the source node and when it was successfully received at the destination. Figure 3.6 shows that the delay incurred by each of the two protocols is longer for both low and high forwarding probabilities. The results also show that the FP-DSR incurs higher delay compared with the FP-AODV. This is due to the fact that the FP-DSR often relies on cached routes for data transmission. However, some of these cashed routes are often stale routes.

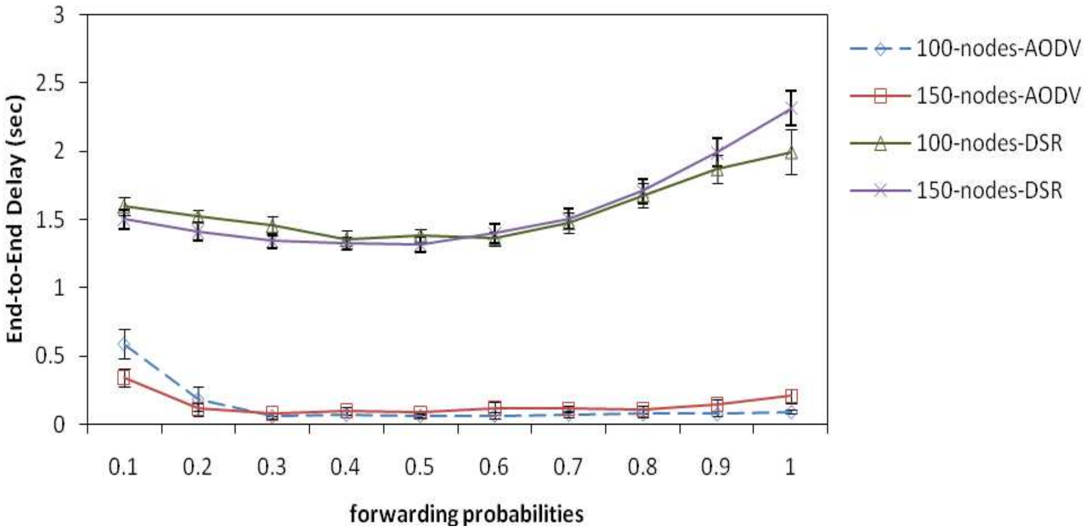


Figure 3.6. End-to-end delay vs. forwarding probabilities for 100-node and 150-node networks.

3.3.2 Effects of Node Mobility

This section demonstrates the effects of node mobility on the performance of FP-AODV and FP-DSR. In this study, 150 nodes are placed over 1000m x 1000m with each node moving according to the random waypoint mobility model with a maximum node speed of V_{max}. The node mobility is varied by changing the value of V_{max}. For each simulation scenario, 10 identical randomly selected source-destination connections are used.

Routing Overhead:

In Figure 3.7 the impact of node mobility on the performance of FP-AODV and FP-DSR in terms of the routing overhead is plotted against the forwarding probability. In particular, the figure demonstrates that across all forwarding probabilities, the routing overhead incurred by FP-AODV and FP-DSR increases with increased node mobility. This is due to the fact that an increase in node mobility results in an increase in the number of broken links and the failure of some route request packets to reach their destinations. Such failures cause another round of route request packet generation and dissemination.

The results in the figure also reveal that for a given maximum node speed, the routing overhead in each of the protocols decreases as the forwarding probability decreases. This is because in moderate to high density networks (e.g.

150 nodes), which guarantee relatively full network connectivity, the number of redundant retransmissions of RREQ packets increases when the forwarding probability increases. However, across all forwarding probabilities, FP-DSR outperforms FP-AODV by reducing the routing overhead for both 5m/sec and 10m/sec. The superior performance of FP-DSR is due to its aggressive use of cached routes.

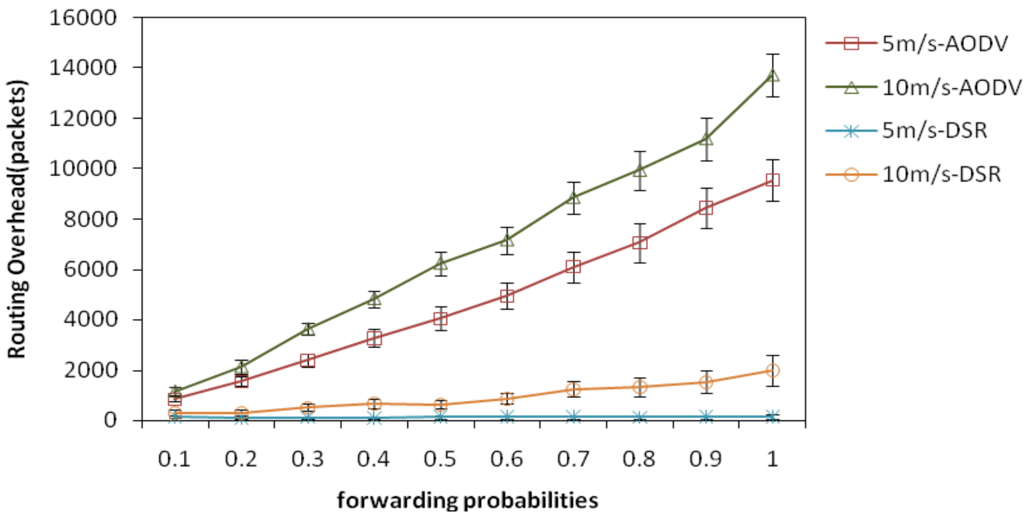


Figure 3.7. Routing overhead vs. forwarding probabilities of 150 nodes placed over a 1000m x 1000m area moving with different maximum speeds.

Collision Rate:

In Figure 3.8, the results of the two routing protocols in terms of average collision rate for different maximum node speeds are plotted against the forwarding probabilities. Overall, across different forwarding probabilities, the collision rate in each of the two routing protocols increases with increased node mobility. For example, in Figure 3.8, the collision rate at p = 1 is increased by approximately 64% and 500% in FP-AODV and FP-DSR respectively when the speed is increased from 5m/s to 10m/s. This is due to the increased number of broken routes as node mobility increases which require more route discovery operations to be initiated for new routes. As a consequence, the congestion levels and the number of collisions in the network are increased.

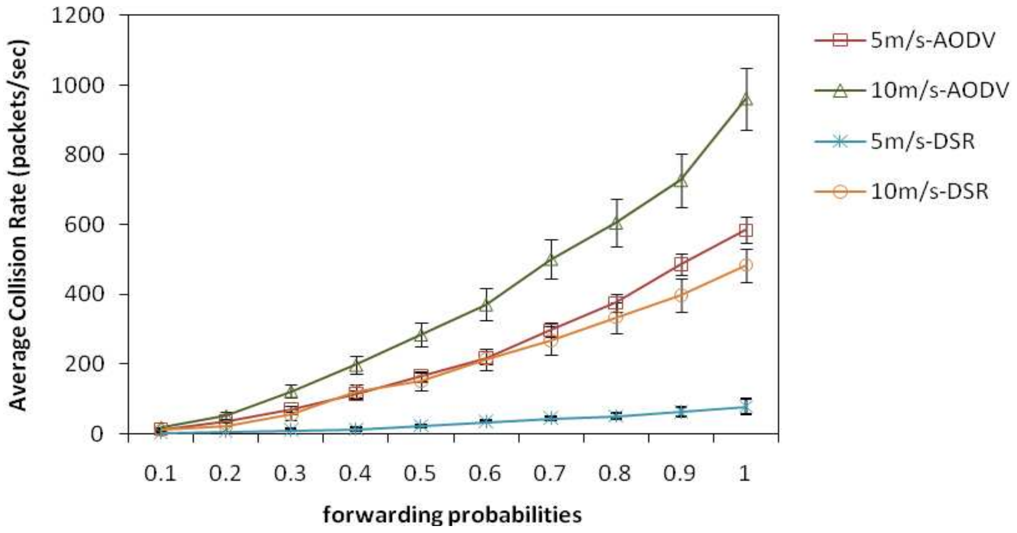


Figure 3.8. Collision rate vs. forwarding probabilities of 150 nodes deployed over 1000m x 1000m area moving with different maximum speeds.

Connectivity Success Ratio:

Figure 3.9 shows a plot of the connectivity success ratio of FP-AODV and FP-DSR for 5m/sec and 10m/sec against the forwarding probability. For FP-AODV, the connectivity success ratio of both speeds first increases as the forwarding probability increases. They start to decrease after reaching a maximum when the forwarding probability is increased. The figure also show that across forwarding probabilities, the connectivity success ratio of FP-AODV decreases as the speed increases. This is due to the increased in the number of broken routes when the mobility is increased.

In FP-DSR, connectivity success ratio first increases when the probability is increased until around $p = 0.6$, when the maximum speed in the network is 5m/s. However, when a relatively high speed is used (e.g. 10m/s), the connectivity of FP-DSR starts to drop after $p = 0.2$. The figure also reveals that, at relatively low forwarding probability, the FP-DSR with relatively fast moving nodes has a higher connectivity than the FP-DSR with slow moving nodes. On the other hand, the connectivity of FP-DSR with fast moving nodes is lower compared with the FP-DSR with slow moving nodes when the forwarding probability is increased. For a given routing protocol, the connectivity decreases as the speed increases when the forwarding probability is set high (e.g. probabilities greater 0.4). The results in Figure 3.9 also reveal that FP-DSR outperforms FP-AODV in both mobility cases across all forwarding probabilities.

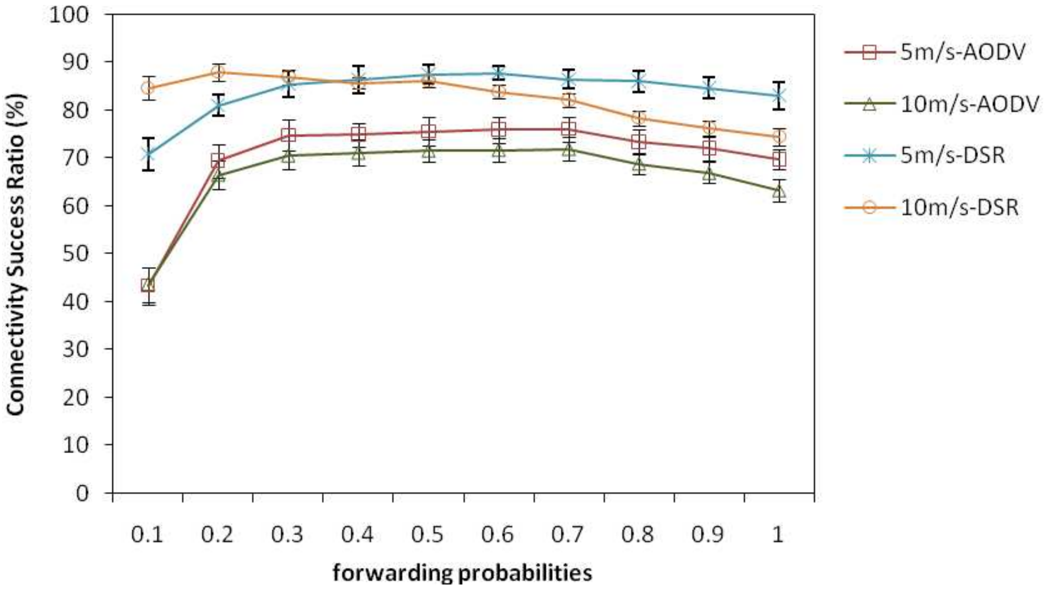


Figure 3.9. Network connectivity vs. forwarding probabilities of 150 nodes placed over 1000m x 1000m area moving with different maximum speeds.

Normalised Network Throughput:

Figure 3.10 depicts the normalised throughput in both FP-AODV and FP-DSR versus the forwarding probability for different maximum speed. It can be seen in Figure 3.10 that for 5m/s and 10m/s, the normalised throughput of FP-AODV increases to a maximum of 96% and 73% respectively when the forwarding probability is increased from 0.1 to 0.7, and dropped to approximately 92% and 64% respectively when the forwarding probability is increased. On the other hand, for a maximum node speed of 10m/s, the throughput in FP-DSR degrades sharply from 89% to 65% when the forwarding probability is increased from 0.1 to 1. At relatively low speed (e.g. 5m/s), the normalised throughput in FP-DSR is slightly affected. Although FP-DSR has a higher connectivity success ratio than FP-AODV for 10m/s as shown in Figure 3.9, the normalised throughput is lower than FP-AODV. This is because some of the routes used for the data transmission in FP-DSR are stale.

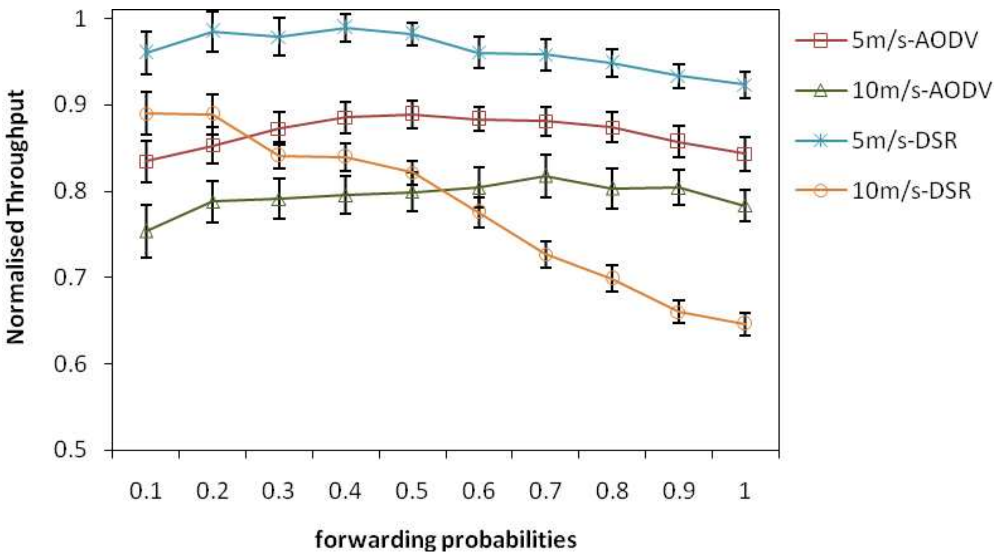


Figure 3.10. Throughput vs. forwarding probabilities of 150 nodes placed over a 1000m x 1000m area moving with different maximum speeds.

End-to-End Delay:

The end-to-end delay of FP-AODV and FP-DSR for different speeds is reported in Figure 3.11. The figure shows that at a given maximum speed, the end-to-end delay incurred by each of the routing protocols is longer when the forwarding probability is set low. This is because at low forwarding probabilities, fewer than the optimal number of nodes forwards the RREQ packets; as a consequence, some of the initiated RREQ packets fail to reach their destinations. The figure also shows that the performance of FP-DSR in relatively high mobility scenarios is worse when compared with FP-AODV. The worse performance of FP-DSR is due to the use of stale routes for data transmission and the time used to transmit large control packets (e.g. RREQ packets) during route discovery. The routing control packets and data packets in FP-DSR are large due to the source routing (see Section 2.3.2.2).

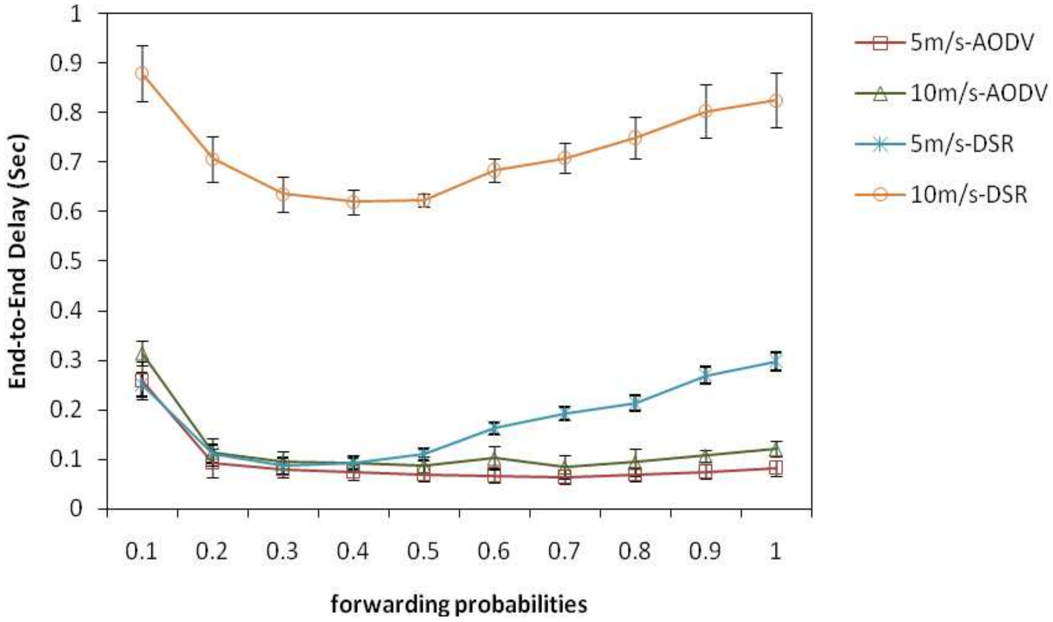


Figure 3.11. End-to-end delay vs. forwarding probabilities of 150 nodes placed over 1000m x 1000m area moving with different maximum speeds.

3.3.3 Effects of Traffic Load

This section demonstrates the effects of traffic load on the performance of FP-AODV and FP-DSR for different forwarding probabilities. In this study, 150 nodes are placed over 1000m x 1000m and each node is moving according to the random way point mobility model with a maximum speed of 20m/s. To investigate the impact of traffic load, the numbers of source-destination connections (or flows) have been varied; 5 and 10 flows. The source destination pair for each of the connections is chosen at random and consists of a CBR flow from the source to destination.

Routing Overhead:

The results in Figure 3.12 show the effects of offered traffic load on the performance of FP-AODV and FP-DSR in terms of routing overhead across different forwarding probabilities. Figure 3.12 shows that significant savings can be achieved by reducing the number of RREQ packets transmitted in highly congested networks when the forwarding probability is set low. However, if the number of retransmissions of RREQ packets is much lower than optimal, this may result in the route search dying out quite early, which will require another round of route discovery.

Compared with FP-AODV, FP-DSR generates less routing overhead across all forwarding probabilities, especially when a large number of traffic flows is used. The savings achieved by FP-DSR in terms of routing overhead are due to the use of cached routes.

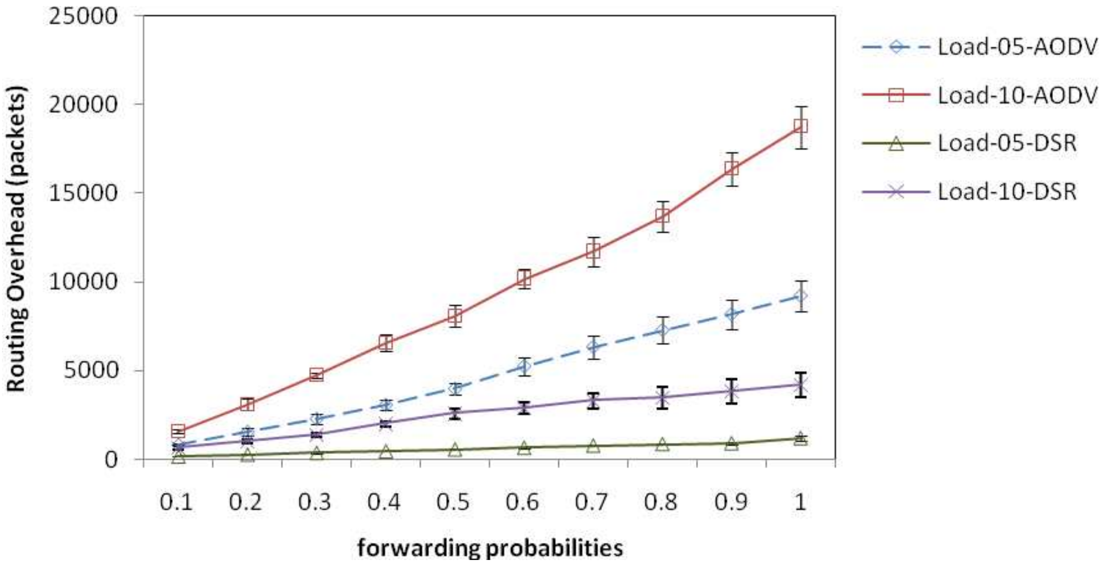


Figure 3.12. Routing overhead vs. forwarding probabilities of 150 nodes placed over 1000m x 1000m area when offered traffics of 5 and 10 flows are used.

Collision Rate:

Figure 3.13 depicts the performance of the two routing protocols in terms of collision rate for different forwarding probabilities when offered loads of 5 and 10 flows are used. The figure reveals that for a given number of offered loads, the collision rate increases almost linearly with increased forwarding probability.

The results in the figure also demonstrate that for a given forwarding probability, the collision rate in each of the routing protocols increases with increased offered load. This is because of the increase in the congestion levels when the number of source destination pairs in the network is increased. Figure 3.13 also reveals that, across all the forwarding probabilities, the FP-DSR protocol incurs a lower collision rate when compared with FP-AODV for both 5 and 10 flows.

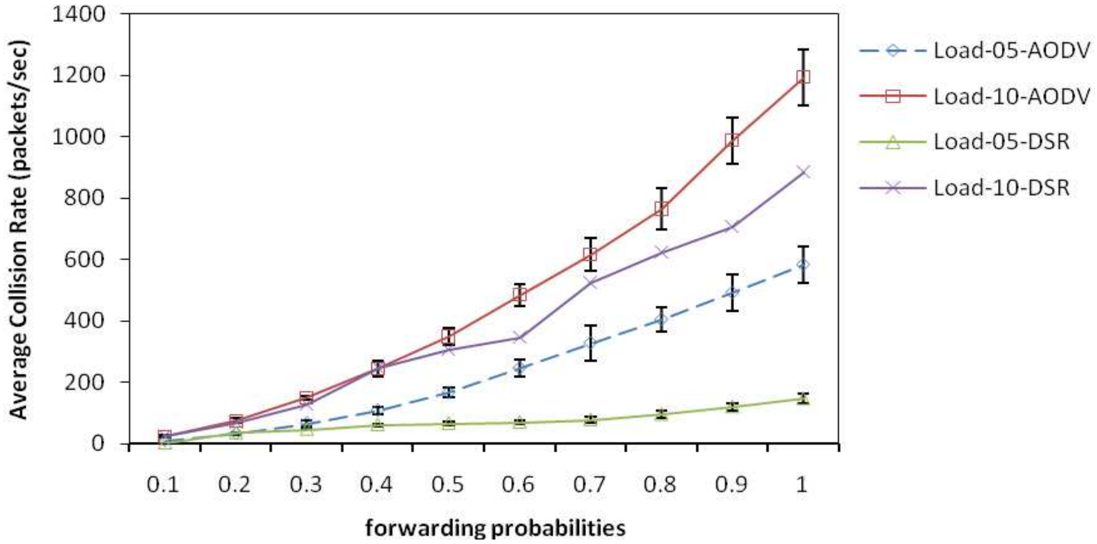


Figure 3.13. Average collision rate vs. forwarding probabilities of 150 nodes placed over 1000m x 1000m area when offered traffics of 5 and 10 flows are used.

Connectivity Success Ratio:

Figure 3.14 plots the performance properties of FP-AODV and FP-DSR in terms of the network connectivity success ratio against forwarding probabilities. The figure reveals that the network connectivity in FP-AODV is low when the forwarding probability is set low (e.g. $p < 0.4$) and when it is set high (e.g. $p > 0.8$). This is due to the fact at low probabilities fewer than optimal number of RREQ packets are transmitted in FP-AODV. On the hand when the probability is set high, more redundant transmission of RREQ packets induce a larger number of packet collisions causing some of the RREQ packets to fail to reach their respective destinations. In FP-DSR, the performance is slightly affected by the varying forwarding probabilities when the offered load is relatively small (e.g. 5 flows). However, at relatively large offered load (e.g. 10 flows), the connectivity dropped sharply with increased forwarding probability. Furthermore, the figure shows that, for a given offered load, the FP-DSR has a clear performance advantage over FP-AODV when the offered load is low and the forwarding probability is set low.

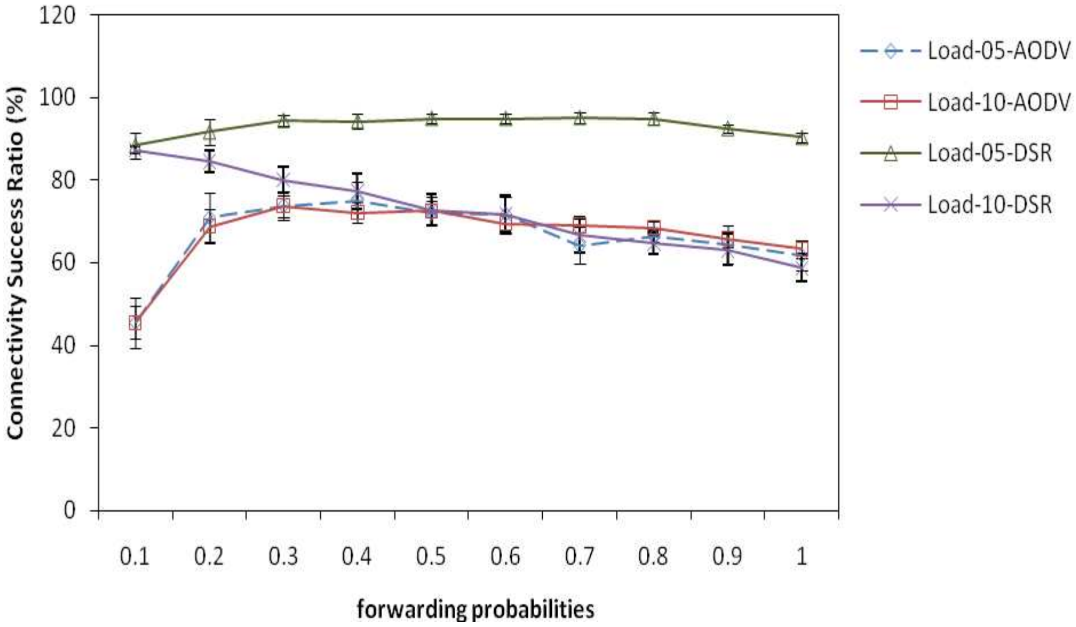


Figure 3.14. Network connectivity vs. forwarding probabilities of 150 nodes placed over 1000m x 1000m area and when offered traffic of 5 and 10 flows are used.

***Normalised Throughput*:**

In Figure 3.15, the performance properties of FP-AODV and FP-DSR in terms of network throughput for offered loads of 5 and 10 flows is plotted against the forwarding probability. The Figure 3.15 reveals that the normalised throughput of FP-AODV increases to a maximum of about 0.80 and 0.76 for 5 and 10 flows respectively when the forwarding probability is increased from 0.1 to 0.7, and dropped to around 0.71 and 0.66 for 5 and 10 flows respectively when forwarding probability is increased from 0.7 to 1. However in FP-DSR, the normalised network throughput degrades sharply with increased forwarding probability when 10 flows is used and remains slightly affected when 5 flows is used.

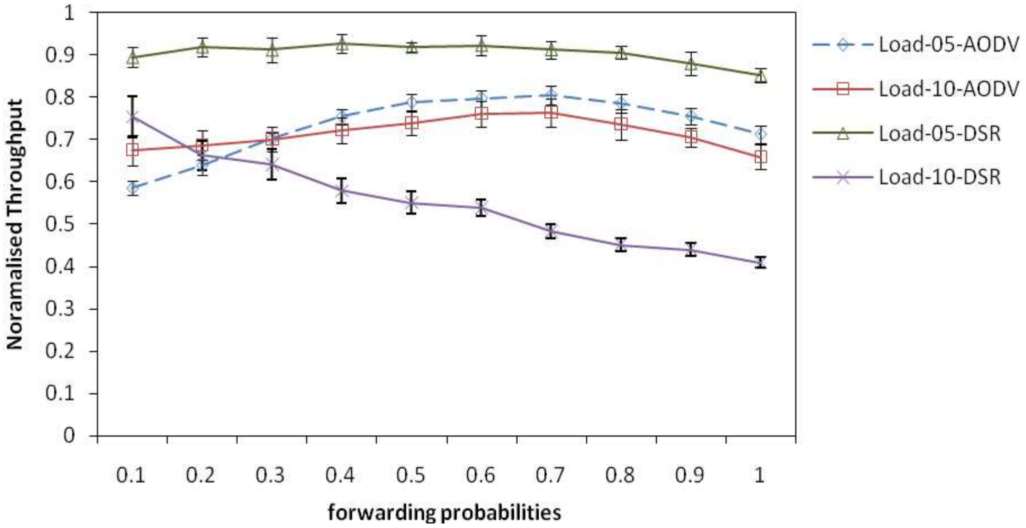


Figure 3.15. Network throughput vs. forwarding probabilities of 150 nodes placed over 1000m x 1000m area and when offered traffic of 5 and 10 flows are used.

End-to-End Delay:

Figure 3.16 presents the end-to-end delay of the two routing protocols versus the forwarding probability for different offered loads. Increasing the number of flows results in an increase in the number of nodes contending for channel and the probability of packet collisions. These phenomena can potentially increase the time elapsed to discover routes, as a consequence the end-to-end delay of the data packets is increased. For example, in Figure 3.16 the end-to-end delay incurred by FP-AODV and FP-DSR at forwarding probability $p = 1$ is increased by around 30% and 270% respectively when the offered load is increased from 5 to 10 flows. The results in Figures 3.16 also show that FP-DSR incurs a much longer delay than FP-AODV for a large number of flows and high forwarding probability. This is due to the high number of stale routes and packet collisions associated with FP-DSR, especially in congested networks.

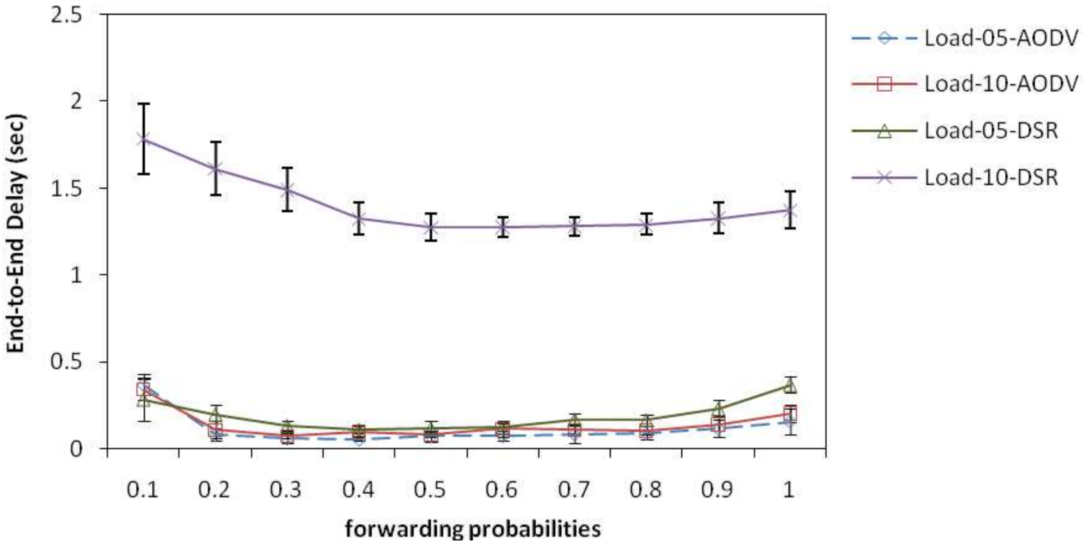


Figure 3.16. End-to-end delay vs. forwarding probabilities of 150 nodes placed over 1000m x 1000m area moving at a maximum speed of 5m/sec when traffic flows of 5 and 10 are used.

3.4 Conclusions

This chapter has conducted the first performance analysis of two on-demand routing protocols that are based on probabilistic route discovery, namely FP-AODV and FP-DSR, in order to assess their behaviour in various network operating environments. The first part of the analysis has been conducted through studying the effects of different network densities in terms of deploying different numbers of nodes over a fixed size topology area. The forwarding probability has been varied from 0.1 to 1 in steps of 0.1. The second part of the analysis has evaluated the effects of node mobility on the performance of probabilistic route discovery in FP-AODV and FP-DSR by varying the maximum node speed. The last part of the analysis has investigated the impact of offered load in terms of the number of traffic flows (i.e. source-destination pairs) on the performance of the two routing algorithms.

The results have revealed that for a given network setup with a given network density and node mobility, considerable savings can be achieved in terms of RREQ packet dissemination and collisions without degrading the overall network performance in terms of network throughput and end-to-end packet delay, provided that an appropriate forwarding probability is selected. For example, the results have revealed that using a forwarding probability of around $p = 0.7$ in a moderate to large sized network can reduce routing overhead as well as the rate of collisions while still achieving a good performance level in terms of throughput and delay.

Chapter 4

Route Discovery with Fixed Probability and Simple Flooding

4.1 Introduction

As has been shown in Chapter 3, the routing overhead associated with the traditional on-demand route discovery process such as that used in AODV [1] and DSR [2] can be significantly reduced by allowing each node in the network to rebroadcast a received RREQ packet with a given forwarding probability. The traditional on-demand routing protocols [1, 2] rely on simple flooding for the dissemination of the RREQ packets. In simple flooding, each node rebroadcasts a received RREQ packet that is received for the first time and discards any subsequent duplicate packets. In fixed probabilistic route discovery, each forwarding node is allowed to rebroadcast a received packet with a fixed forwarding probability regardless of its relative location with respect to the locations of the source and destination.

In this chapter, a new probabilistic route discovery approach is introduced. The new approach reduces the routing overhead by localising the dissemination of RREQ packets to a limited region in the network where the destination is expected to be located. This is achieved by making intelligent use of routing histories at forwarding nodes and the elements of both fixed probabilistic and flooding-based route discovery approaches. If a node has recently forwarded a packet on behalf of a source-destination pair, it is assigned a high forwarding probability, e.g. $p = 1$, and a low forwarding probability otherwise. The forwarding history at a node represents the last recorded time at which the node forwarded a packet on behalf of a given source-destination pair.

The performance analysis of the new probabilistic route discovery approach, referred to as Route Discovery with Fixed probability and Simple Flooding (FF-AODV, for short) has been conducted by comparing it against the traditional AODV [1] and its fixed probabilistic variant (FP-AODV, for short). Simulation results will show that FF-AODV exhibits superior performance characteristics to AODV and FP-AODV with its performance advantages being more noticeable in dense and congested networks.

The rest of the chapter is organised as follows. Section 4.2 describes the proposed probabilistic route discovery algorithm. Section 4.3 analyses the effects of network operating conditions on the performance of the proposed probabilistic route discovery. Finally, Section 4.4 concludes the chapter.

4.2 The New Route Discovery Algorithm

The new algorithm combines the characteristics of two route discovery approaches; namely, those of the fixed probabilistic approach and simple flooding. It makes use of two sets of network information, notably, routing histories and neighbourhood information at mobile nodes. The route discovery algorithm is divided into two phases; the discovery phase and the maintenance phase. The route discovery phase is similar to the fixed probabilistic discovery discussed in Chapter 3. However, the route maintenance phase of the traditional AODV has been modified to incorporate both fixed probabilistic and flooding-based route discovery approaches based on the routing history collected at forwarding nodes.

4.2.1 Route Discovery Phase

The route discovery phase is triggered whenever a node needs to communicate with another node for which it does not have a known route and no prior routing history. The source node broadcasts an RREQ packet to its 1-hop neighbours. Each neighbouring node that receives the RREQ packet forwards it to its neighbours with a forwarding probability p and drops it with a probability $1-p$. The process of dissemination continues until the RREQ packet is received by the destination or a node with a valid route to the destination. The destination replies by sending an RREP packet. The RREP packet is unicast towards the source node 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. The process is similar to the fixed probabilistic route discovery.

However, unlike the fixed probabilistic route discovery, each node forwards the received RREP packet after recording the routing history information, which consists of the source identification, the destination identification and the time at which the RREP packet was received. Also, the routing history information at a node is updated whenever it forwards a data packet towards the destination. The nodes that participate in the forwarding of the RREP and data packets are referred to as active nodes. Each active node maintains its connectivity by using the existing “hello” protocol in AODV [7] which periodically broadcasts its identification (ID) to its 1-hop neighbours.

4.2.2 Route Maintenance Phase

Route maintenance starts when there is a change in the network topology which affects the validity of an active route. Once an active node detects that the next hop towards the destination is unreachable, it propagates a route error packet to inform the source node and other active nodes on the path that the path is no longer valid. The affected paths are subsequently deleted from all the nodes that received the route error packet. The source node upon receiving the route error packet initiates a new route discovery process using the fixed probabilistic and the simple flooding-based route discoveries. Moreover, the process exploits the prior routing history information collected at active nodes just before the route was considered invalid.

This approach assumes that a destination node will not move too far away, too soon from its recently used path if there is a change in the network topology. Therefore, for each source-destination pair the approach defines two zones: namely, the active zone and the inactive zone. The active zone for a source-destination pair consists of the active nodes and their 1-hop neighbours. On the other hand, the inactive zone for a source-destination pair consists of all nodes which have prior routing histories of the source-destination pair and are not neighbours of the active nodes. During the route maintenance phase, all the nodes in the active zone are privileged to forward the RREQ packet by assigning them with high forwarding probabilities. At the same time, the nodes outside the active zone of the source-destination pair are less privileged by using a relatively low forwarding probability.

Specifically, the approach implements three different forwarding probabilities. Firstly, the active nodes are assigned a high forwarding probability of $p = 1$ (i.e. simple flooding). Secondly, the 1-hop neighbours of the active nodes are assigned a medium forwarding probability $p_m < 1$. Finally, the nodes located outside the active zone are assigned a low forwarding probability $p_l < p_m$. Figure 4.1 shows an illustrative example of the new route discovery algorithm and Figure 4.2 presents an outline of the algorithm.

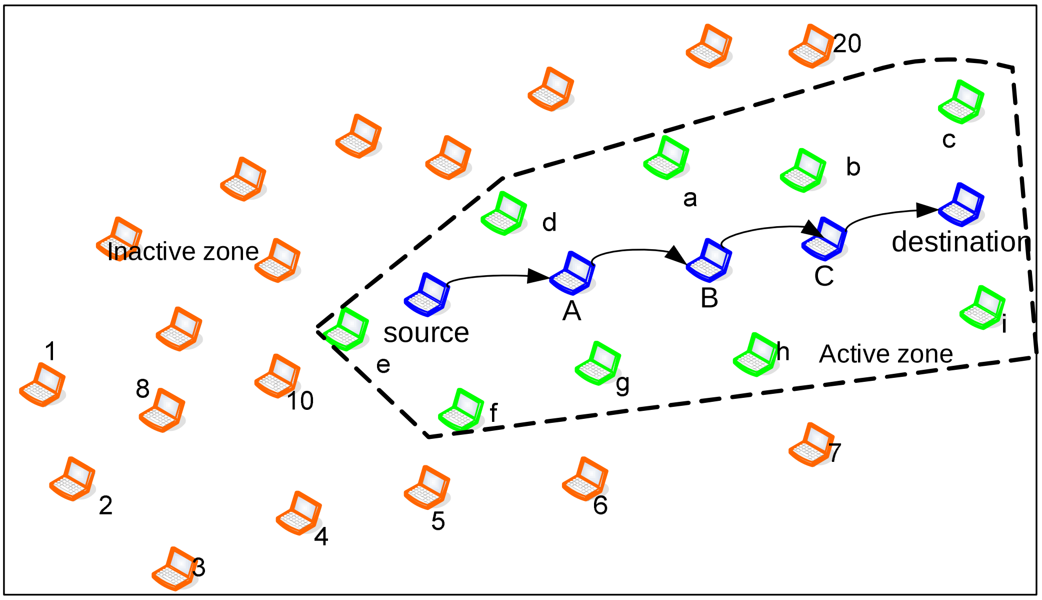


Figure 4.1. An example to illustrate the dissemination process of an RREQ packet using fixed probability and simple flooding.

```
Algorithm: FF-AODV

Source Node:
When originating an RREQ packet
If (routing history exits)
    Mark the RREQ packet as route maintenance
else
    Mark the RREQ packet as a new route discover
Forwarding Nodes:
If (an RREP or DATA packet is received)
  If (routing history exists for the source-destination pair)
      Update routing history entry
  else
      Record a new routing history entry
If (an RREQ packet is received for the first time)
   If (the RREQ packet is marked for route maintenance)
       If (forwarding node is an active node)
           Set the rebroadcast probability to high: p->1 (i.e. simple flooding)
       else If (forwarding node is a neighbour of an active node)
           Set the rebroadcast probability to medium: p->$p_m$
       else
           Set the rebroadcast probability to low: p->$p_l$
  If (the RREQ packet is marked for a new route discovery)
       Set the rebroadcast probability to medium: p->$p_m$
Generate a random number Rnd over the range [0,1]
If ($Rnd \le p$)
    Broadcast the RREQ packet
else
    Drop the RREQ packet
```

Figure 4.2. An outline of the new probabilistic route discovery approach that combines the features of both fixed probabilistic and simple flooding broadcast approaches.

Figure 4.1 provides an illustrative example that describes how an RREQ packet is propagated using the fixed probabilistic and simple flooding-based broadcast methods during the route maintenance phase when the routing history of the source-destination pair is known. The example consists of three sets of nodes identified by the colours blue (i.e. source, **A**, **B**, **C** and destination), green (i.e. **a**, **b**, **c**, …, **i**), red (i.e. 1, 2, 3, …, 20) and one traffic flow connecting the source-destination pair. In Figure 4.1, nodes **A**, **B** and **C** (i.e. the blue nodes) forward data packets on behalf of the source-destination pair. Each of the nodes (i.e. **A**, **B** and **C**) identifies itself as active node for the path by constantly updating the routing history in its cache as data, and RREP packets are forwarded. The active nodes also identify themselves to their 1-hop neighbours, **a**, **b**, **c**, …, **i** (i.e. the green nodes) by periodically transmitting "hello" packets which contain their identifications. These two sets of nodes together form the active zone.

If any of the active nodes (e.g. node **C**) moves out of the transmission range of its active neighbours, then the route between the source-destination pair will no longer be considered a valid route. This will trigger another round of route discovery. In this case, nodes **A**, **B** and **C** forward the RREQ packets using the simple flooding broadcast method. The remaining nodes in the active zone (i.e. **a**, **b**, **c**, …, **i**) forward the RREQ packets using the forwarding probability $P_m < 1$. Finally, the nodes outside the active zone (i.e. nodes **1**, **2**, **3**, …, **20**) forwards the packet with a low forwarding probability $P_l < P_m$.

4.2.3 Selecting the Forwarding Probabilities of P_m and P_l

To evaluate the performance of the new probabilistic route discovery, the current AODV implementation of the NS-2 simulator (v.2.29) [3] has been modified to incorporate the new probabilistic route discovery and the results are compared against the traditional AODV and its fixed probabilistic variant (FP-AODV, for short). In what follows, such a modified AODV is referred to as fixed-flood AODV (FF-AODV, for short).

In the traditional AODV, a given node rebroadcasts a received RREQ packet once and drops all the duplicate packets received. Therefore, there are $N-2$ possible rebroadcasts of an RREQ packet, if no intermediate node has a valid route to the destination and N is the number of nodes in the Network. In the case of FP-AODV, a received RREQ packet at a node is forwarded based on a fixed forwarding probability, p. Since the decision of a node to forward a packet is independent of the others, the total number of possible retransmissions is $p \times (N-2)$, assuming that the destination node exists and that no intermediate node has a valid route to the destination. The FF-AODV uses two different fixed-value probabilities, each assigned at a node based on the state of the routing history at the node. Let N_a be the number of active nodes, N_m be the number of nodes forming the 1-hop neighbours of the active nodes and N_l be the number of nodes located in the inactive zone of the network. If the transmitted RREQ packet is marked as *route maintenance*, then the total number of possible retransmissions of FF-AODV, FP-AODV and AODV are related as follows:

$$1 \times N_a + p_m \times N_m + p_l \times N_l < p \times (N-2) < N-2 \qquad (5.1)$$

The value of p_m has been set to 0.7 based on the simulation results in Chapter 3, while the value of p_l has been set to $\frac{p_m}{2}$. In Figure 4.1, the total number of nodes in the network is $N = 32$, the number of active nodes is $N_a = 3$, the number of nodes forming the 1-hop neighbours of active nodes is $N_m = 9$ and the number of inactive nodes is $N_l = 18$. Therefore the total number of possible broadcasts of an RREQ packet in:

AODV is $N - 2 = 32 - 2 = 30$

FP-AODV is $p_m \times (N-2) = 0.7 \times (32-2) = 0.7 \times 30 = 21$

FF-AODV is $1 \times N_a + p_m \times N_m + p_l \times N_l = 3 + 0.7 \times 9 + 0.35 \times 18 \approx 16$

Although the above analysis is simple and straightforward, it can be used to conclude that by using FF-AODV the number of possible broadcasts of an RREQ packet in the traditional AODV can be reduced by approximately 48%. Furthermore, the number of possible broadcasts in FF-AODV can be reduced by around 25% when compared against the FP-AODV.

4.3 Performance Analysis

The performance analysis of the new proposed probabilistic route discovery has been conducted using the same simulation model and parameters as outlined in Chapter 3 (see Section 3.2).The performance metrics that have been used to conduct the performance analysis include the routing overhead, average collision rate, normalised network throughput, end-to-end delay and route discovery delay. These metrics have been defined in Chapter 2 (see Section 2.7).

The simulation scenarios consist of three different settings, each specifically designed to assess the impact of a particular network operating condition on the performance of the protocols. First, the impact of network density or size is assessed by deploying a different number of mobile nodes over a space of 1000m x 1000m. The second simulation scenario investigates the effects of an offered load on the performance of the routing protocols by varying the number of source destination pairs (flows for short) for each simulation scenario. Lastly, the simulation scenario evaluates the performance impact of node mobility by varying the maximum node speed of a fixed number of mobile nodes in a fixed area of 1000m x 1000m.

4.3.1 Impact of Network Density

In this section the performance impact of network density on the three protocols is examined. The network density has been varied by changing the number of nodes placed in a 1000m x 1000m area of each simulation scenario. Each moves with a random speed chosen between 0 and 20m/sec. For each simulation trial, 10 identical random source-destination pairs are used.

Routing Overhead:

Figure 4.3 illustrates the routing overhead generated by the three routing protocols when the number of nodes is varied. The figure shows that the generated routing overhead in all the three routing protocols increases with increased number of nodes. Moreover, the figure reveals the clear advantage of FF-AODV over AODV and FP-AODV. For instance, compared with the AODV and FP-AODV, the generated routing overhead in FF-AODV can be reduced by approximately 30% and 84% respectively when the number of nodes is relatively small (e.g. 25 nodes). The performance advantage of FF-AODV over the FP-AODV and AODV is further increased in dense networks. For example, in figure 4.3, when the number of nodes is increased to 225 nodes, the generated routing overhead in FF-AODV could be reduced by as much as 73% and 140% less than FP-AODV and AODV respectively.

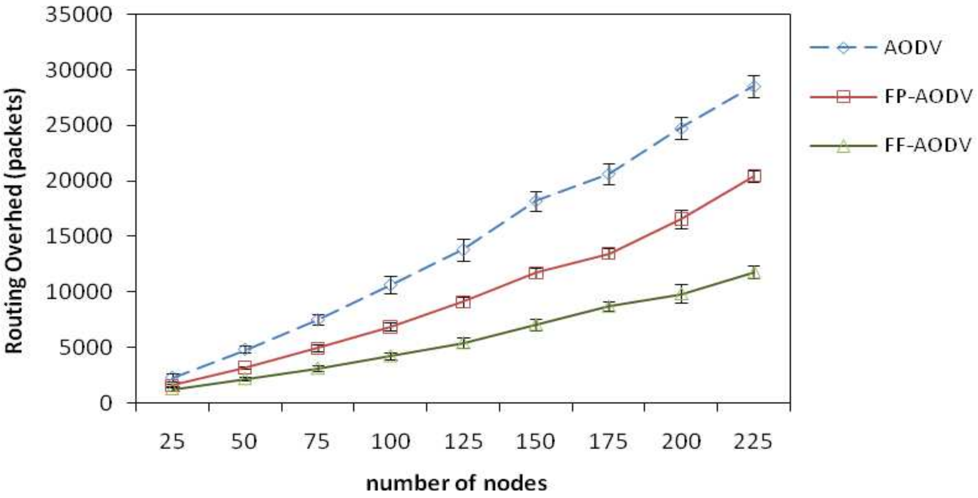


Figure 4.3. Routing overhead versus number of nodes placed over 1000m x 1000m area.

Collision Rate:

Figure 4.4 depicts the number of packet collisions experienced at the MAC per second as the number of nodes increases. It can be seen in the figure that the performance behaviour of the three routing protocols in terms of average collision rate is similar to the routing overhead reported in Figure 4.3. Since data and control packets share the same broadcast wireless medium, the collision rate is high when there are a large number of nodes in the same coverage area transmitting packets at the same time.

The figure also reveals that as the number of nodes increases the superiority of FF-AODV over the FP-AODV and AODV becomes more prominent, confirming the scalability support of the FF-AODV algorithm. When the FF-AODV is used, the probability of two more nodes transmitting at the same time is significantly reduced, because of the fact that most of the nodes outside the active zone have been made to probabilistically suppress their broadcasts. For example, Figure 4.4 shows that the collision rate of FF-AODV could be reduced by approximately 100% and 250% under 225 nodes when compared against the FP-AODV and AODV, respectively.

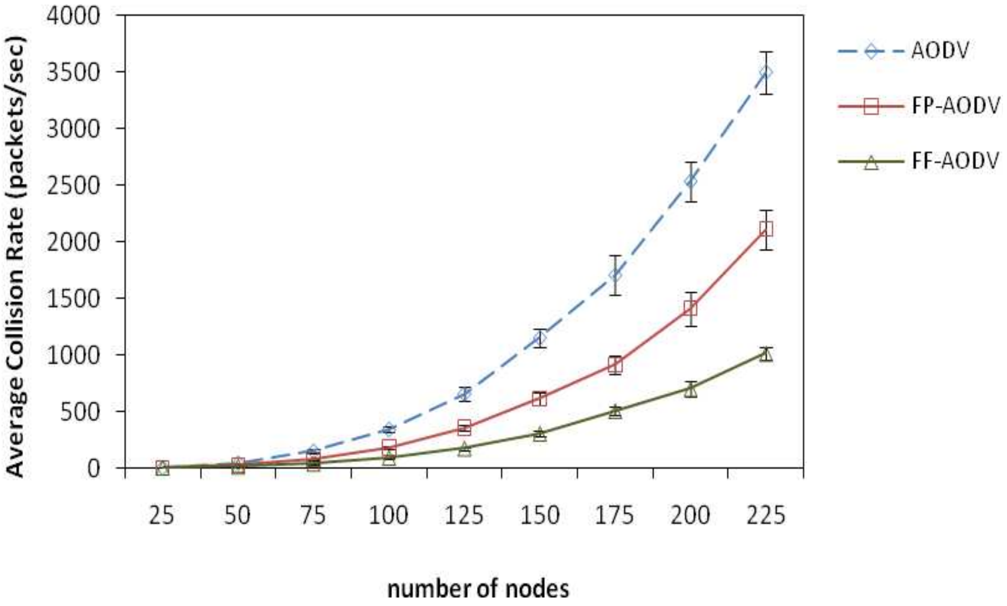


Figure 4.4. Average collision rate versus number of nodes placed over 1000m x 1000m area.

Normalised Network Throughput:

Figure 4.5 depicts the achieved network throughput of all three protocols against network density. Although significant savings on routing overhead is achieved by the probabilistic protocols, the normalised network throughput achieved by the probabilistic protocols is low for both sparse and dense networks. This is due to the fact that in a sparse network (e.g. 25 nodes) most of the nodes are outside the transmission range of each other, causing partitioning in the network. As a consequence some of the RREQ packets failed to reach their respective destinations. On the other hand, in a dense network, the more than optimal number of RREQ packets is disseminated causing an increase in the channel contention and packet collisions, thereby reducing the available bandwidth of actual data communication. As can be seen in Figure 4.5, the network throughput of FF-AODV could be increased by as much as 30% and 70% when compared against AODV and FP-AODV in a relatively dense network (e.g. 225 nodes).

The network connectivity success ratio which measures the percentage of the number of route discovery processes that succeed in finding a route in the three protocols is shown in Figure 4.6. Similar to results in Figure 4.5, the connectivity success ratio in each of the protocols increases to a maximum and drops as the network density increases. The figure also depicts that the simple flooding basing AODV outperforms both the FF-AODV and FP-ADV when the density is relatively low (e.g. 25 nodes). However, in a relatively dense network (e.g. 225 nodes), the FF-AODV performed approximately 10% and 20% better than the FP-AODV and AODV respectively.

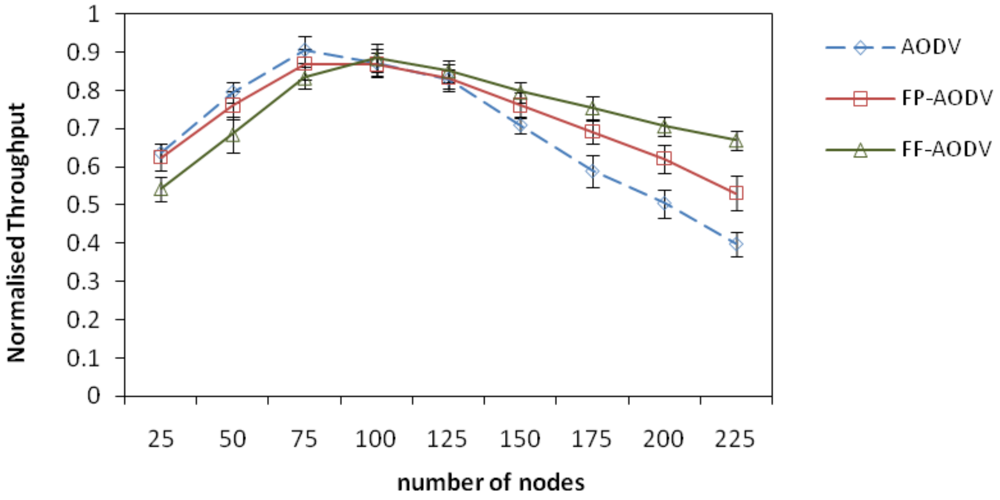


Figure 4.5. **Normalised network throughput versus number of nodes placed over 1000m x 1000m area.**

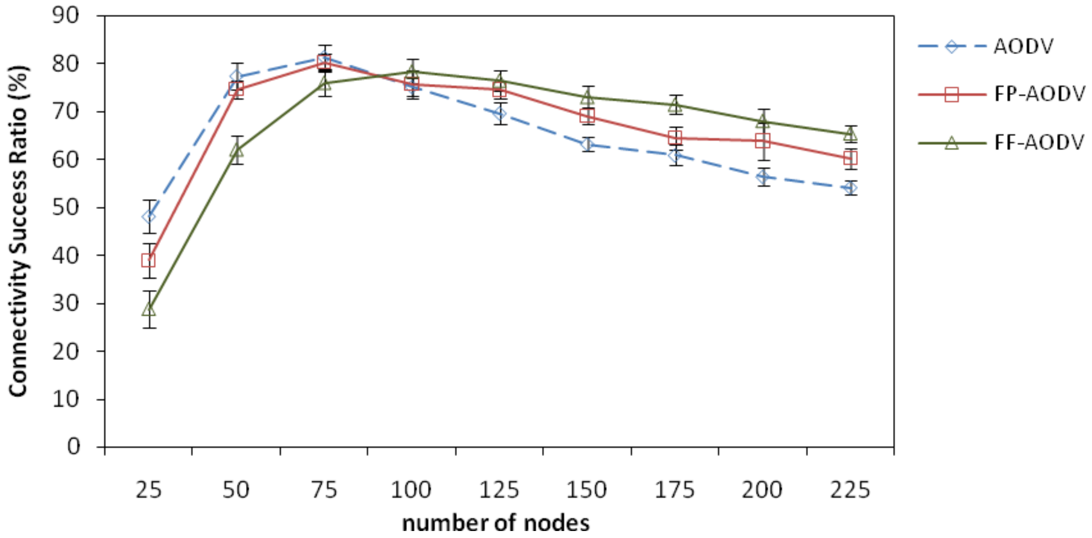


Figure 4.6. Connectivity success ratio versus number of nodes placed over 1000m x 1000m area.

End-to-End Delay:

The results in Figure 4.7 illustrate the performance of the three routing protocols in terms of end-to-end delay when the number of nodes in the network is varied. In on-demand route discovery, data packets at the source node are often queued until a route to the destination is established. Therefore, if the time used to discover the route is relatively longer, then the total time required to transmit the data packets from source to destination is increased. As shown in figure 4.7, the delay incurred by each of the three routing protocols decreases to a minimum when the number of nodes is increased from 25 to 100 nodes and increases after reaching a minimum value as the number of nodes increases from 100 to 225 nodes. The poor performance of the three protocols in a relatively sparse network is due to the poor network connectivity associated with sparse networks.

The figure also reveals that high channel contentions, congestion and packet collisions resulting from a dense network (e.g. 225 nodes) could degrade the end-to-end delay of the protocols. The results in Figure 4.7 show that, in a dense network, FF-AODV outperforms FP-AODV and AODV by reducing the delay by approximately 53% and 85% respectively. This is because the contention for the communication channel and the packet collisions are reduced as a result of a reduction in the routing overhead.

Figure 4.8 depicts the performance of the three routing protocols in terms of route discovery delay over varying network density. The performance comparison in terms of route discovery presents similar performance trend as end-to-end delay shown in Figure 4.7. FF-AODV performs poorly in sparse networks. However, in a relatively dense network, FF-AODV outperforms the AODV and its fixed probabilistic variant.

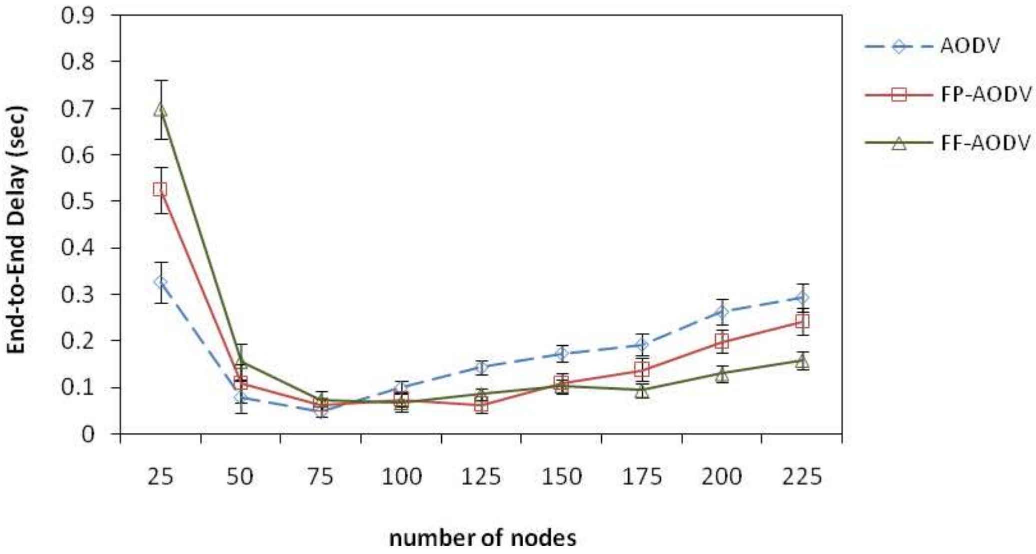


Figure 4.7. End-to-end delay versus number of nodes placed over 1000m x 1000m area.

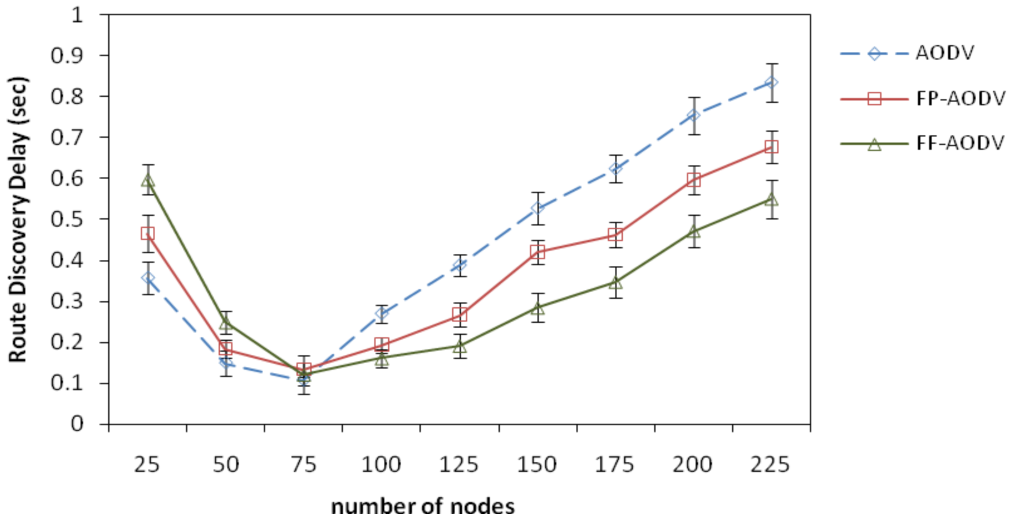


Figure 4.8. Route discovery delay versus number of nodes placed over 1000m x 1000m area.

4.3.2 Impact of Offered Load

In this section, the effects of offered load on the performance of the protocols have been investigated. Simulation runs have been conducted for the three protocols, FF-AODV, FP-AODV and AODV, where the offered load is varied by increasing the number of source-destination pairs (flows, for short) from 1 to 40. The topology for each simulation scenario consists of 150 nodes placed randomly on a flat area of 1000m x 1000m, each moving with the random waypoint mobility with speed between 0 and 20m/sec.

Routing Overhead:

Figure 4.9 depicts the performance of FF-AODV, FP-AODV and AODV in terms of routing overhead versus offered loads. The figure shows that the generated routing overhead for the three routing protocols increases with increased offered loads. This performance behaviour is expected since increasing the offered loads leads to an increase in the number of source nodes initiating route discovery operations. It can also be noticed from the figure that for a given offered load, the generated routing overhead of FF-AODV is much lower compared with that of FP-AODV and AODV. In figure 4.9 for example, at a high offered load (e.g. 40 flows), the routing overhead in FF-AODV is reduced by approximately 60% and 140% when compared against FP-AODV and AODV, respectively.

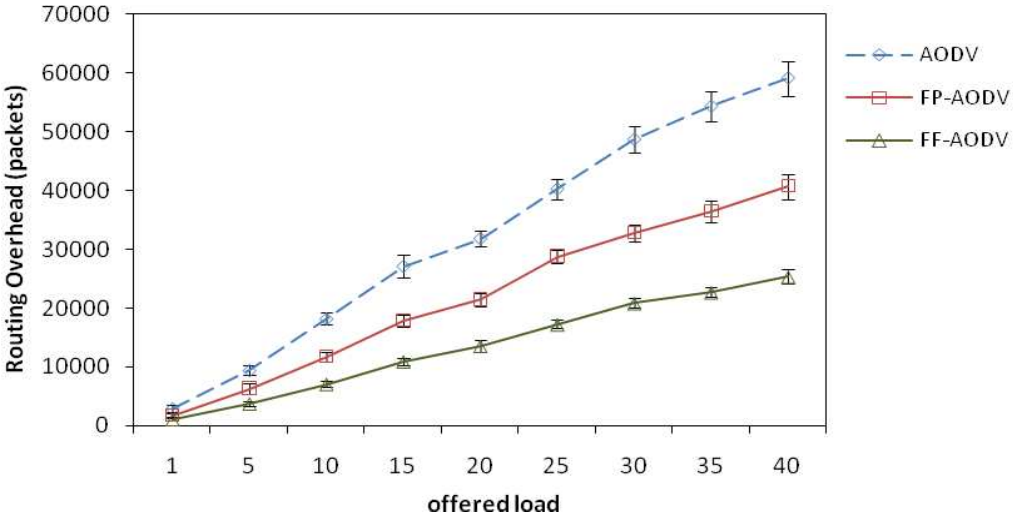


Figure 4.9. Routing overhead versus offered load for a network of 150 nodes placed in 1000m x 1000m area.

Collision Rate:

The results presented in Figure 4.10 show the performance behaviour of the three routing protocols in terms of average collision rate versus the offered load. The figure reveals that when the offered load is increased, the average collision rate of all the three routing protocols is also increased. This is because, when the offered load is increased, the number of RREQ packets generated and disseminated is also increased. Consequently, the probability of two or more nodes transmitting at the same time within the same transmission range is increased which leads to an increase in the collision rate. However, for a given offered load, the average collision rate of FF-AODV is much lower compared with FP-AODV and AODV. For example at an offered load of 40, the collision rate in FF-AODV is reduced by approximately 70% and 200% when compared with the FP-AODV and AODV respectively.

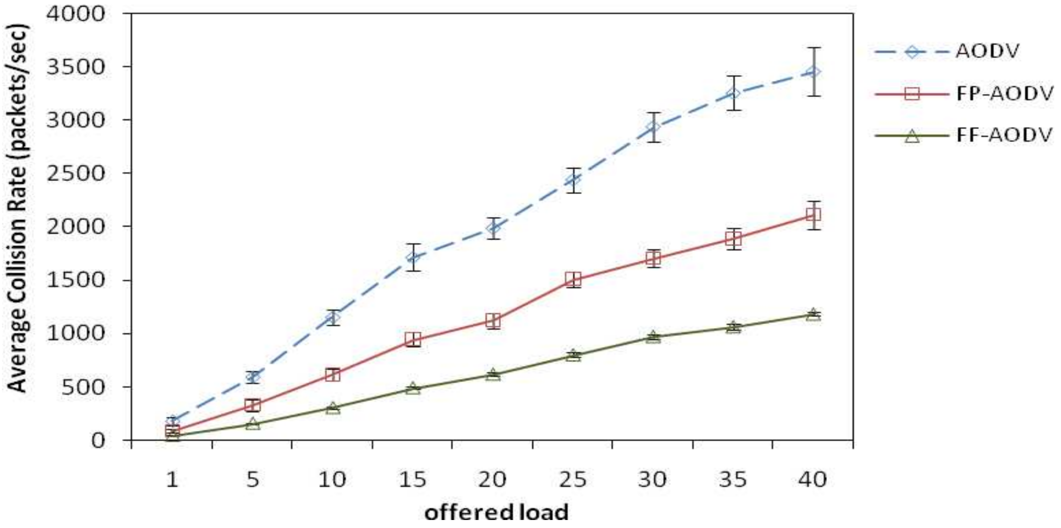


Figure 4.10. Average collision rate versus offered load for a network of 150 nodes placed in 1000m x 1000m area.

Normalised Network Throughput:

Figure 4.9 reports the results of the network throughput versus offered load for all the three routing protocols. It can be noticed in the figure that the normalised throughput achieved by the three protocols degrades as the offered load increases. The figure also shows that the performance difference of the three routing protocols becomes more noticeable when the offered load is increased. This is because at high offered loads, most of the generated data packets are dropped resulting from collisions and channel contention caused by a high congestion level. For example, at 40 flows, the normalised network throughput in FF-AODV is increased by an average of up to 15% and 36% when compared with the FP-AODV and AODV respectively.

Figure 4.12 shows that as the offered load increases the connectivity success ratio for each of the protocols decreases. For example, when the offered load is set low (e.g. 1 flow), the connectivity success ratio reaches a maximum of 79%, 75% and 73% in FF-AODV, FP-AODV and AODV respectively. On the other hand, when the offered load is set high (e.g. 40 flows), the connectivity ratio of the routing protocols, FF-AODV, FP-AODV and AODV is dropped to around 58%, 54% and 46% respectively.

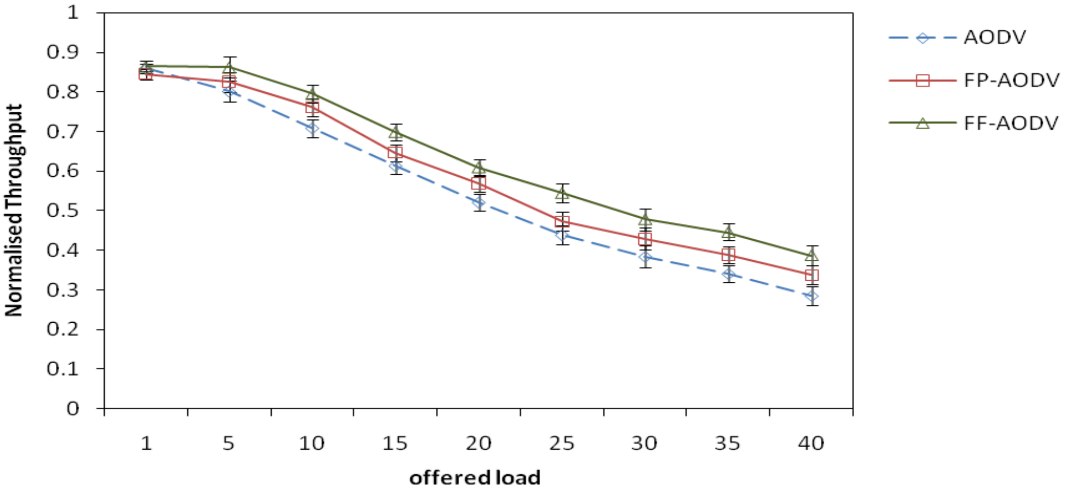


Figure 4.11. Network throughput versus offered load for a network of 150 nodes placed in 1000m x 1000m area.

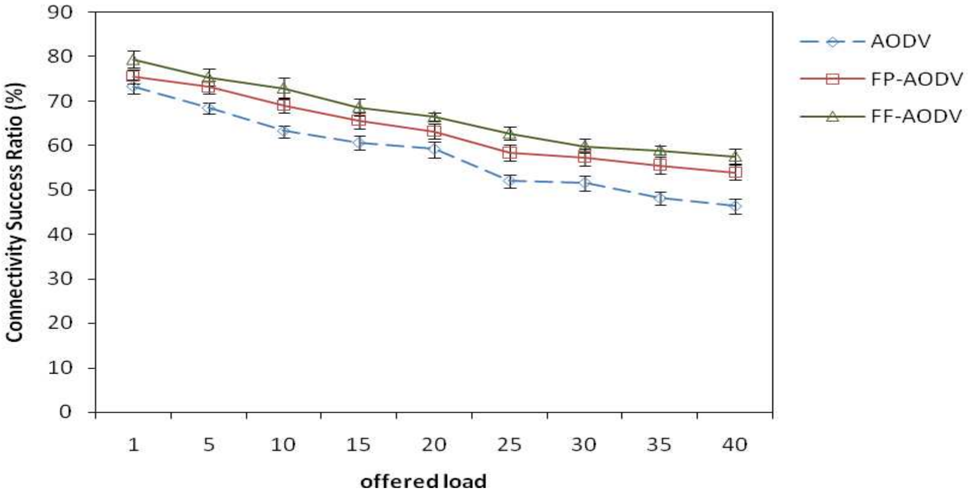


Figure 4.12. Connectivity success ratio versus offered load for a network of 150 nodes placed in 1000m x 1000m area.

End-to-End Delay:

Figure 4.13 shows the impact of offered load on the performance of the routing protocols in terms of end-to-end delay. The figure shows that the delay incurred by FF-AODV is shorter and comparable to those in FP-AODV and AODV when the offered load is less than 20 flows. This is because the congestion level is relatively low. However, the performance difference among the three protocols is noticeable at offered loads greater than 25 flows. For example, at offered load of 40 flows, the delay incurred by FF-AODV is reduced by approximately 22% and 41% when compared against FP-AODV and AODV respectively.

In Figure 4.14, the route discovery delay is plotted against the offered load. As shown in the figure, the route discovery delay increases with increased channel contention and packet collisions resulting from the increased number of source-destination pairs. Across the offered loads, the FF-AODV achieved the shortest delay compared with the FP-AODV and AODV.

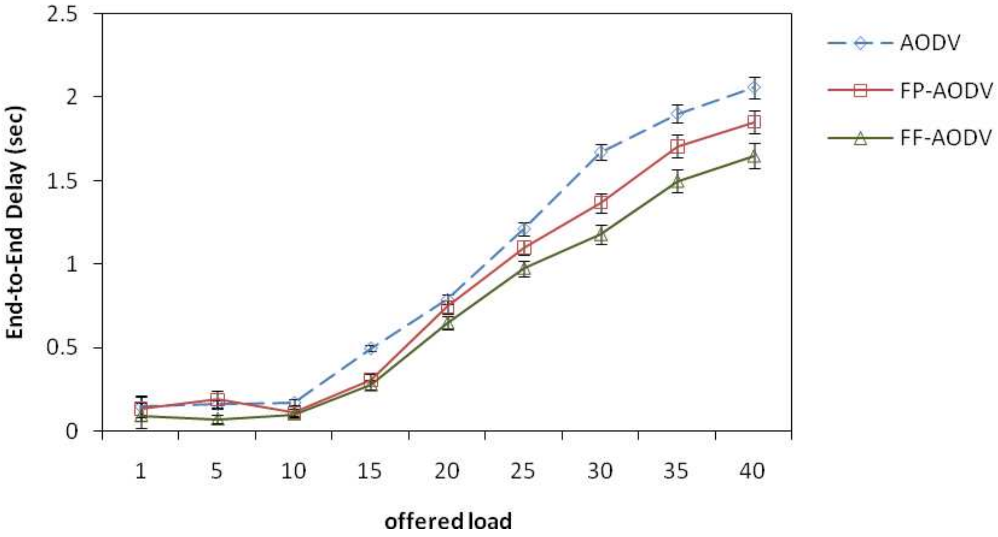


Figure 4.13. End-to-end delay versus offered load for a network of 150 nodes placed in 1000m x 1000m area.

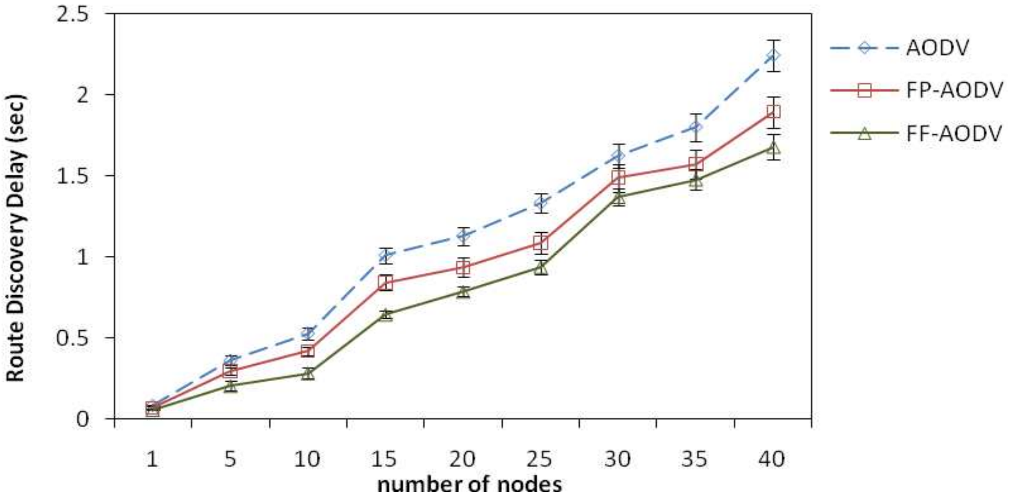


Figure 4.14. End-to-end delay versus offered load for a network of 150 nodes placed in 1000m x 1000m area.

4.3.3 Impact of Node Mobility

To evaluate the effects of node mobility on the performance of the three protocols, different maximum node speeds in the network have been considered. The speeds are chosen over a range in order to simulate human slow walk speed and vehicular speed. The speeds ranging from 1m/sec to 5m/sec are assumed to model human movements from a slow walk to a fast run while the speeds ranging from 10m/sec to 25m/sec are assumed to model vehicular motion, from slow movements in urban areas to fast movements on highways. Each simulation run consists of a network of 150 nodes placed over a simulation area of 1000m x 1000m. The offered load has been fixed at 10 flows.

Routing Overhead:

In Figure 4.15, the routing overhead generated by the three routing protocols is plotted against the maximum node speed. As shown in the figure, the routing overhead generated by each of the routing protocols increases as the node mobility increases. This is due to the fact that when the node mobility is increased the frequency of topology changes is also increased. This can potentially trigger more new route maintenance processes, resulting from the broken routes. As a consequence larger numbers of RREQ packets are generated and disseminated.

However, the results in the figure show that FF-AODV has a clear performance advantage over the AODV and FP-AODV across all node speeds. By focusing the dissemination of the RREQ packets on the anticipated location of the destination, the FF-AODV has significantly reduced the routing overhead by approximately 58% and 130% when compared against the FP-AODV and AODV respectively at relatively high node mobility (e.g. 25m/sec)

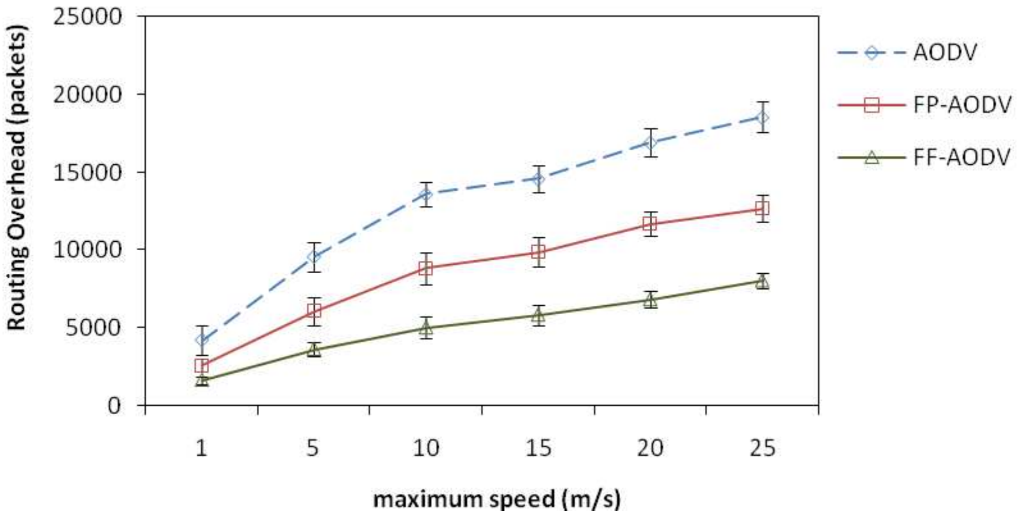


Figure 4.15. Routing overhead versus node mobility for a network of 150 nodes placed in 1000m x 1000m area.

Collision Rate:

Figure 4.16 shows the results of the three routing protocols in terms of collision rate versus the maximum node speed. The figure shows that the average collision rate for each of the protocols increases as the node mobility increases. This is because when the node mobility increases, the number of RREQ packets generated and disseminated in the network is also increased; thus the probability of two or more nodes in the same range transmitting at the same time is also increased. Consequently, the number of MAC collisions is increased.

The results in Figure 4.16 also depict that for a given maximum node speed, FF-AODV performs better than AODV and FP-AODV. For example, at a low speed of 1m/sec, the collision rate of FF-AODV can be reduced by approximately 94% and 295% when compared with FP-AODV and AODV respectively. This is because the number of nodes transmitting the RREQ packets during the route maintenance phase is significantly reduced in FF-AODV. As a consequence, the number of collisions per second is reduced.

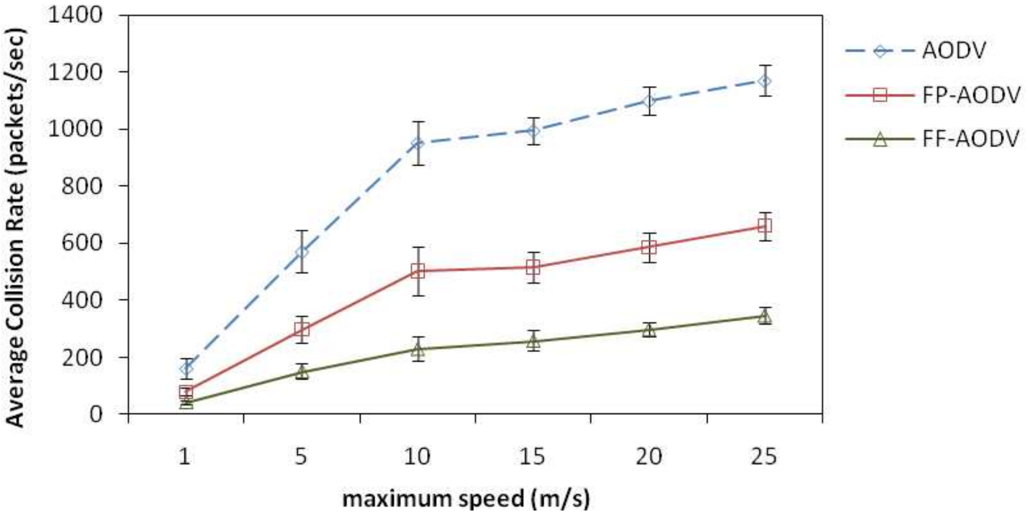


Figure 4.16. Average collision rate versus node mobility for a network of 150 nodes placed in 1000m x 1000m area.

Normalised Network Throughput:

Figure 4.17 depicts the achieved normalised network throughput versus node mobility for the three routing protocols. The figure shows that the normalised throughput achieved by each of the three protocols degrades as the maximum node speed increases. This performance behaviour is due to the high rate of collisions exhibited by the protocols when more RREQ packets are generated and disseminated throughout the network. Moreover, when the collision rate increases some of the generated RREQ packets fail to reach their destinations, which cause some of the data packets waiting at the interface queues to be dropped. The figure also shows that for a given node speed, the FF-AODV slightly outperformed the AODV and its fixed probabilistic variant by as much as 26% and 10% respectively.

The connectivity success ratio of the three routing protocols is reported in Figure 4.18. Like the throughput, the connectivity success ratio decreases as the mobility increases. This is due to the increase in the number of RREQ packets disseminated and the associated number of collisions in the network when the mobility increased (see Figures 4.15 and 4.16)

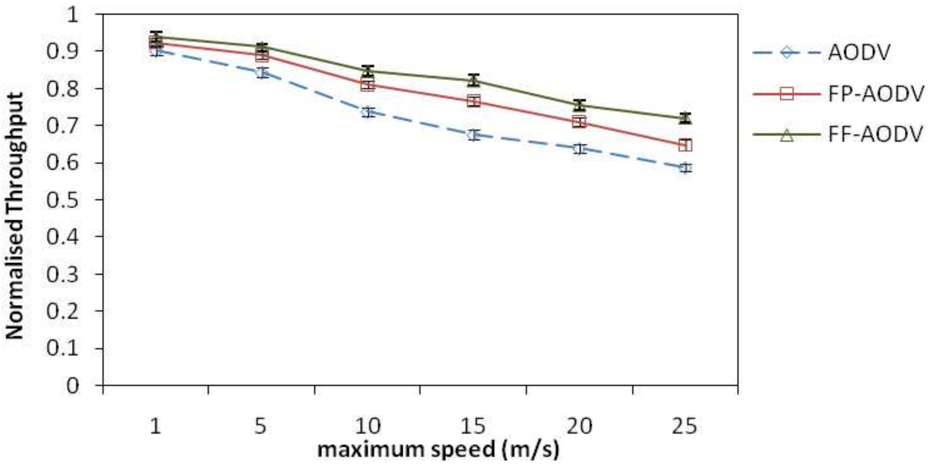


Figure 4.17. Network throughput versus node mobility for a network of 150 nodes placed in 1000m x 1000m area.

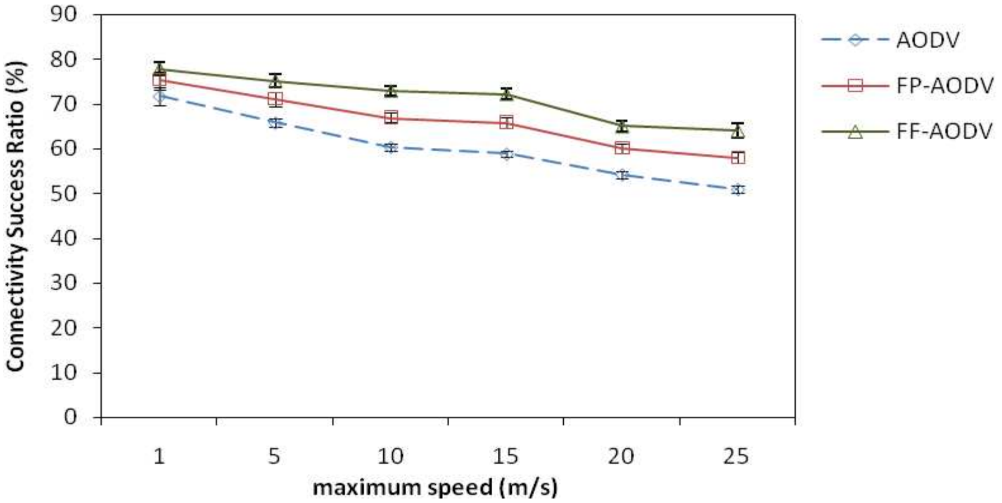


Figure 4.18. Connectivity success ratio versus node mobility for a network of 150 nodes placed in 1000m x 1000m area.

End-to-End Delay:

The results in Figure 4.19 depict the impact of node mobility on the performance of FF-AODV, FP-AODV and AODV in terms of end-to-end delay. As shown in Figures 4.15 and 4.16, the number of RREQ packets generated and disseminated in the network has a significant impact on packet collisions. If the collision rate is high, more RREQ packets fail to reach their destinations, which caused the number of retransmissions to increase. This in turn increases the route discovery latency as shown in Figure 4.20. As a consequence the end-to-end delay of the data packets waiting at interface queues for paths to be established is increased.

The figure also shows the performance of FF-AODV is comparable with that of FP-AODV when the mobility is relatively low. However, in a relatively high mobility (e.g. 20m/s) the FF-AODV outperforms both the FP-AODV and AODV by as much as 28% and 60% respectively.

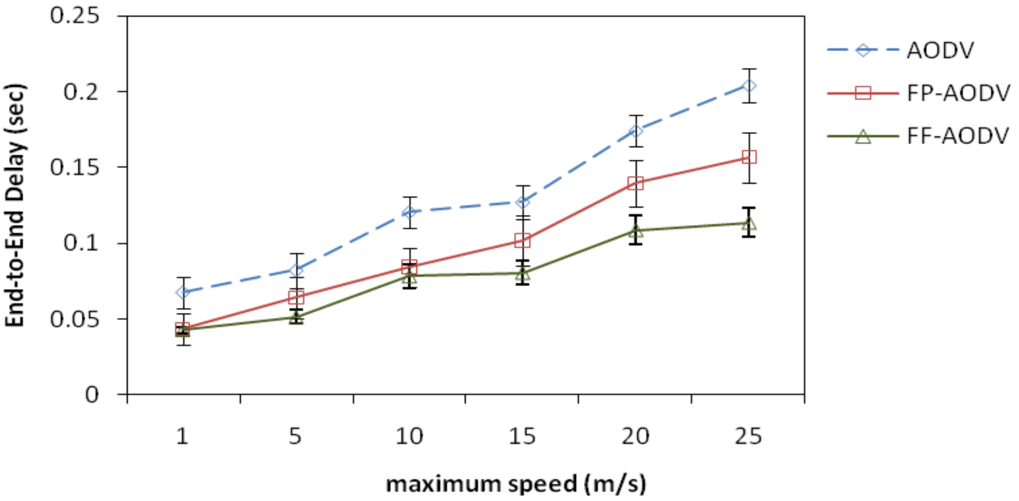


Figure 4.19. End-to-end delay versus node mobility for a network of 150 nodes placed in 1000m x 1000m area.

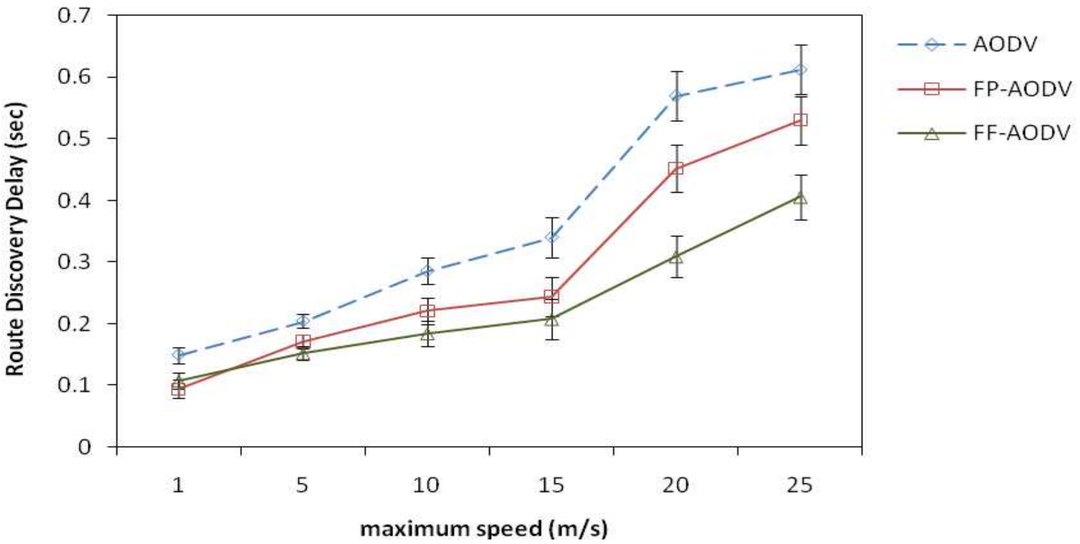


Figure 4.20. Route discovery delay versus node mobility for a network of 150 nodes placed in 1000m x 1000m area.

4.4 Conclusions

This chapter has presented a new probabilistic route discovery approach which combines the elements of fixed probabilistic and flooding-based route discovery approaches. This approach utilises routing histories at mobile nodes to limit the dissemination of RREQ packets towards the anticipated location of the destination. The Ns-2 implementation of the AODV routing protocol has been modified to incorporate the new probabilistic route discovery which has been referred to in this chapter as the Fixed probabilistic and Simple Flooding (FF-AODV, for short).

Numerous simulation runs have been conducted on the FF-AODV routing protocol and the performance results have been compared against those of the traditional AODV and its fixed probabilistic variant, namely FP-AODV. The performance analysis has been conducted under different network operating conditions. Firstly, the impact of network density on the performance of the routing protocols is assessed by varying the number of nodes placed in a fixed topology area. Secondly, the impact of offered load on the performance of the routing protocols is assessed by varying the number of source-destination pairs. Finally, the performance analysis of the routing protocols has been conducted under varying node mobility by varying the maximum node speed in the network.

The first part of the performance analysis which considered the impact of the network density has shown that the new FF-AODV outperforms the traditional AODV and FP-AODV in terms of routing overhead, average collision rate, normalised network throughput and end-to-end delay in most considered cases of network density.

In the second performance analysis, which has considered varying the offered load in the network, a similar superior performance of FF-AODV over AODV and FP-AODV in terms of routing overhead, average collision rate throughput and delay has been noticed.

The third part of the performance analysis which has considered the effects of node mobility on the performance of the protocols has revealed that FF-AODV performs better than AODV and FP-AODV in most of the performance metrics for low and high mobility scenarios. Although the achieved network throughput for all three routing protocols degrades with increased node mobility, the proposed FF-AODV achieves a relatively better network throughput in high mobility settings as it manages to reduce channel contention and packet collisions by reducing the routing overhead.

Chapter 5

Adjusted Probabilistic Route Discovery

5.1 Introduction

The network topology in MANETs is highly dynamic due to node movement and nodes joining and leaving the network [37]. As a consequence, the node distribution is often random and changes frequently. Therefore, the forwarding probability p for the probabilistic dissemination of broadcast packets should be set dynamically to reflect the local topological characteristics of a given node; e.g. whether the node is located in a sparse or a dense region [77, 106].

As has been discussed in Chapters 3 and 4, the routing overhead associated with the route discovery process of a traditional on-demand routing protocol, e.g. AODV [7], can be significantly reduced by allowing each node in the network to rebroadcast a received RREQ packet with a given probability. In the case of the fixed probabilistic route discovery approach, the forwarding probability at a given node is fixed regardless of its local topological characteristics. However, to achieve a significant reduction of the routing overhead without degrading network throughput, the forwarding probability p should be set high for a sparse network and low for a dense network. This is because if p is set low for a sparse network, the network may suffer from poor network connectivity (see Figures 4.5 and 4.6). As a consequence, the network throughput degrades. On the other hand, if p is set high for a dense network, the network may suffer from the broadcast storm problem [49, 50] which often results in increased channel contention and packet collision at the MAC layer [77].

In order to strike a fair balance between the tradeoffs of ensuring a reduction of the broadcast storm problem and maintaining acceptable levels of network connectivity for a given network topology, the forwarding probability at a node should be dynamically adjusted. To achieve this, a new adjusted probabilistic route discovery approach (AP for short) is proposed in this chapter. The proposed adjusted probabilistic approach exploits the neighbourhood information available to a node in order to adjust the forwarding probability. Compared with FF-AODV, the traditional AODV [7] and its fixed probabilistic counterpart, simulation results will show that the new adjusted probabilistic approach for route discovery can improve various performance metrics, including routing overhead, MAC collisions, network throughput and end-to-end delay, for various network sizes and network operating conditions.

The rest of the chapter is organised as follows. Section 5.2 describes in detail the proposed adjusted probabilistic route discovery approach and presents the algorithm. Section 5.3 analyses the effects of network operating conditions on the performance of the proposed probabilistic route discovery algorithm. Finally, Section 5.4 concludes the chapter.

5.2 Adjusted Probabilistic Route Discovery Algorithm

In the traditional AODV [7], an intermediate node rebroadcasts all RREQ packets that have been 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 broadcasts of an RREQ packet in AODV is $N-2$. In the fixed probabilistic route discovery, the number of possible broadcasts of an RREQ packet is $p \times (N-2)$.

5.2.1 Neighbour Density

In a network of random distribution of mobile nodes as in MANETs, there are regions of varying degrees of node density (e.g. sparse and dense regions). Therefore the fixed probabilistic approach suffers from an unfair distribution of p, since every node is assigned 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.

A node in a dense network should be assigned a low forwarding probability in order to reduce the broadcast redundancy. On the other hand, a node in a sparse network should be assigned a relatively high forwarding probability. To achieve this, the neighbourhood information at each node is used based on the existing “hello” protocol implementation in the AODV.

In the “hello” protocol, every node periodically broadcasts “hello” (i.e. the node’s identification) packet to its immediate neighbours. Each node upon receiving the “hello” packets constructs a 1-hop neighbour list. Hello intervals of 1 second have been considered for the protocol as recommended in the AODV RFC [7].

Figure 5.1 shows connectivity success ratio of traditional AODV verses network density (i.e. varying number of nodes placed in a fixed area of 1000m x 1000m) for different transmission ranges. The figure shows the connectivity success ratio of the transmission ranges first increases as the number of nodes increase, and then it reaches a maximum and decreases as the number of nodes increases. As shown in Figure 5.1, the number of nodes at which the connectivity success ratio is at a maximum are 70, 115 and 195 for transmission ranges 250m, 200m and 150m, respectively. To estimate the network density of each of the scenarios, the average number of neighbours at a node in each of the network is determined.

Let A be the area of the ad hoc network, N be the number of mobile nodes deployed in the network, and R the signal transmission range of each node. The average number of neighbours at a node, n_f in the network can be obtained by using the following formula:

$$n_f = (N-1)\frac{\pi R^2}{A} \qquad 5.1$$

Using equation 5.1 and a network area of 1000m x 1000m, the average number of neighbours at a node in a network with (70 nodes and 250m transmission range), (115nodes and 200m transmission range) and (195nodes and 150m transmission range) has been found to be around 14 nodes. Therefore on average, a node is considered to be in a dense network when its number of number of neighbours is $n > 14$ and in a sparse network otherwise.

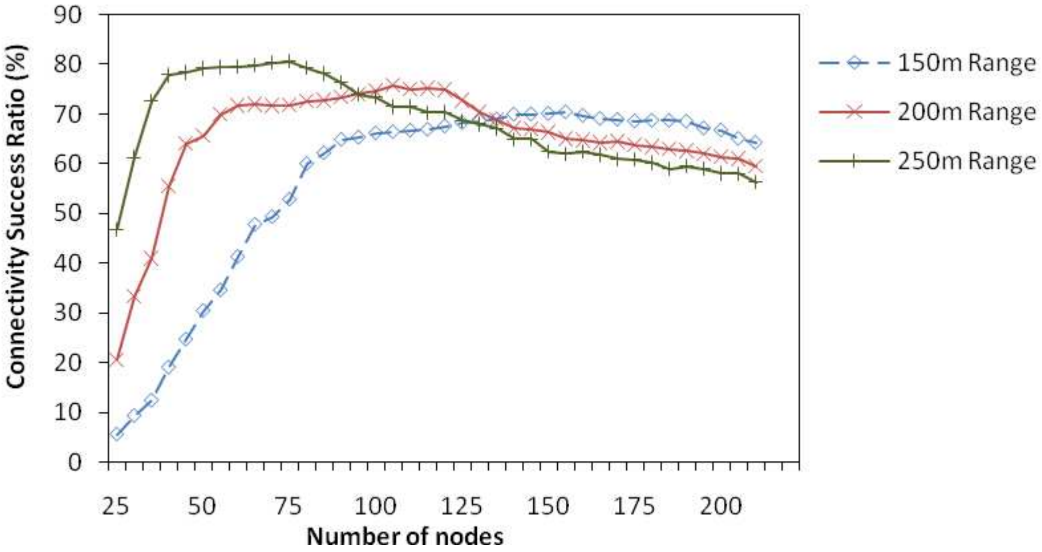


Figure 5.1. Network connectivity success ratio versus network density for different transmission ranges.

5.2.2 Forwarding Probability in the Adjusted Probabilistic Route Discovery

In the new AP algorithm, a given node is assigned a forwarding probability according to its local density, measured by the number of neighbours at the node. Using the new AP algorithm, Table 5.1, shows four nodes **A**, **B**, **C** and **D** and their forwarding probabilities. The number of neighbours at nodes **A**, **B**, **C** and **D** are 10, 20, 30, and 40 respectively. Using the average neighbour density for the boundary between the sparse and dense network, $n_f = 14$ determined in Section 5.2.1, the nodes are categorized in different degrees of network densities. Each row in the table represents a category number of a forwarding node and its corresponding forwarding probability at the node. Each category is defined by the number neighbours at a forwarding node and $n_f = 14$. A tick on a row indicates that the node on the corresponding column belongs to the category on the row.

Node **A** is assumed to be located in a relatively sparse network since the number of its neighbours is $n < 14$ (i.e. in category $i = 0$), therefore node **A** is assigned a forwarding probability of $p = 1$ (i.e. simple flooding).

Since the number of neighbours at nodes **B**, **C** and **D** are all larger than the 14, (i.e. $B(n), C(n), D(n) > n_f$), the AP algorithm has categorised them to be located in relatively dense networks and therefore each is assigned a forwarding probability, $p \leq p_f < 1$. Node **B** is the next highest in terms of number of neighbours which is between n_f and $2n_f$, and so it is assigned the next lowest forwarding probability of $p = p_f$. Node **C,** whose number of neighbours is between $2n_f$ and $3n_f$ is assigned the next lowest probability of $p = p_f / 2$, and so on.

Figure 5.2 depicts the forwarding probability at a node using the AP algorithm versus the number of neighbours at the node for $p_f = 0.7$. The value of $p_f = 0.7$ has been chosen for the performance analysis of the AP algorithm because when used in AP, it will achieve a relatively high network connectivity success ratio with relatively low routing overhead. As shown in Figures 5.4 and 5.5, using forwarding probabilities lower than 0.7, will generate relatively low routing overhead, but will achieve low network connectivity. On the other hand, when probabilities greater than 0.7 are used, they will generate a relatively high routing overhead and achieved network connectivity comparable to that of 0.7. In Figure 5.3, an outline of the new route discovery algorithm is presented.

Table 5.1. Categories of forwarding nodes and the corresponding forwarding probabilities.

		Number of neighbours (*n*)				
Category Number	**Neighbour Category** $n_f = 14$	**A (10)**	**B (25)**	**C (40)**	**D (55)**	**Forwarding Probability (p)**
$i = 0$	$n \leq n_f$	√	X	X	X	$p = 1$
$i = 1$	$n_f < n \leq 2n_f$	X	√	X	X	$p = p_f$
$i = 2$	$2n_f < n \leq 3n_f$	X	X	√	X	$p = \frac{p_f}{2}$
$i = 3$	$3n_f < n \leq 4n_f$	X	X	X	√	$p = \frac{p_f}{3}$
-	-	-	-	-	-	-
-	-	-	-	-	-	-
$i = r$	$rn_f < n \leq (r+1)n_f$	X	X	X	X	$p = \frac{p_f}{r}$

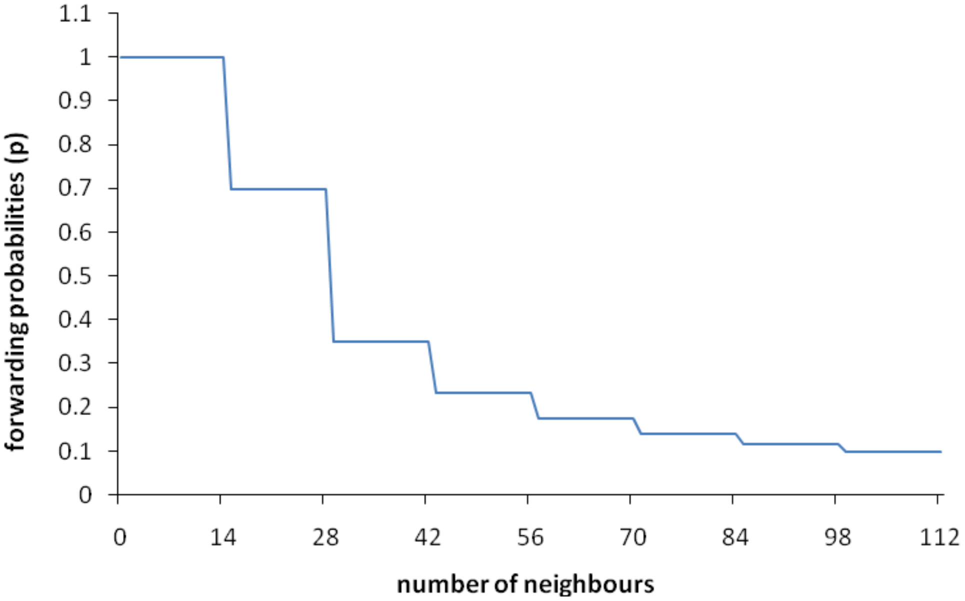


Figure 5.2. A graph forwarding probability at a forwarding node versus number of neighbours at the node.

Algorithm: AP-AODV

```
Upon receiving an RREQ packet at node x
Get the number of neighbours n at node x
Set the category number, $i = 0$
If (the RREQ packet is received for the first time)
  While ($i \geq 0$)
      If ($n \leq n_f$)
           Node x is in a sparse network (i.e. Category: i = 0)
          Set rebroadcast probability to high: $p \to 1$
          Exit the Loop
      else If ($(i+1) \times n_f < n \leq (i+2) \times n_f$)
            Node x is a relatively dense network (i.e. Category $i+1$)
            Set rebroadcast probability to high : $p \to \frac{p_f}{i+1}$
            Exit the Loop
      end If
      $i \to i+1$
   end While
      Generate a random number Rnd over the range [0, 1]
      If ( $Rnd \leq p$ )
           Rebroadcast the RREQ packet
      else
          drop the RREQ packet
      end If
else If (the RREQ is a duplicate received)
     drop the RREQ packet
end If
```

Figure 5.3. A brief outline of the AP-AODV route discovery algorithm.

5.3 Performance Analysis

To evaluate the performance of the AP algorithm for route discovery process, the implementation of the AODV routing protocol in the Ns-2 simulator [113] has been modified to incorporate the functionality of the AP algorithm. In what follows, the modification of the traditional AODV is referred to as AP-AODV. The simulation results of AP-AODV are compared against the FF-AODV (in Chapter 4), the traditional AODV and its fixed probabilistic variant, FP-AODV.

The simulation model and system parameters in section 3.2 have been repeated in this section for the performance evaluation of the proposed adjusted probabilistic route discovery.

5.3.1 Initial probability (P_f)

The first set of simulation studies in this chapter investigates the initial probability threshold value p_f to be used for the performance analysis of AP-AODV. To select a suitable initial threshold probability for the proposed protocol, several runs of simulations have been conducted over the different probability values ranging from 0.1 to 0.9, using the AP-AODV as the base routing protocol.

Figure 5.5 depicts the routing overhead generated by AP-AODV and Figure 5.4 reports the network connectivity success ratio achieved for different initial probability values when the network density is varied from25 to 225 nodes. The results in the Figures reveal that, both the generated routing overhead and the network connectivity success ratio of AP-AODV increase with increased initial probability. However, as can be seen in the figure, the network connectivity success ratio achieved by AP-AODV for probabilities greater than 0.6 are significantly comparable, even though the routing overhead continues to increase for probabilities greater than 0.6. To balance the trade-off that exists between reducing the routing overhead in the network and the achieving a good network connectivity success ration, as well as the initial probability value and network density, an initial probability value of 0.7 has been adopted for the subsequent performance analysis of AP-AODV.

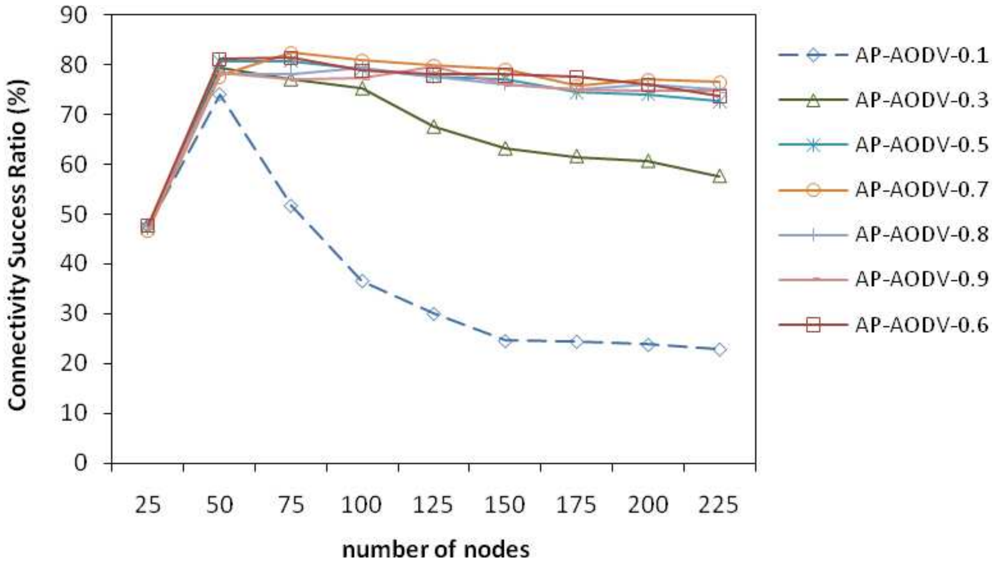


Figure 5.4. Network connectivity success ratio versus network density for different initial forwarding probabilities in AP-AODV.

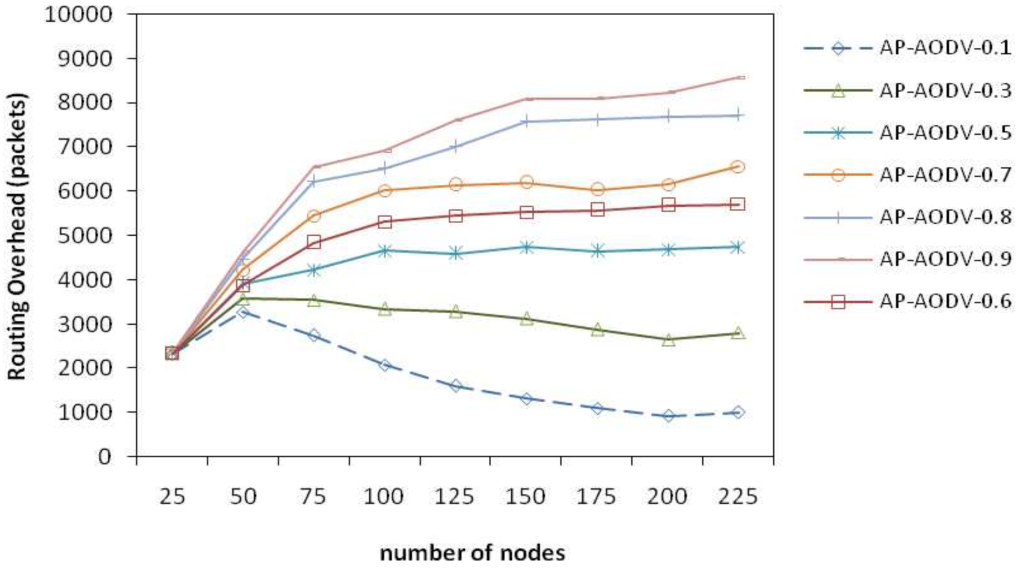


Figure 5.5. Routing overhead versus network density for different initial forwarding probabilities in AP-AODV.

5.3.2 Impact of Network Density

In this section, the performance impact of network density on the four protocols is examined. The network density has been varied by changing the number of nodes deployed over a 1000m x 1000m area in each simulation scenario. Each node moves with a random speed between 0 and 20m/sec. For each simulation trial, 10 identical randomly selected source-destination connections (i.e. traffic flows).

Routing Overhead:

Figure 5.6 shows the performance of the four routing protocols in terms of routing overhead versus network density. As shown in the figure, the routing overhead generated by AP-AODV is relatively high when compared against FF-AODV and FP-AODV in a sparse network. This is because in a sparse network most of the forwarding nodes using AP-AODV are allowed to retransmit the received RREQ packets in order improve the connectivity success ratio. However in a dense network AP-AODV performs better than FF-AODV, FP-AODV and AODV by reducing the routing overhead by as much 56%, 211% and 335% respectively.

These reductions could be explained by the fact that when the forwarding probability at a node is set according to the local density of the forwarding node, the number of redundant retransmissions of the RREQ packet can be significantly reduced, and as a consequence the overall routing overhead is reduced.

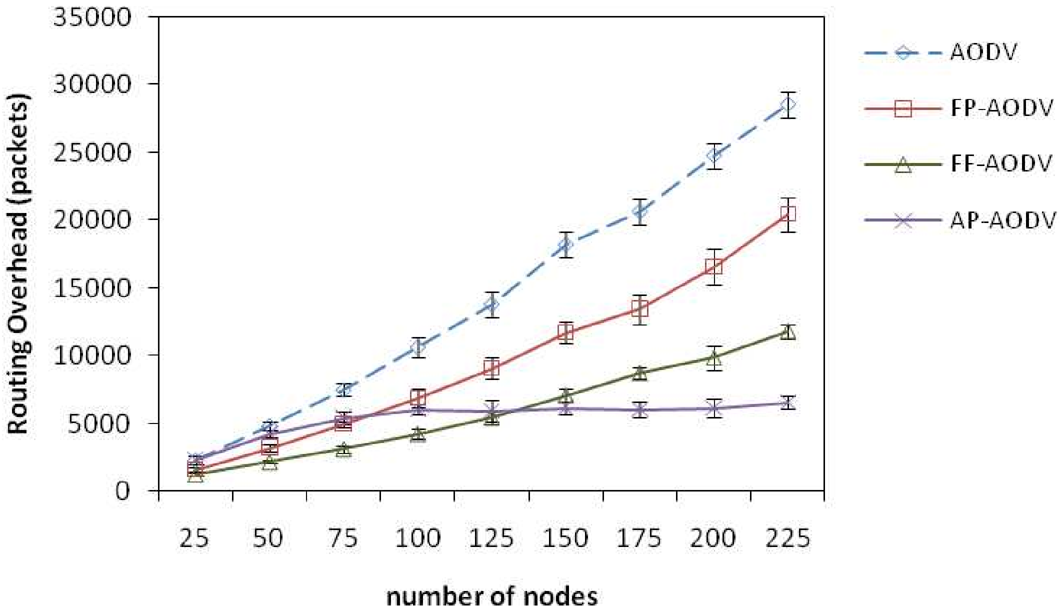


Figure 5.6. Routing overhead versus number of nodes placed over 1000m x 1000m area.

Collision Rate:

Figure 5.7 shows the average collision rate at the MAC layer versus the network density. When the network density is increased, the collision rate for each of the four routing protocols is increased. When the network density is low (e.g. 50 nodes), AP-AODV performed about 30% better AODV, and about 47% and 190% worse than FP-AODV and FF-AODV respectively. However, in a relatively dense network, AP-AODV has a clear performance advantage over the FF-AODV, AODV and FP-AODV by as much as 260%, 660% and 1160% respectively.

Since the RREQ packets are broadcast packets, they are transmitted only when the communication medium has been sensed idle. Therefore the transmission of RREQ packets is not in accordance with the request-to-send and clear-to-send protocol of the MAC layer [1]. As a consequence, when the number of nodes is increased, the probability of more than two nodes transmitting at the same time is increased which can lead to an increase in the number of packet collisions.

However, by using a probabilistic broadcast approach, some nodes are forced to suppress their broadcast which reduces the number of RREQ packets in the network. As a consequence the average collision rate is reduced

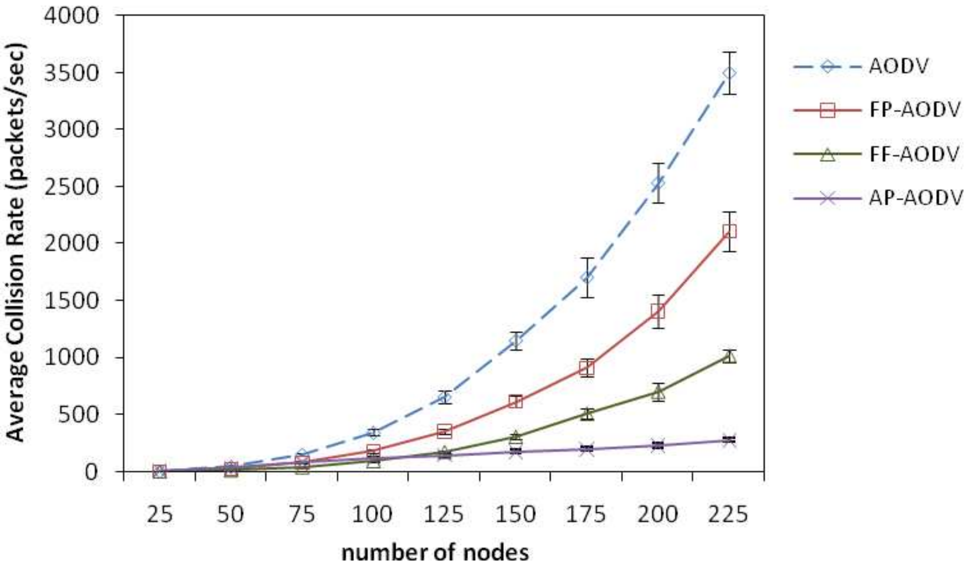


Figure 5.7. Average collision rate versus number of nodes placed over a 1000m x 1000m area.

Normalised Network Throughput:

Figure 5.8 depicts the achieved normalised network throughput of all the protocols against network density. The results show that the normalised throughput of each the four protocols first increases with increased network density, it reaches a maximum and reduces as the network density increases.

This is because at low network density (e.g. 50 nodes), the connectivity success ratio is low due network partitions (See Figure 5.9). At the low density, the FF-AODV performed worse compared with the AP-AODV, FP-AODV and AODV which together have comparable data delivery capacity. This is because the rebroadcast probability at a forwarding node in FF-AODV does not take into consideration the neighbour density.

However, when the network density is increased, the superiority of AP-AODV over FF-AODV, traditional AODV and FP-AODV becomes more noticeable. As can be seen in the figure, the normalised throughput achieved by AP-AODV is increased by around 20%, 50% and 100% when compared with FF-AODV, FP-AOV and AODV respectively in a dense network (e.g. 225 nodes). This is due to the reduction of routing overhead achieved by reducing the forwarding probability when the network density is increased, which frees some of the communication channel bandwidth for the transmission of actual data packets.

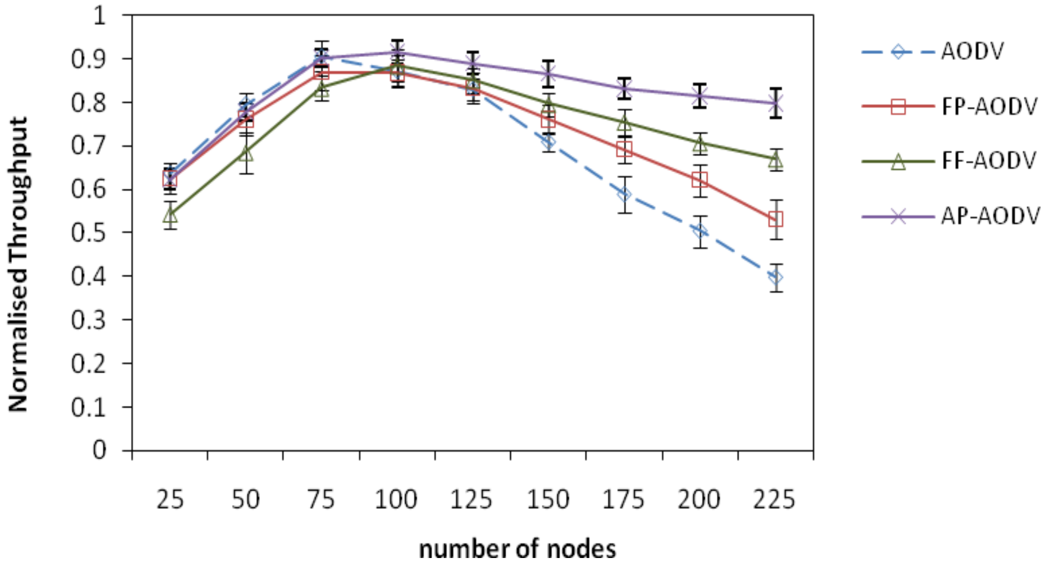


Figure 5.8. Network throughput versus number of nodes placed over a 1000m x 1000m area.

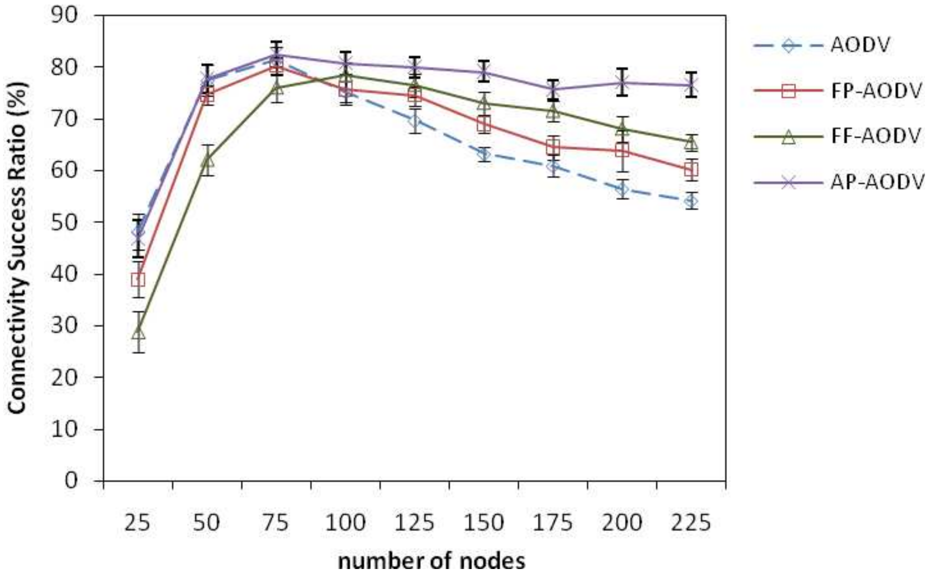


Figure 5.9. Network connectivity success ratio versus number of nodes placed over a 1000m x 1000m area.

End-to-End Delay:

Figure 5.10 demonstrates the effects of network density on the performance of all four protocols in terms of end-to-end delay. The results show that, in a relatively sparse network, the end-to-end delay of each of the protocols decreases as the network density increases. On the other hand, in a relatively dense network, the delay increases as the network density increases. This is because in a dense network, most of the originated RREQ packets fail to reach their destinations due to high probability of packet collisions and channel contention caused by excessive redundant retransmissions. This can potentially increase the route discovery delay, thus the time required for data packets to be transmitted from the source to destination nodes is increased.

The figure also reveals that in the case of a sparse network (e.g. 50 nodes) where the network is poorly connected, the end-to-end delay in all the protocols is longer. In this scenario, the probabilistic routing protocols are outperformed by the traditional AODV. For instance, at 50 nodes, the delay incurred by AODV is reduced by approximately 23%, 67% and 13% when compared against AP-AODV, FF-AODV and FP-AODV respectively. Similar performance behaviour is observed in terms of route discovery delay as shown in Figure 5.11.

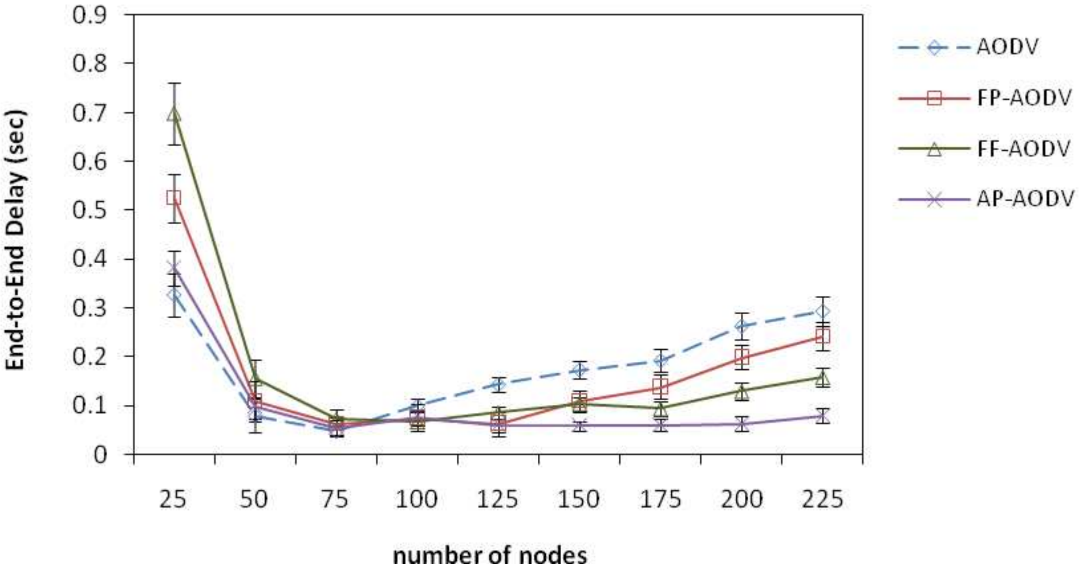


Figure 5.10. End-to-end delay versus number of nodes placed over a 1000m x 1000m area.

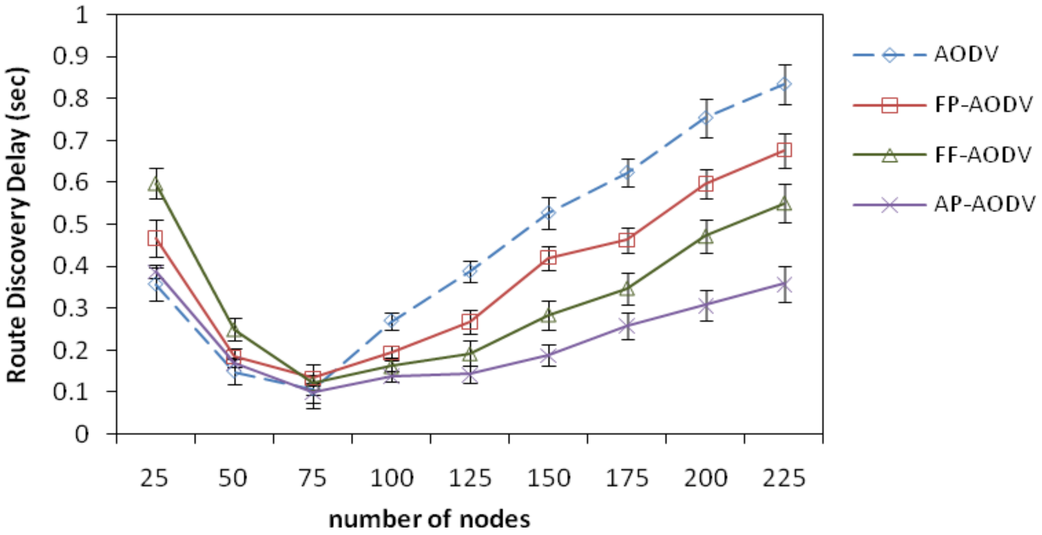


Figure 5.11. Route discovery delay versus number of nodes placed over a 1000m x 1000m area.

5.3.3 Impact of Offered Load

The section above has considered the case of a fixed offered load of 10 source-destination pairs over different network densities. To evaluate the impact of offered load on the performance of the four routing protocols, this section has considered various numbers of source-destination pairs (flows, for short) over 150 nodes placed in a 1000m x 1000m area. Each node moves with speed randomly chosen between 1 and 20m/s. The number of flows has been varied over the range 1, 5, 10, …, 40.

Routing Overhead:

The results in Figure 5.12 show the performance of the four routing protocols in terms of routing overhead versus offered load. The figure shows that the generated routing overhead in each of the four routing protocols increases as the number of flows increases. The larger the number of source-destination connections there are in the network, the more RREQ packets are generated. For instance, when the number of connections is increased from 10 to 15, the routing overhead generated by AP-AODV, FF-AODV, FP-AODV and AODV is increased by approximately 85%, 89%, 85% and 93% respectively.

Figure 5.12 also reveals that the AP-AODV and FF-AODV have comparable performance level for different offered loads. However, they both outperform the AODV and FP-AODV in both light and relatively heavy offered load.

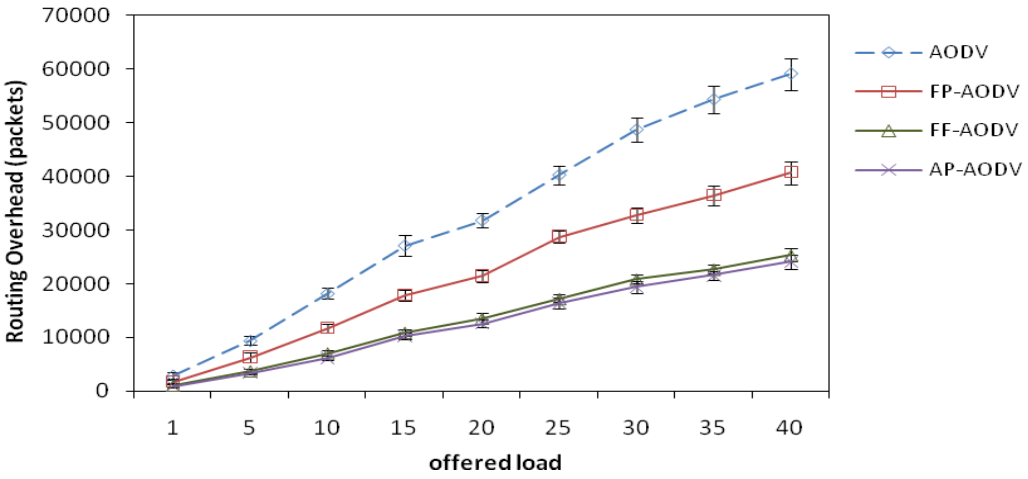


Figure 5.12. Routing overhead versus offered load for a network of 150 nodes placed in a 1000m x 1000m area.

Collision Rate:

In Figure 5.13, the average collision suffered by the network per unit simulation time for all the four routing protocols is plotted against the offered load. Like the generated routing overhead shown in Figure 5.12, the average collision rate increases almost linearly as the offered load increases. This is because when the offered load is increased by increasing the number of source-destination pairs, the number of RREQ packets generated and disseminated throughout the network is also increased. As a consequence, the probability of two or more nodes in the same coverage area transmitting at the same time is increased and hence the packet collision rate is increased. For example, when the offered load is increased from 1 to 5 flows (i.e. at a low offered load), the average collision rate of AP-AODV, FF-AODV, FP-AODV and AODV is increased by approximately 170%, 260%, 268% and 230% respectively.

The results in Figure 5.13 also reveal that AP-AODV followed by FF-AODV performs better than the FP-AODV and AODV for all considered offered loads. For instance, compared with the FF-AODV, FP-AODV and AODV, the average collision rate of AP-AODV is reduced by as much as 80%, 266% and 639% respectively when light offered load is used and about 40%, 148% and 306% respectively when heavy offered load (e.g. 40 flows) is used.

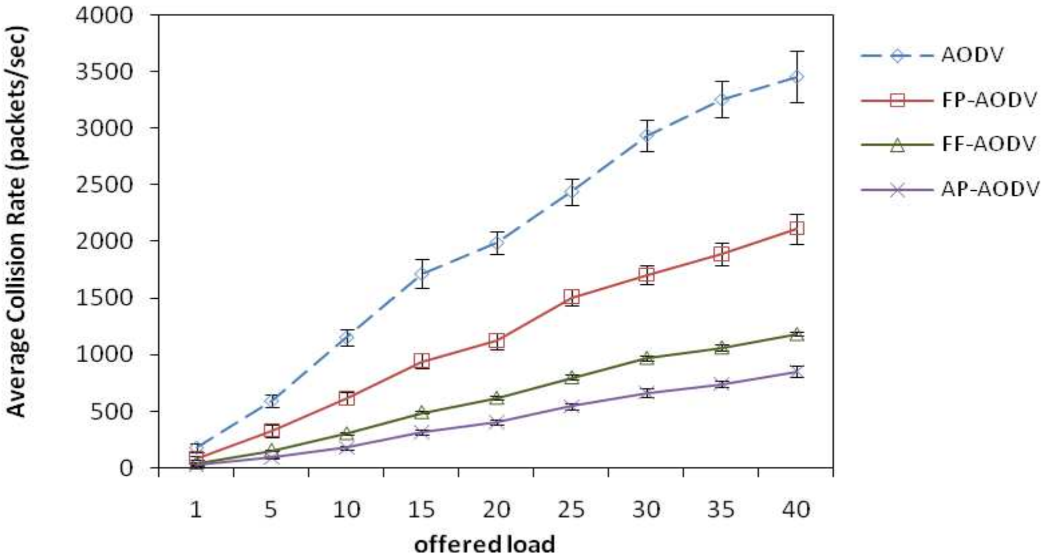


Figure 5.13. Average collision rate versus offered load for a network of 100 nodes placed in a 1000m x 1000m area.

Normalised Network Throughput:

Figure 5.14 shows the performance of the four routing protocols in terms of achieved normalised network throughput when the offered load is varied from 1 to 40 flows. The figure reveals that the normalised throughput of all the protocols decreases as the offered load increases. This is because when the number of flows is increased, the number of nodes initiating route discovery operations is also increased. As a consequence, more RREQ packets are generated and disseminated throughout the network. Consequently, the packet collisions and channel contention is increased, which reduces the available bandwidth for actual data the communication, thereby degrading the network throughput.

It can be noticed from Figure 5.14 that the superiority of AP-AODV over the other three versions of AODV becomes more noticeable in the case of a high offered load (e.g. 40 flows). For instance, at 40 flows the normalised throughput of AP-AODV is approximately 15%, 22% and 42% better than the FF-AODV, FP-AODV and AODV.

In Figure 5.15, the connectivity success ratio decreases as the offered load increases. This is because some of the generated RREQ packets failed to reach their respective destinations due to increased in the number of packet collisions when the number of source-destination pairs in the network is increased.

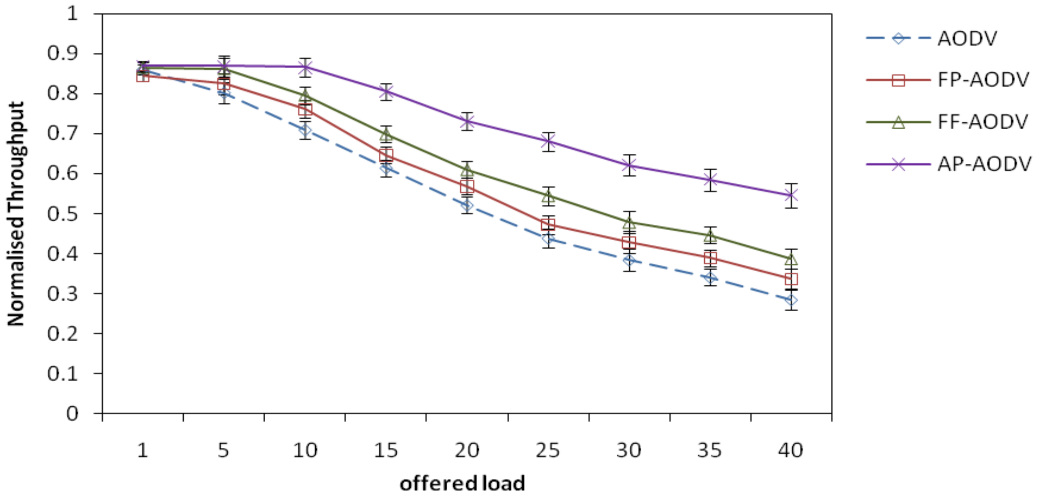


Figure 5.14. Network throughput versus offered load for a network of 150 nodes placed in a 1000m x 1000m area.

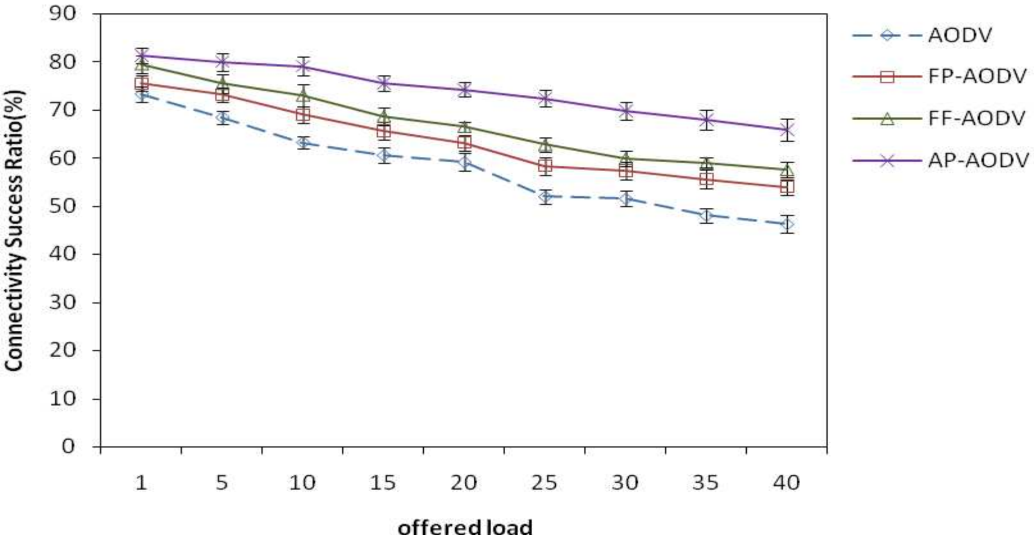


Figure 5.15. Network connectivity success ratio versus offered load for a network of 150 nodes placed in a 1000m x 1000m area.

End-to-End Delay:

Figure 5.16 shows the effects of offered load on the performance of the four routing protocols in terms of average end-to-end delay. The figure reveals that the end-to-end delay of each of the four protocols is slightly affected by increasing the offered load from 1 to 10 flows. However, the delay of each of the protocols increases sharply when the offered load is increased from 10 to 40 flows. This is because when the number of flows is larger than 10, the network generates more than an optimal number of routing control packets (e.g. RREQ packet), as a consequence the packet collisions and channel contention are increased. This phenomenon results in a significant increase of the end-to-end delay of the protocols. The figure also shows that the end-to-end delay of AP-AODV outperforms the FF-AODV, FP-AODV and AODV by approximately 30%, 46% and 73% respectively when the offered load is 40 flows.

In Figure 5.17, the route discovery delay of each of the four routing protocols is plotted against the offered load. The figure shows that the route discovery delay increases as the offered load increases.

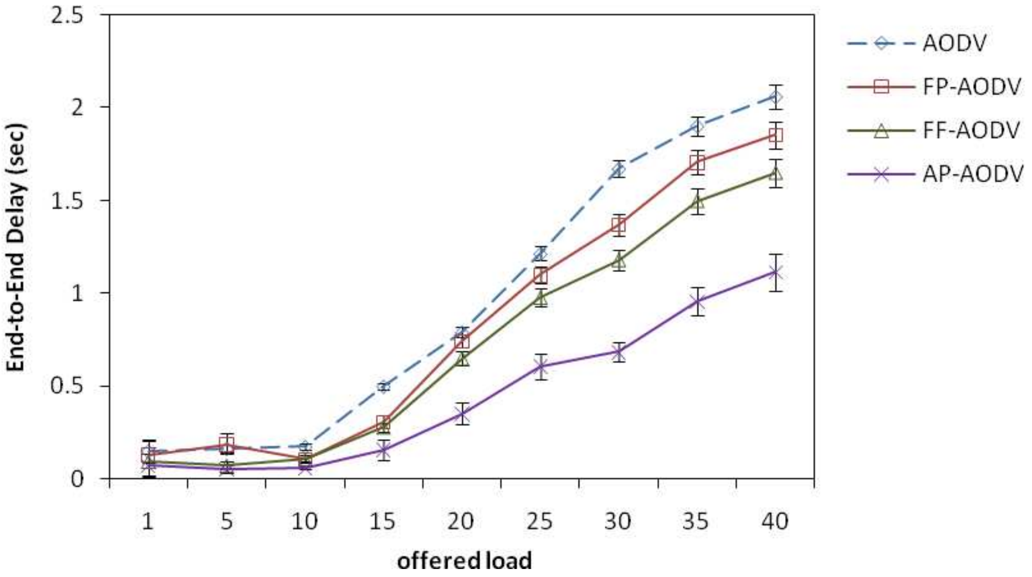


Figure 5.16. End-to-end delay versus offered load for a network of 150 nodes placed in a 1000m x 1000m area.

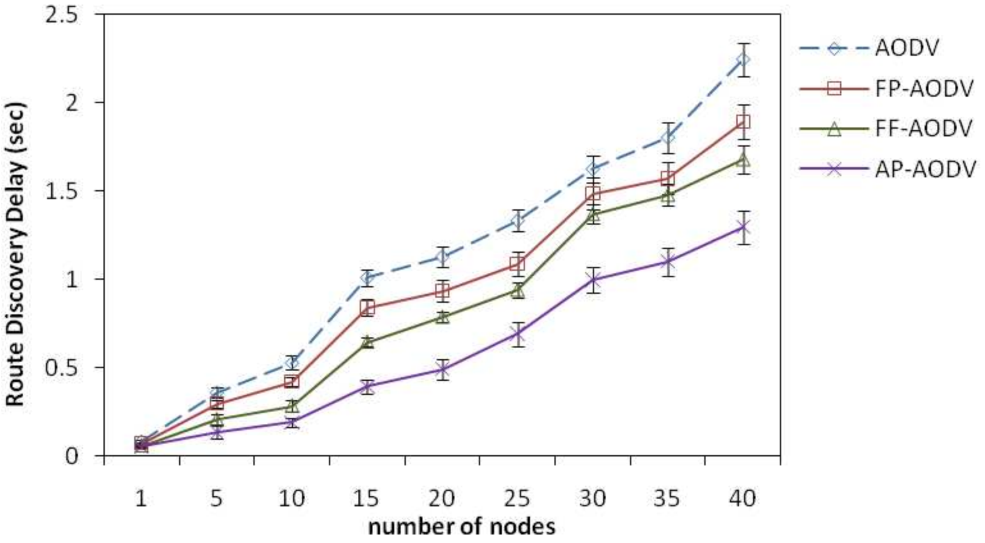


Figure 5.17. Route discovery delay versus offered load for a network of 150 nodes placed in a 1000m x 1000m area.

5.3.4 Impact of node mobility

This section presents the effects of mobility of nodes on the performance of the four routing protocols. The mobility of 150 nodes placed in a 1000m x 1000m area has been varied by changing the maximum node speed in the network from

1, 5, 10, …, 25m/sec. An offered load of 10 flows has been considered in each simulation scenario

Routing Overhead:

Figure 5.18 illustrates the routing overhead generated by AP-AODV, FF-AODV, FP-AODV and AODV when the mobility of nodes is varied. The figure reveals that the routing overhead generated by the four routing protocols increases with increased maximum node speed. This is because when node mobility increases, the existing paths in the network may be broken, as a consequence, more RREQ packets are generated and disseminated, which increases the routing overhead. For instance, the routing overhead of AP-AODV, FF-AODV, FP-AODV and AODV increases by approximately 70%, 120%, 135% and 127% respectively when the node mobility is increased from 1m/sec to 5m/sec.

The figure also shows that for low mobility (e.g. 1m/sec), the performance of AP-AODV is comparable to that of FF-AODV. However, at relatively high mobility, the AP-AODV outperforms the FF-AODV, FP-AODV and AODV.

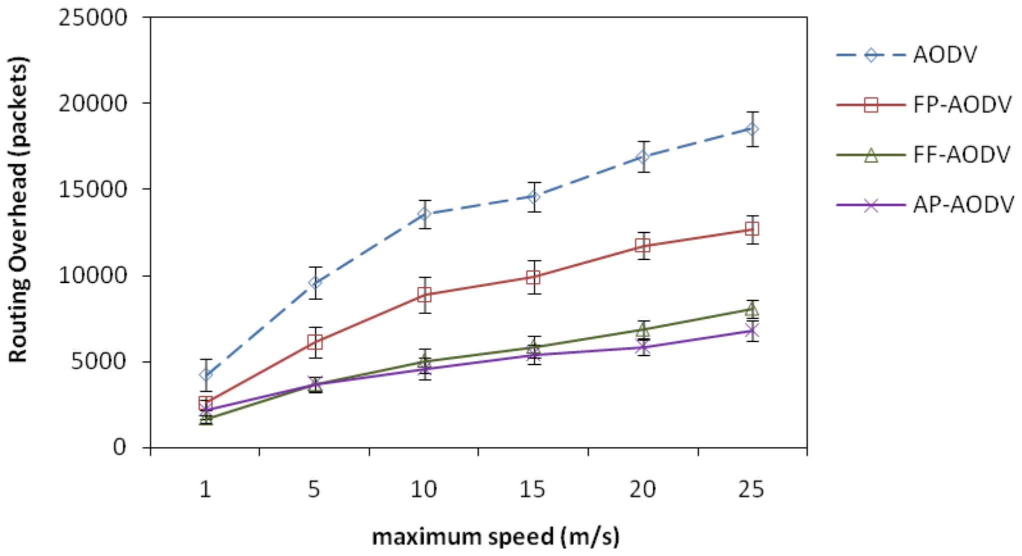


Figure 5.18. Routing overhead versus maximum node speed for a network of 150 nodes placed in a 1000m x 1000m area.

Collision Rate:

In Figure 5.19 the average collision rate for each of the four protocols is plotted against the maximum node speed. The results in the Figure show that the average collision rate increases as the node mobility increases. This is because of the increase in the number of RREQ packets disseminated throughout the network, which is caused by broken paths and the failure of RREQ packets to get to their destinations. For example, when the maximum node speed is increased from 1m/sec to 5m/sec, the average collision rate of AP-AODV, FF-AODV, FP-AODV and AODV is increased by around 106%, 260%, 266% and 153% respectively.

The results in Figure 5.19 also reveal that at low speed (e.g. 1m/sec) the average collision rate of AP-AODV is comparable to that of FF-AODV but lower than both FP-AODV and AODV. On the other hand, at a relatively high speed (e.g. 25m/sec), the collision rate of AP-AODV is approximately 80%, 240% and 505% lower when compared against FF-AODV, FP-AODV and AODV respectively.

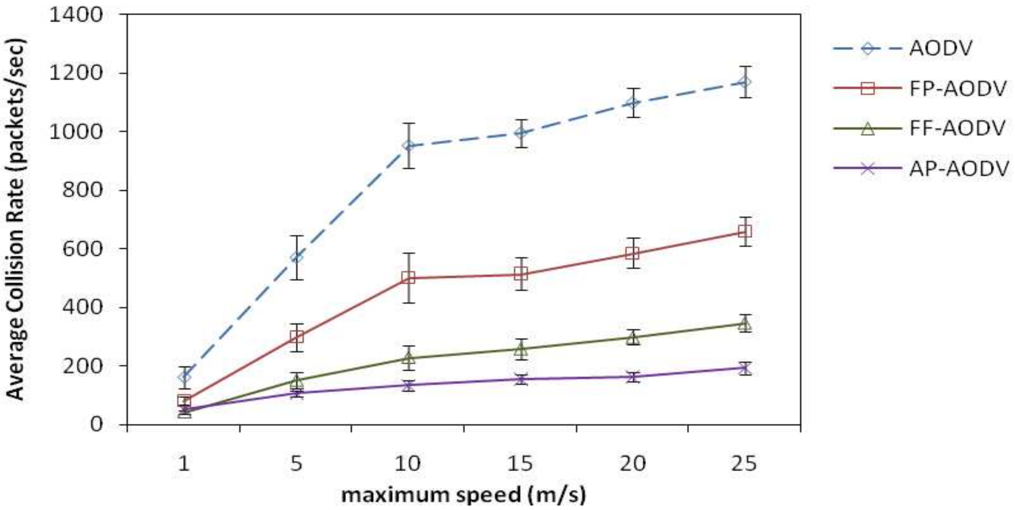


Figure 5.19. Average collision rate versus maximum node speed for a network of 150 nodes placed in a 1000m x 1000m area.

Normalised Network Throughput:

Figure 5.20 plots the normalised network throughput achieved by the four routing protocols against the maximum node speed. The figure shows that the achieved normalised network throughput of AP-AODV is slightly affected by the increased node mobility while those of FF-AODV, FP-AODV and AODV decreases by as much as 30%, 43% and 54% respectively when the node mobility is increased from 1m/sec to 25m/sec. Similar performance behaviour of each of the four routing protocols is noticed in Figure 5.21 when the network connectivity success ratio is plotted against the maximum node speed. These performance behaviours are due to a number of reasons including the following.

Firstly, when the node mobility increases, the network topology changes more frequently and unpredictably which leads to frequent path breaks. Secondly, the broken routes resulting from the frequent topology changes triggers more new route discovery operations, which leads to an increase of the routing overhead. As a consequence, the probability of packet collisions is increased.

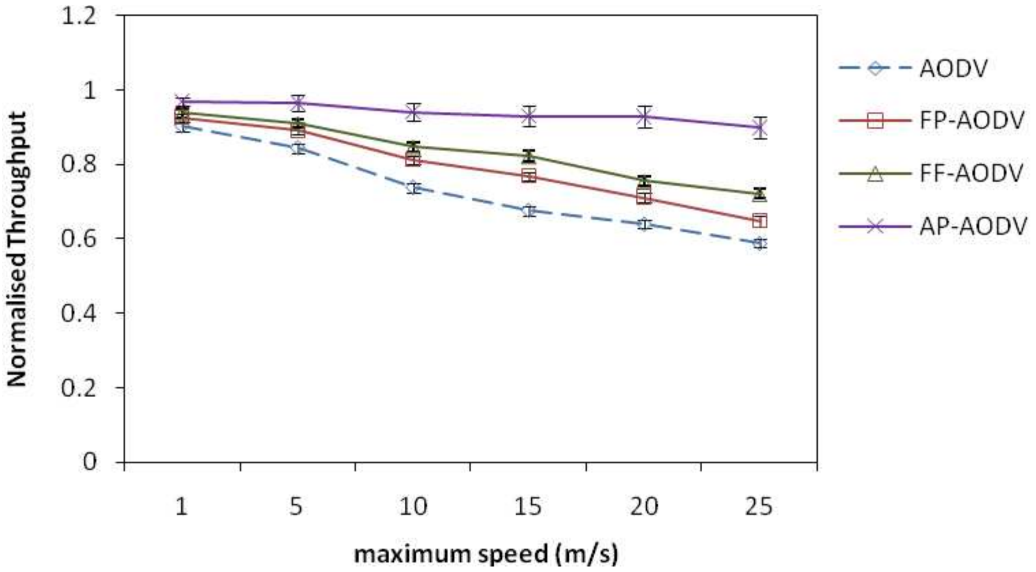


Figure 5.20. Network throughput versus maximum node speed for a network of 150 nodes placed in a 1000m x 1000m area.

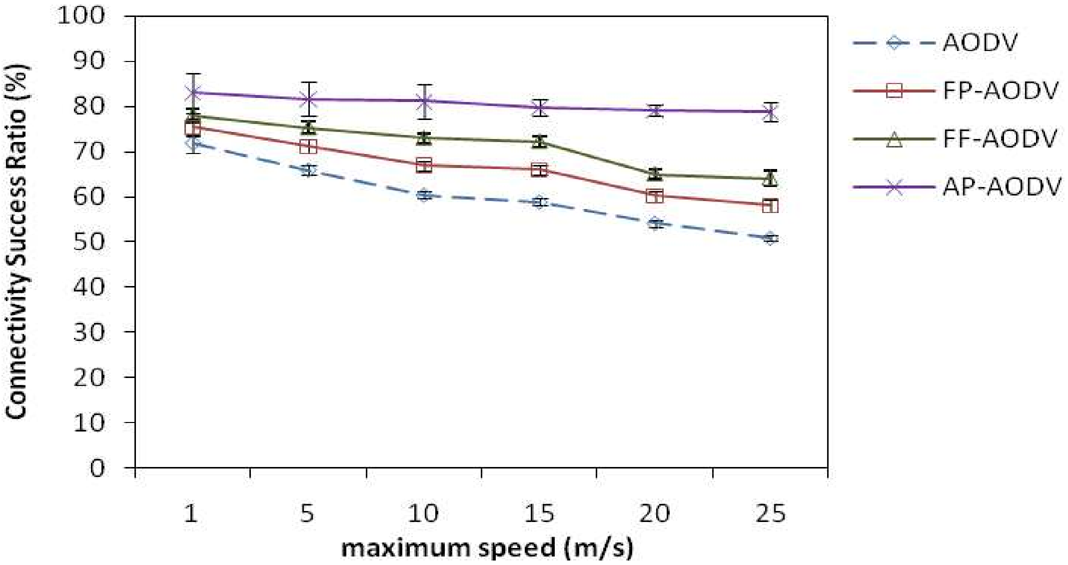


Figure 5.21. Connectivity success ratio versus maximum node speed for a network of 150 nodes placed in a 1000m x 1000m area.

End-to-End Delay:

Figure 5.22 depicts the average end-to-end delay experienced by data packets transmitted from source to destination against the maximum node speed. The figure shows that the delay incurred by each of the four protocols increases with increased maximum node speed. This is due to the frequent path breaks which are associated with increased node mobility. When the frequency of path breaks is increased, the average end-to-end delay of data packets waiting to be transmitted is increased because new paths need to be established. Moreover, frequent path breaks can lead to stale routes at mobile nodes which can result in an overall increase in the end-to-end delay of data packets. However, across node speeds the delay incurred in AP-AODV is shorter than those in FF-AODV, FP-AODV and AODV. Figure 5.23 shows that the route discovery delay of each of the protocols also increases as the node speed increases.

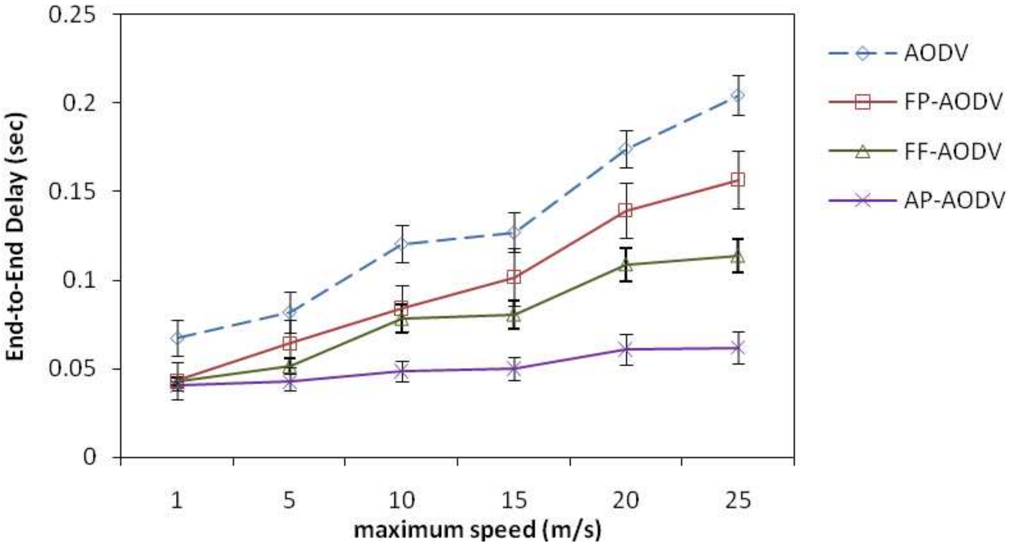


Figure 5.22. End-to-end delay versus maximum node speed for a network of 150 nodes placed in a 1000m x 1000m area.

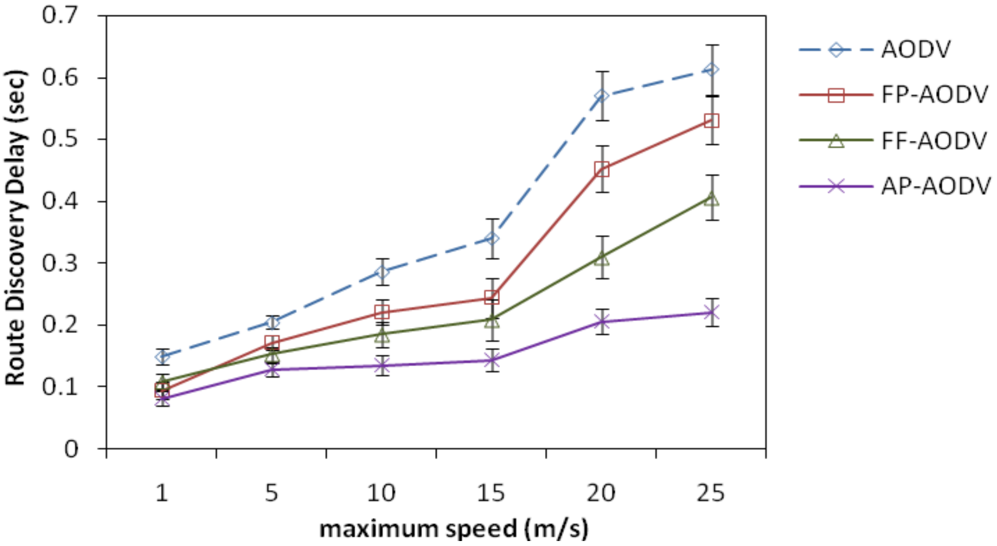


Figure 5.23. Route discovery delay versus maximum node speed for a network of 150 nodes placed in a 1000m x 1000m area.

5.4 Conclusions

This chapter has suggested a new adjusted probabilistic route discovery algorithm. The new algorithm has been incorporated in the AODV routing protocol and has been referred to as AP-AODV. The AP-AODV utilises local topological information (e.g. the neighbourhood information at a node) for the selection of an appropriate forwarding probability for a rebroadcast of the received RREQ packets.

Extensive analysis by means of Ns-2 simulations has been conducted on the new adjusted probabilistic routing protocol and the results are compared with FF-AODV in Chapter 4, the traditional AODV and its fixed probabilistic variant, namely FP-AODV. The performance analysis has been conducted considering various system parameters. Firstly, the performance impact of the network density on the routing protocol is assessed by varying the number of nodes placed in a fixed topology area. Secondly, the impact of the offered load on the performance of the routing protocols is assessed by varying the number of source-destination pairs (flows for short). Finally, the performance analysis of the routing protocols has been conducted under varying node mobility by varying the maximum node speed in the network.

The first part of the performance analysis which considered the impact of the network density has shown that the new adjusted probabilistic routing protocol, AP-AODV, outperforms FF-AODV, FP-AODV and AODV in terms of routing overhead, average collision rate, normalised network throughput and end-to-end delay when the network density is relatively high. However, in the case of low network density (e.g. 25 nodes in a 1000m x 1000m area) the performance of the new protocol is comparable to AODV in most considered performance metrics.

The second performance analysis considered the case of varying offered loads for a fixed network density. Similar superior performance behaviour of AP-AODV over the other three routing protocols in terms of routing overhead, average collision rate, normalised throughput and end-to-end has been noticed when the offered load is increased.

In the final part of the performance analysis which considered the effects of node mobility, AP-AODV performed better than the other three protocols in terms of routing overhead and average collision rate for low and high mobility scenarios. Although the achieved normalised network throughput for all four routing protocols degrades with increased node mobility, the proposed adjusted probabilistic routing protocol achieved a relatively better network throughput in high mobility settings as it reduces channel contention and packet collisions by reducing the routing overhead.

Chapter 6

Dynamic Probabilistic Route Discovery

6.1 Introduction

In Chapter 3, the fixed probabilistic route discovery approach (FP-AODV) was discussed. In this approach, an RREQ packet received at a node is forwarded based on a fixed-value forwarding probability. In Chapter 4, a probabilistic route discovery approach which combines the functionalities of both the fixed probabilistic route discovery approach in FP-AODV and simple flooding based route discovery in the traditional AODV has been proposed. Chapter 5 demonstrates that the performance of the probabilistic route discovery could be improved when the local neighbour density of the forwarding node is exploited.

In this chapter, a new probabilistic route discovery approach which is referred to as *dynamic probabilistic route discovery* (DPR, for short) is proposed. Unlike the fixed and adjusted probabilistic route discovery approaches that utilise predetermined forwarding probabilities (See Chapters 3, 4 and 5), the nodes in DPR dynamically compute their forwarding probabilities using a *probability function* which depends on the local neighbour density at a forwarding node and the number of its neighbours that have been covered by the broadcast (i.e. covered node set).

The rest of the chapter is organised as follows. Section 6.2 describes in detail the proposed dynamic probabilistic route discovery approach and presents its algorithm. Section 6.3 analyses the effects of network operating conditions on the performance of the proposed probabilistic route discovery. Finally, section 6.4 concludes the chapter.

6.2 A Dynamic Probabilistic Route Discovery Algorithm

Since the probability function of the DPR algorithm depends on the node density and the *covered node set* (i.e. the set of neighbours that have received the broadcast packets) at a forwarding node, it is crucial to incorporate a neighbourhood information gathering algorithm in order to use the functionalities of the DPR algorithm. Similar to the AP-AODV in Chapter 5, the DPR algorithm first partitions the network into sparse and dense networks using the local neighbour density at a node. The nodes in the sparse networks are allowed to forward the broadcast packet with a probability $p = 1$, while in a dense network the node is allowed to forward the broadcast packet with a probability $p < 1$, which is determined by the neighbour density at the forwarding node and the covered neighbour set (i.e. the neighbours of the forwarding node that have also received the broadcast).

The use of covered neighbour set to control the dissemination of broadcast packets has been proposed in broadcasting with self pruning [45, 47, 104]. According to the design of the self pruning scheme [104], each node (e.g. node *Y*) before forwarding the broadcast packet piggybacks the set of its 1-hop neighbours, $N(Y)$ to the packet. When node X receives the broadcast packet from node Y for the first time, it decides to rebroadcast the packet according to the status of the set $N(X) - N(Y)$, as shown in Figure 1. If the set $N(X) - N(Y)$ is empty (i.e. when node X can not cover new neighbours), node X refrains from retransmitting the broadcast packet.

In [45], the authors have suggested that each node must have at least 2-hop neighbourhood information which is collected via periodic exchange of “hello” packets among neighbouring nodes. Despite the fact that the use of at least 2-hops neighbour information of the network will help reduce the number of forwarding nodes in the network, the communication overhead associated with the collection of more than 1-hop neighbourhood information is prohibitive, particularly in a dense network.

The self pruning method proposed in [104] is simple since it only requires 1-hop neighbourhood information to make the rebroadcast decision. However, it is still associated with significant broadcast redundancy since the decision to rebroadcast a packet solely depends on the covered neighbour set. For example a node in dense network is compelled to forward the broadcast packet even if as much as 99% of its 1-hop neighbours have also received the broadcast packet. The DPR reduces this redundancy by assigning a low forwarding probability at a node with high number of covered neighbours and a high forwarding probability at a node with low number of covered neighbours.

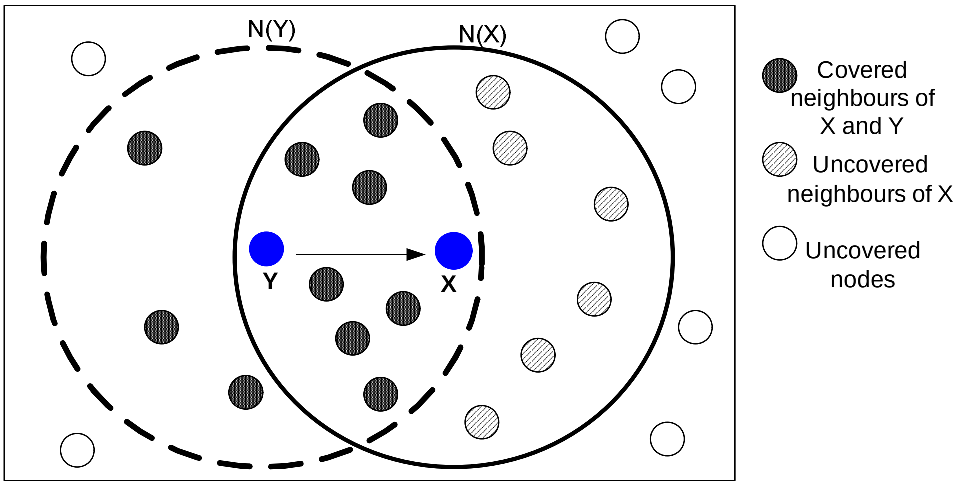


Figure 6.1. Illustration of two communicating nodes with covered neighbour set.

The performance analysis of DPR has been conducted using a modified version of the traditional AODV which incorporates a neighbourhood information gathering algorithm. The information gathering algorithm in AODV uses a periodic exchange of “hello” packets among neighbouring nodes to collect 1-hop neighbourhood information at a node. The details of the neighbourhood information gathering have been discussed in Section 5.2.1. The average neighbour density which defines the boundary between a sparse network and a relatively dense network has been found to be $n_f = 14$ in Section 5.2.1. This value has been adopted for use in the DPR to distinguish between the sparse and dense regions in the network. Therefore, in the DPR, as shown in equation (1) a node in a dense network (i.e. its number of neighbours $n > n_f$) forwards a received RREQ packet with a probability p < 1 and with a probability p = 1 (i.e. simple flooding) when it is in a sparse network (i.e. its number of neighbours $n \leq n_f$). Figure 6.2 depicts a graph of forwarding probabilities of four forwarding nodes in DPR with different number of neighbours versus the covered neighbour sets at the nodes.

6.2.1 The Forwarding Probability in DPR

Let n be the number of neighbours at a node X and let n_c be the number of neighbours of X that are covered by the broadcast (i.e. received the RREQ packet). The forwarding probability at node X is defined as follows:

$$p_X = \begin{cases} 1 & ; \quad n \le n_f \\ 1 - e^{-\left(\frac{n-n_c}{n}\right)} & ; \quad n > n_f \end{cases} \tag{1}$$

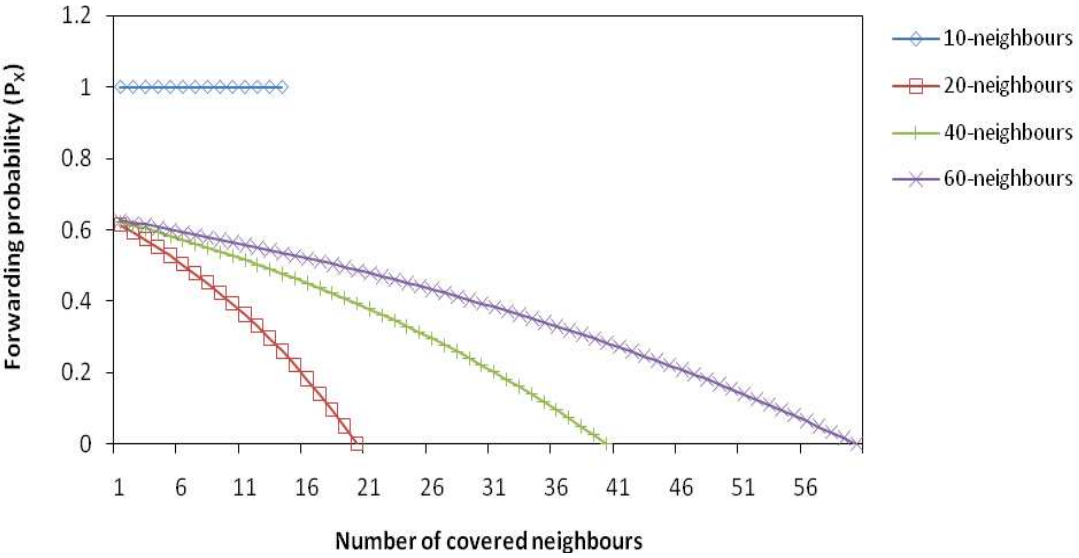


Figure 6.2. Forwarding probability at node X versus number of covered neighbours for different number of neighbours at node X.

6.3 Performance Analysis

To evaluate the performance of the dynamic probabilistic route discovery algorithm (i.e. DPR), the implementation of the AODV routing protocol in the Ns-2 simulator (v.2.29) [113] has been modified to incorporate the functionality of the DPR algorithm and the self pruning algorithm [104]. In what follows, the modifications of the traditional AODV have been referred to as DPR-AODV and SP-AODV respectively. The simulation result of DPR-AODV and SP-AODV are compared against the traditional AODV and its fixed probabilistic variant (i.e. FP-AODV).

The simulation model and system parameters that have been used for the performance analysis in this chapter are similar to those used in Chapters 3, 4 and 5. The performance metrics that have been considered to conduct the performance analysis include the routing overhead in terms of packets, routing overhead in terms of bytes, collision rate, normalised network throughput, end-to-end delay and route discovery delay. These metrics have been defined in Chapter 2 (see Section 2.7).

6.3.1 Impact of Network Density

This section examines the impact of network density on the performance of the four protocols. The network density has been varied by changing the number of nodes deployed over a 1000m x 1000m area of each simulation scenario. Each node in the network moves with a random speed chosen between 0 and 20m/sec. For each simulation trial, 10 identical randomly selected source-destination connections (i.e. traffic flows) are used.

Routing Overhead

Figure 6.3 shows the performance of the four routing protocols in terms of routing overhead versus network density. As shown in the figure, the routing overhead generated by each of the four routing protocols increases almost linearly as the network density increases. The results in the figure reveal that for a given network density, the routing overhead generated by DPR-AODV is lower compared with those of the SP-AODV, FP-AODV and AODV. The performance behaviour of the DPR-AODV can be explained by the fact that when the forwarding probability at a node is set according to its local density and covered node set, the number of redundant retransmissions of the RREQ packet can be significantly reduced, and as a consequence the overall routing overhead is reduced.

As discussed in Section 6.2, the DPR-AODV and SP-AODV piggyback the list of their 1-hop neighbours in the RREQ packets before forwarding them. As a consequence, the routing overhead of DPR-AODV and SP-AODV is increased in terms of number of bytes transmitted. Figure 6.4 depicts the performance comparisons of the four routing protocols in terms of routing overhead measured in bytes. Even though the DPR-AODV has registered the lowest routing overhead in terms of number of packets transmitted as shown in Figure 6.3, the reduction of the routing overhead by the DPR-AODV is relatively low when measured in terms of number of bytes transmitted. For example at 225 nodes, the routing overhead of DPR-AODV is approximately 300% lower than that of AODV when measured in terms of number of packets transmitted. On the other hand, it is about 95% lower than that of AODV when measured in terms of number of bytes transmitted.

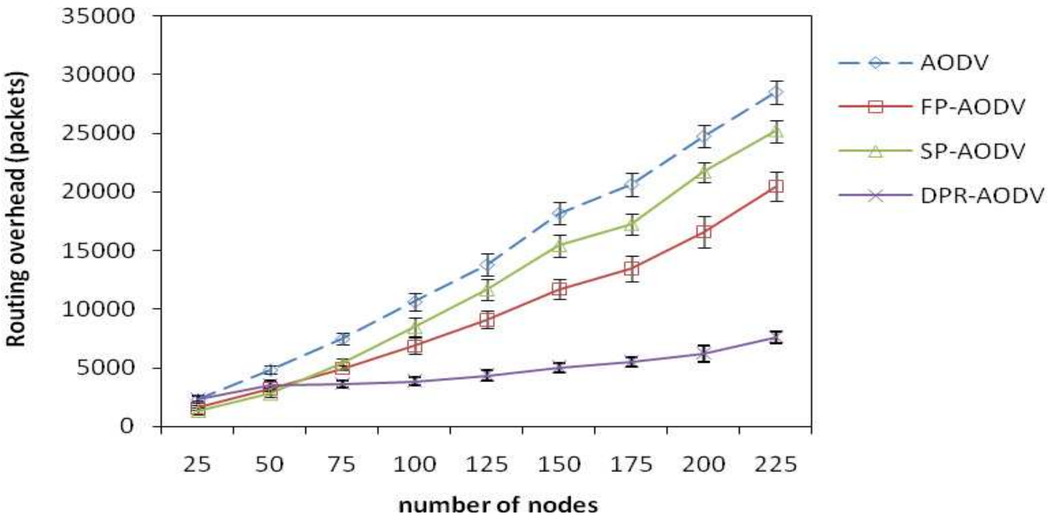


Figure 6.3. Routing overhead versus number of nodes placed over a 1000m x 1000m area.

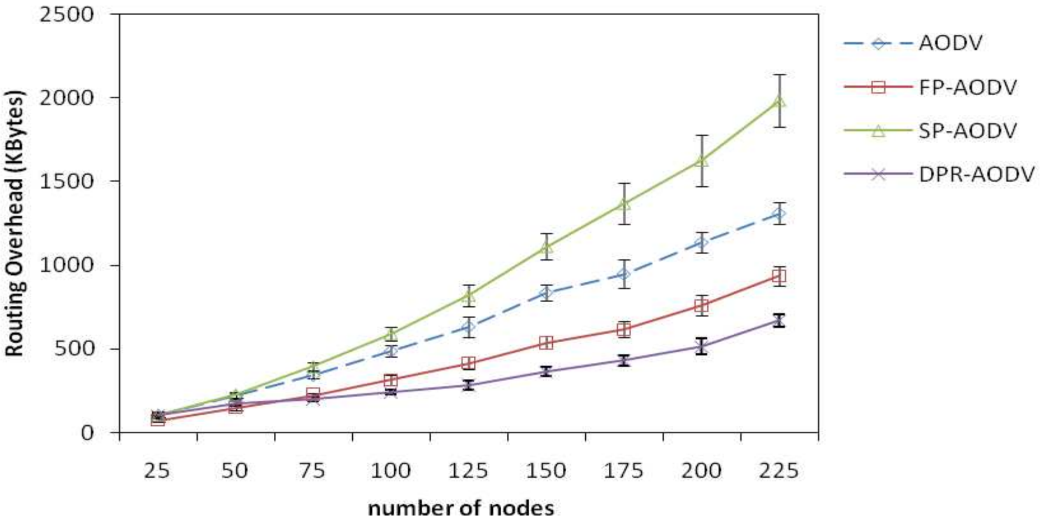


Figure 6.4. Routing overhead in terms of bytes versus number of nodes placed over a 1000m x 1000m area.

Collisions Rate:

The results in Figure 6.5 depict the average number of packet collisions per second versus network density. Since data and control packets share the same physical channel, the collision probability is increased when the dissemination of RREQ packets is not appropriately controlled. Figure 6.5 shows that when the network density is increased, the collision rate of each of the four routing protocols is also increased. The figure also reveals that for a given network density, DPR-AODV outperforms SP-AODV, FP-AODV and AODV. Even though in Figure 6.3, SP-AODV outperforms the AODV in terms of number of RREQ packets transmitted, it can be seen in Figure 6.5 that the collision rate of SP-AODV is comparable to that of AODV for a given network density. This is due to the increased in size (in terms of bytes) of the RREQ packets in SP-AODV.

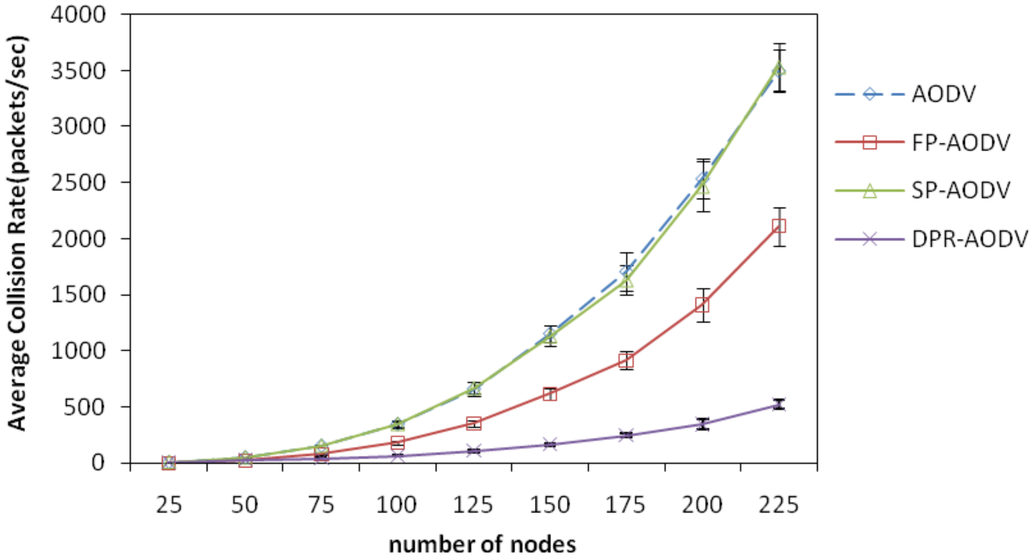


Figure 6.5. Average collision rate versus number of nodes placed over a 1000m x 1000m area at a maximum node speed of 5m/sec.

Network Throughput:

In Figure 6.6, the normalised aggregate network throughput is plotted against the network density. The figure shows that the normalised throughput for each of the routing protocols is low when the network density is set low (e.g. 25 nodes). This is due to the poor network connectivity associated with sparse networks as shown in Figure 6.7. On the other hand, in a dense network where excessive redundant retransmissions of control packets (e.g. RREQ packets) is predominant, the channel contention and packet collisions are increased, thereby lowering the bandwidth available for data transmission. Therefore, if measures are taken to control the redundant retransmissions of RREQ packets in a dense network, the degradation of the throughput can be reduced. As shown in Figures 6.6 and 6.7, DPR-AODV outperforms SP-AODV, FP-AODV and AODV when the network is relatively dense. The improved performance of DPR-AODV in a dense network is due to the significant reduction in the number of retransmissions of RREQ packets.

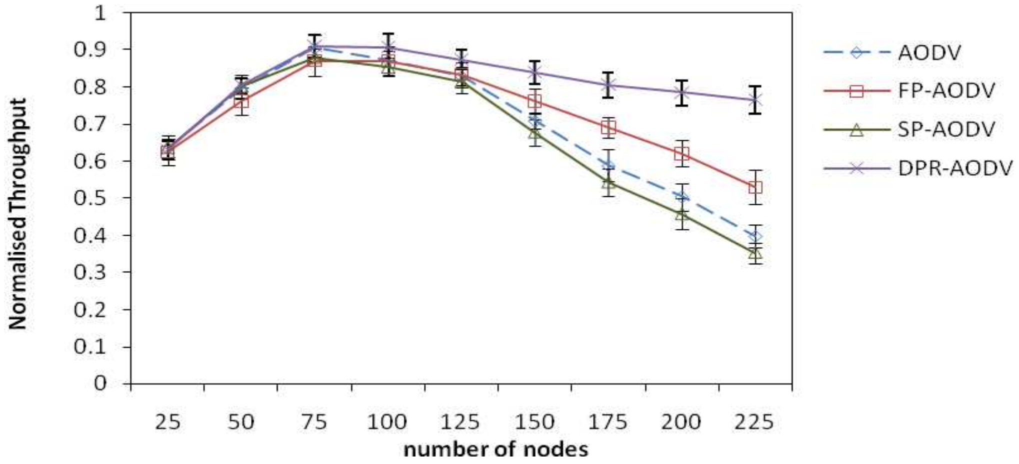


Figure 6.6. Normalised network throughput versus number of nodes placed over a 1000m x 1000m area.

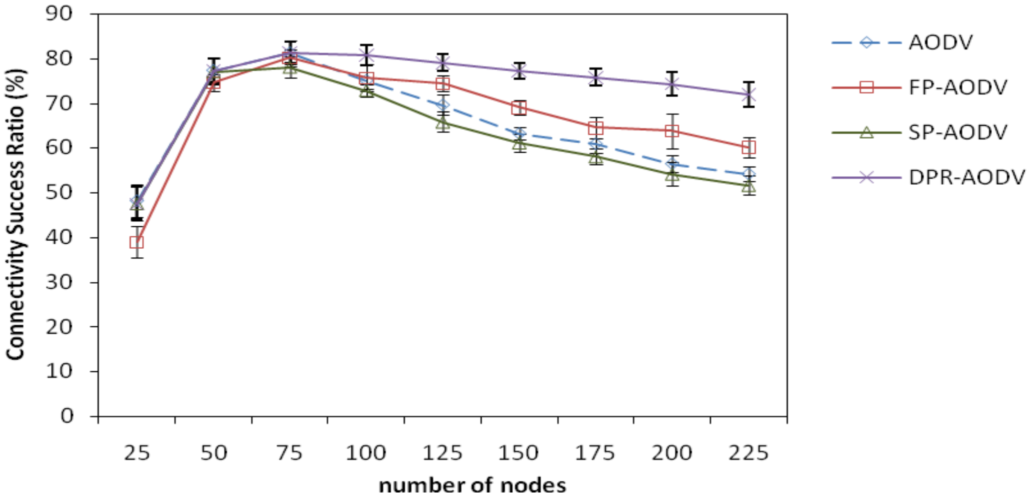


Figure 6.7. Network connectivity success ratio versus number of nodes placed over a 1000m x 1000m area.

End-to-End Delay:

Figure 6.8 plots the impact of network density on the performance of the routing protocols in terms of end-to-end delay. The figure shows that the end-to-end delay for each of the routing protocols is relatively high for both sparse and dense networks. In a sparse network, the RREQ packets fail to reach their respective destinations because of poor network connectivity. On the other hand, in a relatively dense network, most of the originated RREQ packets fail to reach their destinations due to the increased probability of packet collisions and channel contention caused by excessive redundant retransmissions of the RREQ packets. This potentially increases the route discovery delay (see Figure 6.9), thus the time required for data packets to be transmitted from the source to destination nodes is increased. In a sparse network, the DPR-AODV performs comparably to AODV and SP-AODV and outperforms FP-AODV. However in a dense network, DPR-AODV performs better than all the other three protocols. This is due to the significant reduction in both the routing overhead and the collision rate as shown in Figures 4 and 6 respectively.

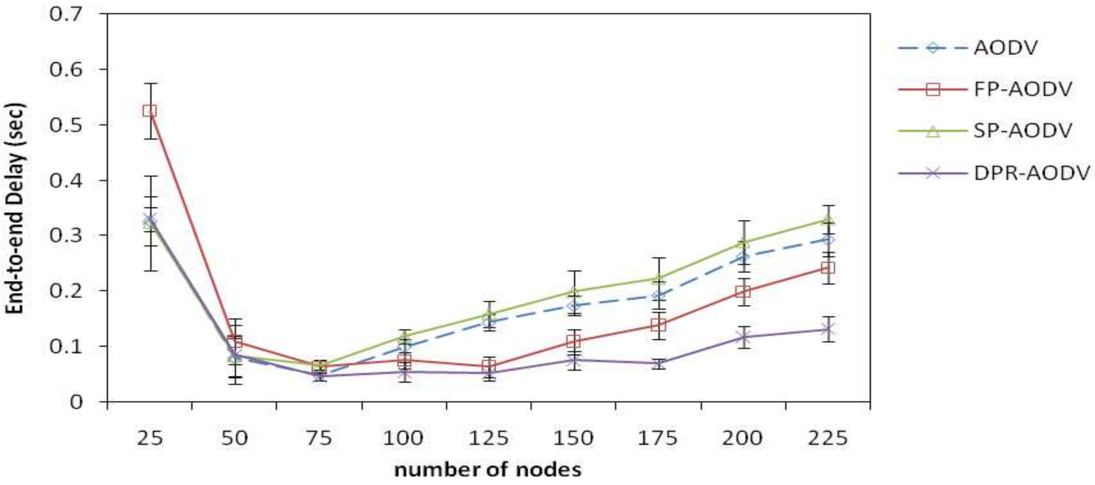


Figure 6.8. End-to-end delay versus number of nodes placed over a 1000m x 1000m area.

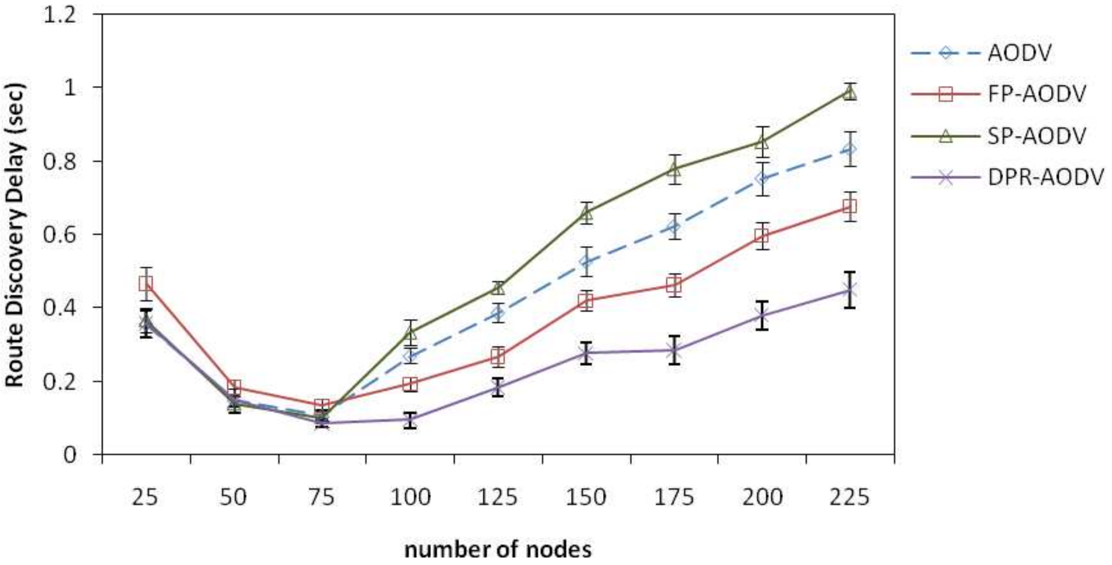


Figure 6.9. Route discovery delay versus number of nodes placed over a 1000m x 1000m area.

6.3.2 Impact of Offered Load

To evaluate the impact of offered load on the performance of the four routing protocols, this section has considered different numbers of source-destination pairs (flows, for short) over a 150 node network. The offered load has been varied over the range 1, 5, 10, …, 40 flows.

Routing Overhead:

In Figures 6.10 and 6.11, the routing overhead generated by the four routing protocols is plotted against the offered load. The figures show that the routing overhead of each of the four routing protocols increases as the number of flows increases. The results in both Figure 6.10 and Figure 6.11 also reveal that DPR-AODV has a clear performance advantage over SP-AODV, FP-AODV and AODV across all offered loads for both in terms of packets and in bytes. This is because DPR-AODV implements a route discovery operation with a relatively fewer number of nodes participating in the forwarding of the RREQ packets.

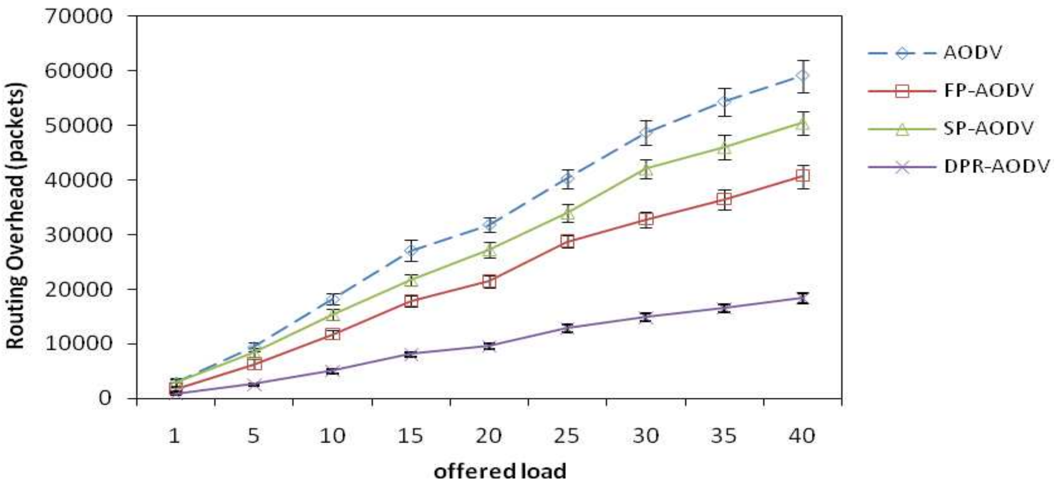


Figure 6.10. Routing overhead in terms of number of packets versus offered load for a network of 150 nodes placed in a 1000m x 1000m area.

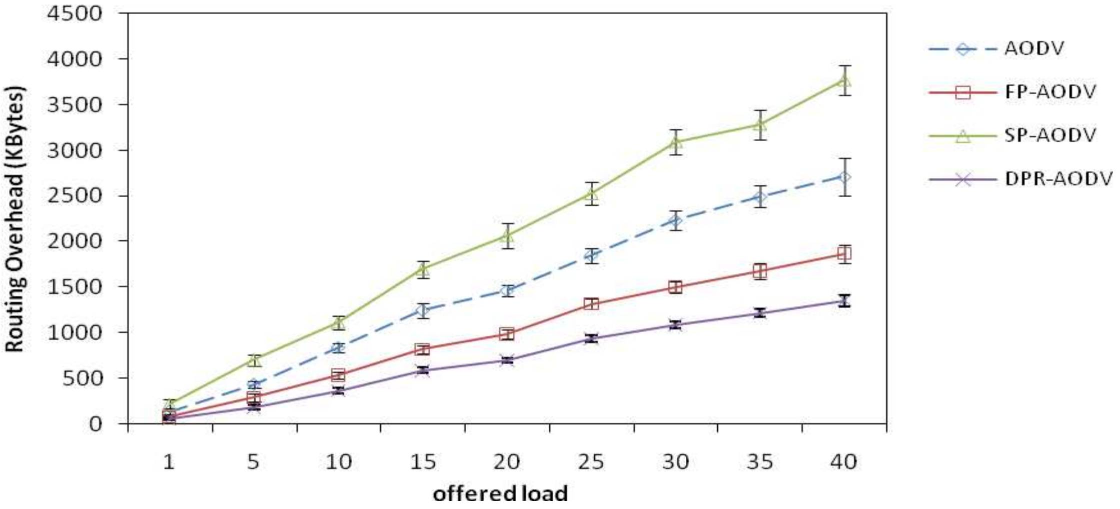


Figure 6.11. Routing overhead in terms of bytes versus offered load for a network of 150 nodes placed in a 1000m x 1000m area.

Collision Rate:

The results in Figure 6.12 depict the collision rate of all four routing protocols versus offered load. Like the routing overhead generated as shown in Figures 6.10 and 6.11, the collision rate increases almost linearly as the offered load increases. This is because when the offered load is increased by increasing the number of flows, the number of RREQ packets generated and transmitted is increased. Consequently, the packet collision rate is increased.

It can be noticed from Figure 6.12 that DPR-AODV outperforms SP-AODV, FF-AODV, FP-AODV and AODV for all offered loads considered. Even though the performance of SP-AODV in terms of routing overhead (in packets) is better than AODV, the performance of SP-AODV in terms of collision rate is comparable to AODV as shown in Figure 6.12. This is because a large percentage of the RREQ packets generated in SP-AODV are involved in collisions since the size of such packets are large. Despite the fact that DPR-AODV uses similar technique of piggybacking neighbour list on the RREQ packets, the collision rate is relatively low because a large number of the RREQ packets are dropped because of the forwarding probabilities, thereby reducing the channel contention.

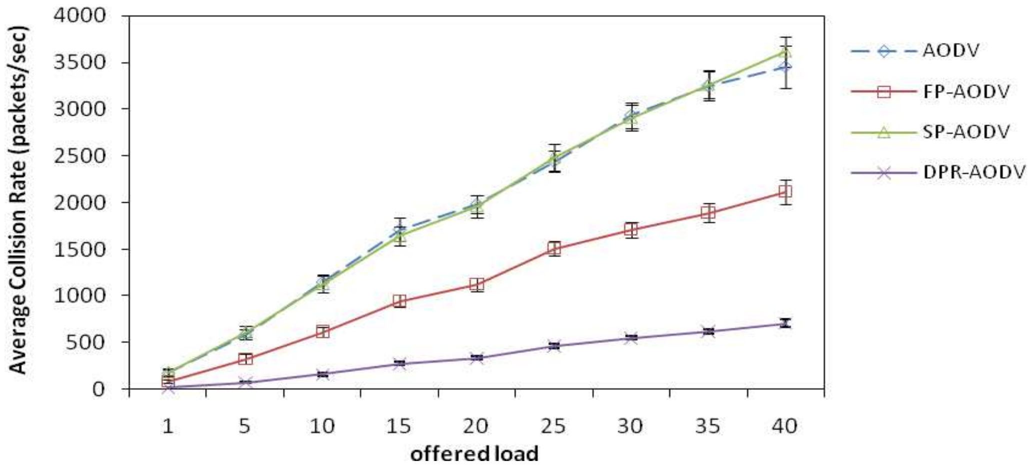


Figure 6.12. **Average collision rate versus offered load for a network of 150 nodes placed in a 1000m x 1000m area.**

Normalised Network Throughput:

Figure 6.13 shows the performance of the routing protocols in terms of normalised network throughput when the offered load is varied from 1 to 40 flows. The figure reveals that the normalised network throughput for all the routing protocols decreases as the offered load increases. This is because when the offered load is increased, the number of nodes initiating route discovery operations is also increased. As a consequence, more RREQ packets are generated and transmitted, causing an increase of the channel contention and packet collisions. This phenomenon reduces the number of data packets delivered at their destinations, thereby causing degradation of the overall network throughput. However it can be seen in Figure 6.13 that the superiority of DPR-AODV over the other versions of AODV becomes more noticeable when the offered load is increased. In Figure 6.14, the network connectivity success ratio is plotted against the offered load. The results in Figure 6.14 show that the performance behaviour for each of the protocols in terms of connectivity success ratio is similar to the normalised throughput in Figure 6.13.

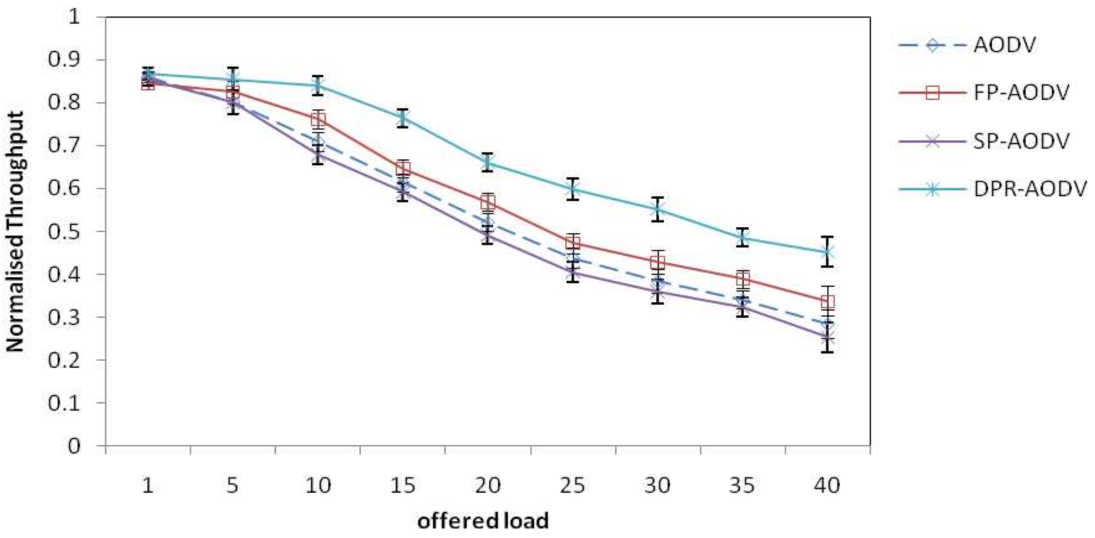


Figure 6.13. Normalised throughput versus offered load for a network of 150 nodes placed in a 1000m x 1000m area.

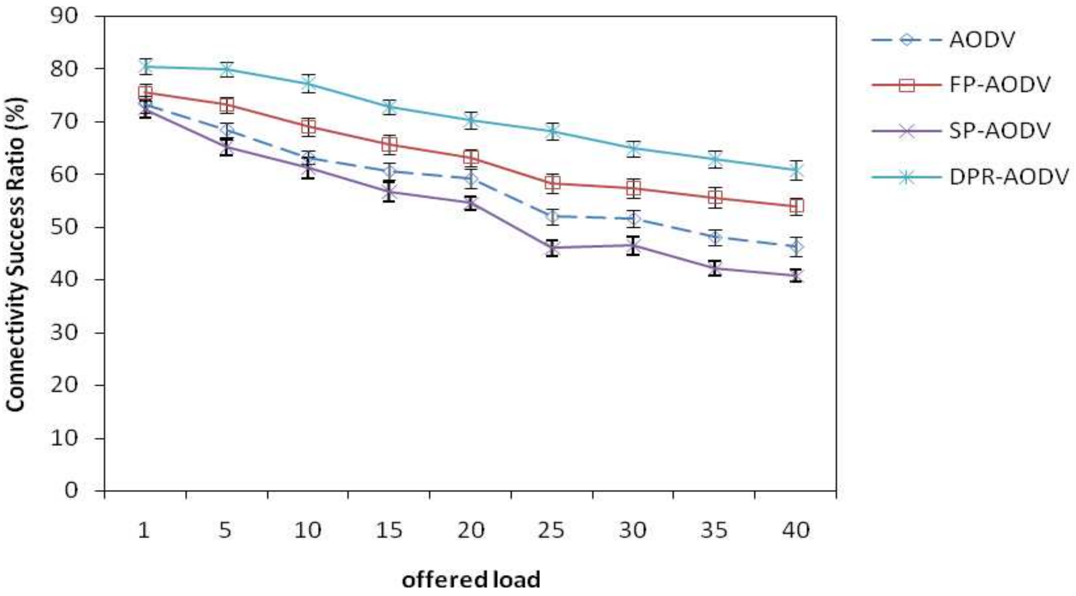


Figure 6.14. Network connectivity success ratio versus offered load for a network of 150 nodes placed over a 1000m x 1000m area.

End-to-End Delay:

In Figure 6.15, the results in terms of end-to-end delay are plotted against the offered load. The results in the figure show that the end-to-end delay incurred by each of the routing protocols increases as the offered load increases. The figure also shows that DPR-AODV performs better than the other three versions of AODV when the offered load is increased. Figure 6.16 shows similar performance trends of each of the four protocols in terms of route discovery delay.

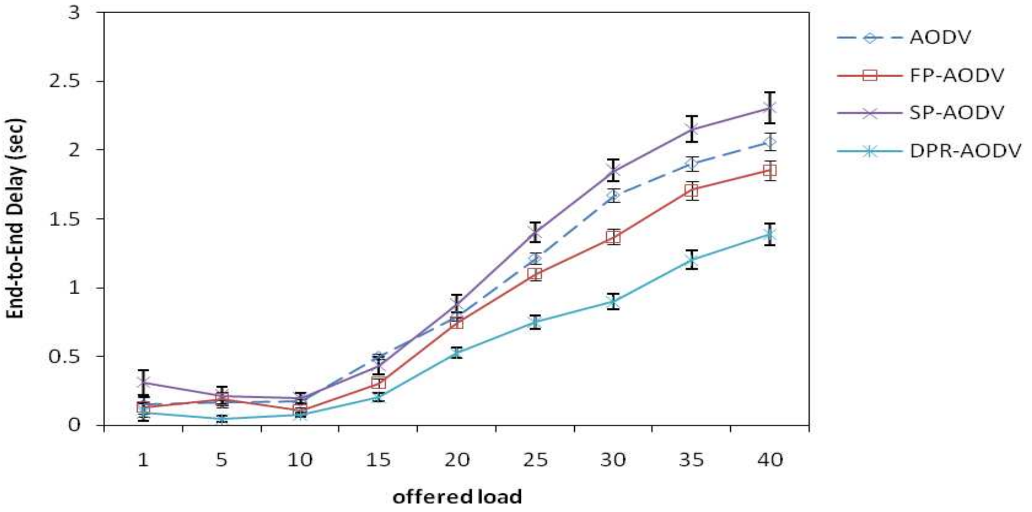


Figure 6.15. End-to-end delay versus offered load for a network of 150 nodes placed in a 1000m x 1000m area.

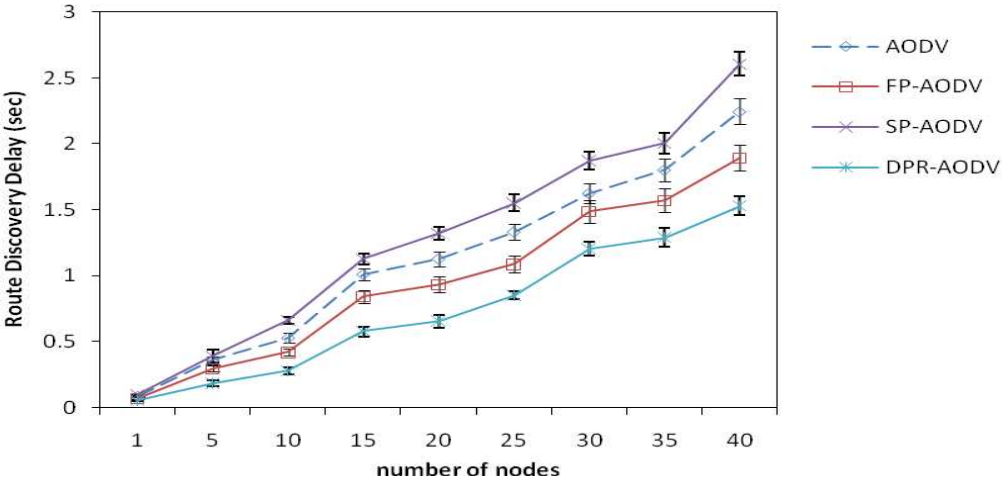


Figure 6.16. Route discovery delay versus offered load for a network of 150 nodes placed in a 1000m x 1000m area.

6.3.3 Impact of node mobility

This section presents the effects of node mobility on the performance of the five protocols. A set of simulation experiments has been conducted where the mobility of 150 nodes placed over a 1000m x 1000m area has been varied by changing the maximum node speed in the network. The maximum speed in the network has been varied from 1m/sec to 25m/sec. An offered load of 10 flows has been considered in each simulation scenario.

Routing Overhead:

Figure 6.17 plots the routing overhead generated by the four routing protocols against the maximum node speed. The results depict that the routing overhead generated by each of the routing protocols increases with increased maximum node speed. This is because when node mobility increases, the network topology changes frequently, thus more RREQ packets are generated and disseminated to maintain broken paths or to establish new paths. These activities potentially increased the overall routing overhead. Across maximum node speed, DPR-AODV performs better than SP-AODV, FP-AOV and AODV.

In Figure 6.18, the routing overhead measured in terms of bytes is plotted against the maximum node speed. The performance behaviour of each of the routing protocols in Figure 6.17 is similar to that in Figure 6.18. The routing overhead of each of the routing protocols increases when the maximum node speed in the network is increased.

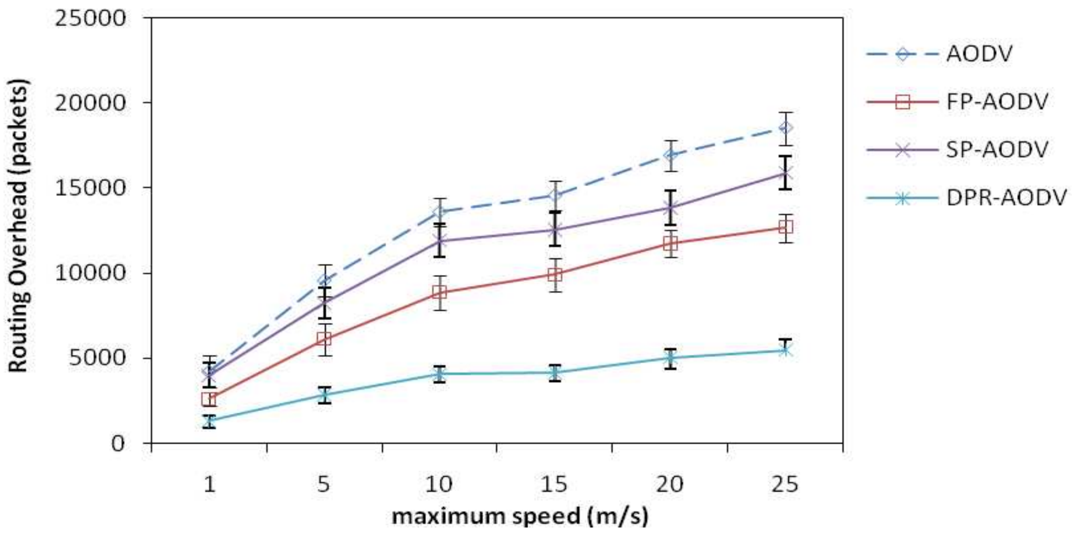


Figure 6.17. Routing overhead in terms of number of packets versus maximum node speed for a network of 150 nodes placed in a 1000m x 1000m area.

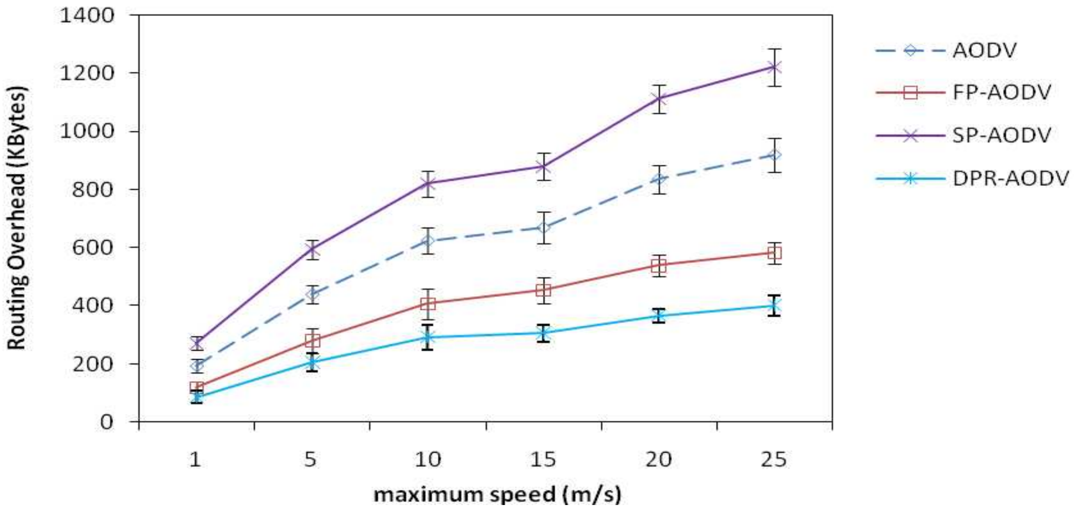


Figure 6.18. Routing overhead in terms of bytes versus maximum node speed for a network of 150 nodes placed in a 1000m x 1000m area.

Collision Rate:

In Figure 6.19 the average collision rate for each of the four routing protocols is plotted against the maximum node speed. The results in the Figure show that the average collision rate for each of the protocols increases as the node mobility increases. This is due to the increase in the frequency of broken routes which leads to an increase in the number of RREQ packets generated and disseminated. Figure 6.19 also reveals that the collision rate in DPR-AODV is significantly reduced when compared against those of SP-AODV, FP-AODV and AODV.

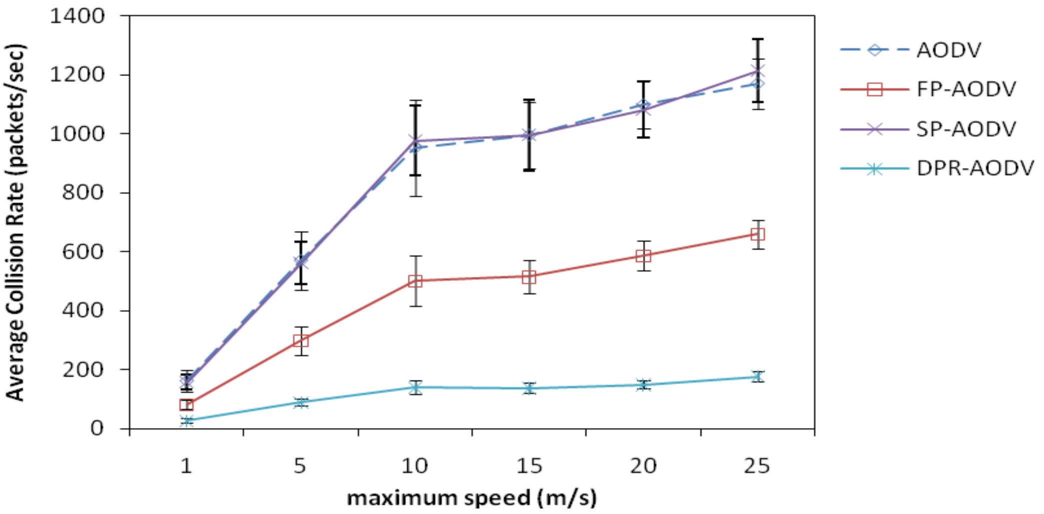


Figure 6.19. Average collision rate versus maximum node speed for a network of 150 nodes placed in a 1000m x 1000m area.

Normalised Network Throughput:

Figure 6.20 depicts the normalised network throughput of each of the four routing protocols versus maximum node speed, while Figure 6.21 shows the network connectivity success ratio versus maximum node speed. In Figure 6.20, the results show that the normalised network throughput of each of the protocols degrades with increased node mobility. This can be due to several reasons including the following. Firstly, when node mobility increases, the network topology changes more frequently and unpredictably which increases the number of broken routes. Secondly, the broken routes resulting from the frequent topology changes trigger more new route discovery and maintenance processes which increased the number of RREQ packets generated and disseminated in the network. As a consequence the probability of packet collisions is increased. Although DPR-AODV performs relatively better than the other three protocols (i.e. SP-AODV, FP-AODV and AODV), its superiority over the three protocols becomes more noticeable when the node mobility is relatively faster.

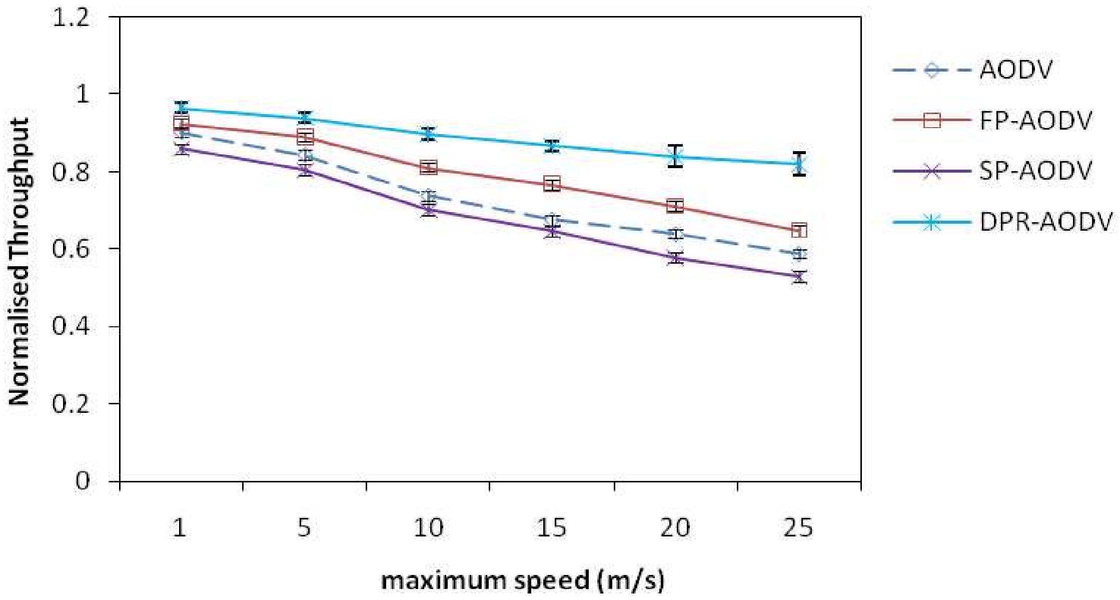


Figure 6.20. Normalised throughput versus maximum node speed for a network of 150 nodes placed in a 1000m x 1000m area.

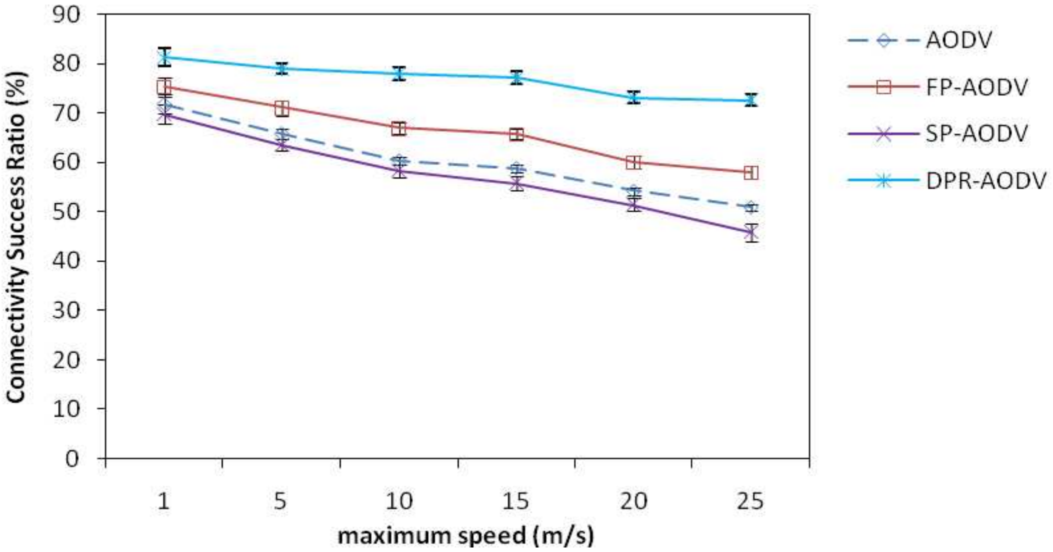


Figure 6.21. Connectivity success ratio versus maximum node speed for a network of 150 nodes placed in a 1000m x 1000m area.

End-to-End Delay:

Figures 6.22 depicts the average end-to-end delay of data packets of each of the four routing protocols versus maximum node speed, while Figure 6.23 shows a plot of route discovery delay against maximum node speed. The figures show that the average delay incurred in each of the four protocols increases with increased maximum node speed. This is due to the frequent path breaks associated with increased node mobility. The figures also shows that the average delay incurred in DPR-AODV is shorter when compared against SP-AODV, FP-AODV and AODV in a network with fast moving nodes.

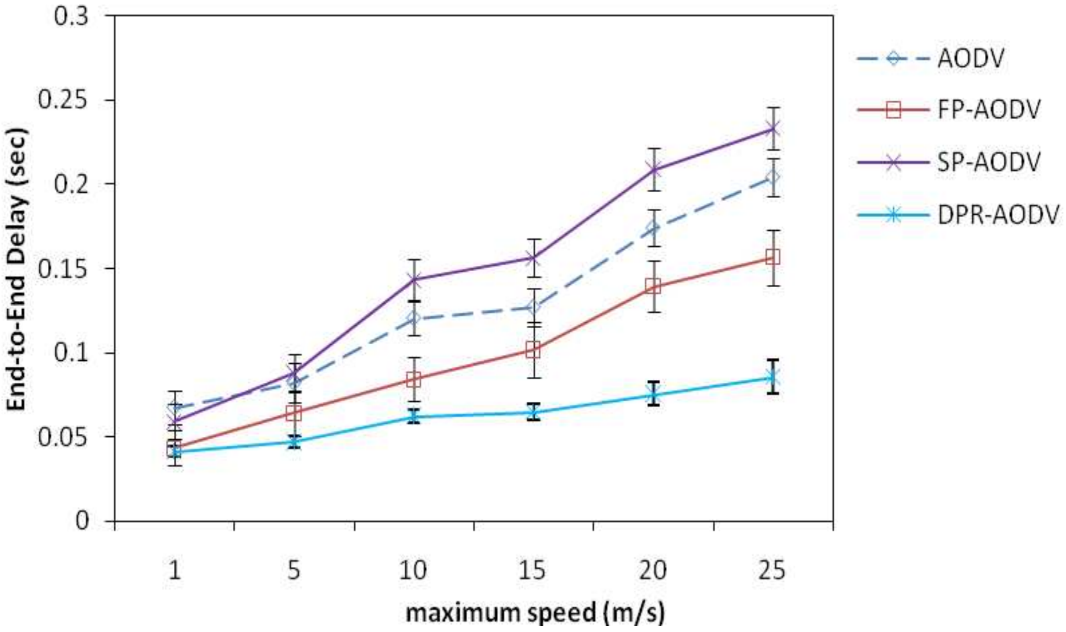


Figure 6.22. End-to-end delay versus maximum node speed for a network of 150 nodes placed in a 1000m x 1000m area.

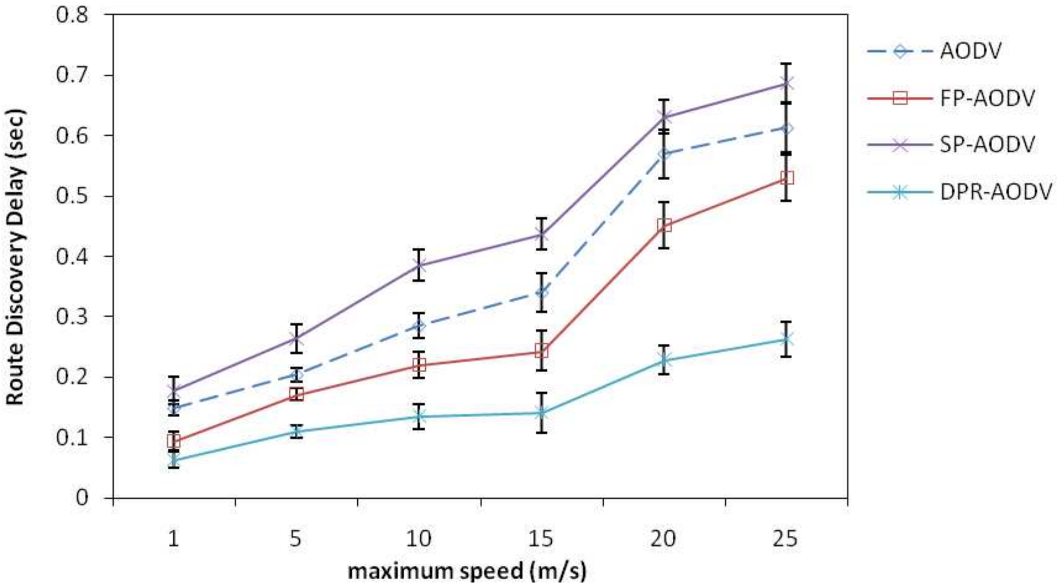


Figure 6.23. Route discovery delay versus maximum node speed for a network of 150 nodes placed in a 1000m x 1000m area.

6.4 Conclusions

This chapter has presented a new probabilistic route discovery approach for routing in MANETs named here as Dynamic Probabilistic Route discovery (DPR), where the forwarding probability at a node is dynamically computed based on its neighbour density and its covered neighbours set. The chapter has compared the performance of DPR against that of other probabilistic route discovery approaches suggested in the previous chapters and a self pruning based route discovery approach by incorporating them into the modified versions of the traditional AODV implementation in Ns-2. The versions of AODV examined in this chapter include DPR-AODV, SP-AODV, FP-AODV, and the traditional AODV.

The performance of the routing protocols is measured in terms of the usual performance metrics that have been used in the existing performance analysis of MANETs routing protocols including routing overhead, average collision rate, network throughput and end-to-end delay. Performance analysis has been conducted considering various system parameters. Firstly, the impact of the network density on the performance of the routing protocols is assessed by varying the number of nodes placed in a fixed topology area. Secondly, the impact of the offered load on the performance of the routing protocols is assessed by varying the number of source-destination pairs (flows for short). Finally, the performance analysis of the routing protocols has been conducted under varying node mobility by varying the maximum node speed in the network.

The simulation results of the first performance analysis have shown that the performance of the four protocols in terms of routing overhead and collision rate degrades considerably when the number of nodes is increased. However, for all considered network densities, the performance improvements of the four routing protocols in terms of routing overhead (in packets) and collision rate in order from the lowest to the highest are DPR-AODV, FP-AODV, SP-AODV and AODV. In the same order, when the overhead is measured in terms of bytes, the performance improvements are DPR-AODV, FP-AODV, AODV and SP-AODV. In terms of network throughput and end-to-end delay, DPR-AODV again outperforms the other versions of AODV particularly in a dense network.

The simulation results of the second performance analysis have shown that the performance of the four routing protocols in terms of routing overhead and collision rate increases with increased offered loads. The results also show that the performance of DPR-AODV in all considered performance metrics is better than the other versions of AODV for all offered loads. Similar performance behaviours are noticed in the case of normalised network throughput and end-to-end delay when the offered load is varied.

In the third performance analysis, the results have depicted that the performance levels of DPR-AODV is relatively better than the other three routing protocols in terms of routing overhead and average collision rate across all considered node speeds. In terms of network throughput and end-to-end delay, the performance of DPR-AODV is better than SP-AODV, FP-AODV and AODV for most node speeds.

Chapter 7

Conclusions and Future Directions

7.1 Introduction

Mobile Ad hoc Networks (MANETs) have attracted a lot of attention among the research community over recent years [11, 37, 43, 124]. This has been motivated by recent advances in mobile computing devices and wireless technology and the potential applications that could be realised using such networks [33], ranging from simple civil and commercial applications to complicated high-risk emergency services and battlefield operations. Although the nodes in MANETs share many of the properties of their counterparts in the traditional wired network, they present certain unique challenges arising from the inherent nature of the wireless communication medium, the distributed function of their medium access mechanism [1, 24] and the frequent topology changes associated with their mobility [37, 123]. Much research effort [1, 11, 24, 33, 37, 43] has been devoted to finding solutions to these challenging issues over the past few years.

The provision of efficient routing protocols that can cope with the frequent topology changes and the limited shared channel bandwidth is one of the most significant challenges for MANETs and is crucial for the basic operations of the network [4]. To achieve this, a number of routing protocols have been proposed [4, 7-9, 37, 62, 70, 48], which can be categorised roughly into reactive/on-demand [7, 8] and proactive [9, 48] routing protocols. The proactive routing algorithms are considered not scalable because of the excessive routing overhead associated with the periodic dissemination of routing tables among all the nodes in the network. However, the reactive on-demand routing protocols are considered more scalable than their proactive counterparts, since they transmit routing control packets only whenever a route discovery operation is initiated. However, on-demand routing protocols adopt the simple flooding broadcast approach for route discovery operations, which has been shown to severely limit the potential performance gains of the network [37, 77] due to the excessive retransmissions of the RREQ packets.

To reduce the excessive retransmissions of RREQ packets in on-demand route discovery, a number of algorithms have been suggested [40, 41, 46, 54, 63, 64, 77, 82]. Examples include location-based [46, 54], zone-based [40, 41], back-bone based [63, 64] and probabilistic based algorithms [77, 82]. However, some of these algorithms [46, 54] require the services of GPS receivers [56] in order to collect the location information of mobile nodes. Others collect global topological information on network at the cost of additional control overhead in order to build virtual communication backbones on behalf of the source-destination pairs [63, 64]. In order to reduce the overhead associated with the route discovery operation in a MANET, without the use of global topological information about the network or additional devices such as a GPS receiver, probabilistic broadcast schemes [49, 81, 106] have recently been adopted for on-demand route discovery operations [77, 82].

7.2 Summary of the results

The major focus of this research has been the design and analysis of new probabilistic route discovery algorithms for routing protocols in MANETs, such as AODV [7] and DSR [8], that can significantly reduce the routing overhead and packet collisions that associated with the traditional simple flooding based route discovery in AODV while improving end-to-end delay and normalised network throughput. Summarised below are the major contributions made in this research study.

- Most probabilistic broadcast algorithms proposed in the literature [49, 81, 106] have been studied in limited scenarios [49, 81, 106] where the network traffic consists of broadcast packets only. Further, there has been relatively very little investigation on the effects of such broadcast algorithms in normal environments where broadcasts coexist with unicast background data traffic. An important example is route discovery in on-demand routing protocols [7, 8], which has the ultimate aim of delivering a data packets to a particular single node (i.e. destination). Motivated by this observation, the first part of this research has analysed the performance of fixed-value probabilistic route discovery while considering important system parameters of a MANET, notably, network density, offered traffic, and node mobility over a wide range of predetermined forwarding probabilities.

- In this performance analysis, existing implementations of the AODV [7] and DSR [8] routing protocols in the Ns-2 simulator [113] have been modified in order to incorporate the probabilistic route discovery operation, enabling nodes to forward RREQ packets with a fixed forwarding probability. Extensive simulation analysis has revealed that given a set of system parameters, the performance behaviour of the probabilistic versions of the two routing protocols, FP-AODV and FP-DSR, can be improved significantly if appropriate forwarding probabilities are chosen. This study is the first in the literature that conducts a performance analysis of probabilistic route discovery in two well-known on-demand routing protocols to highlight the relative performance merits of different forwarding probabilities under a variety of system parameters.

- It can be noted that in the case of fixed probabilistic route discovery (e.g. FP-AODV), the received RREQ packet is forwarded with a fixed probability value at a mobile node, regardless of the relative geographic locations of the source and destination node pairs as well as the local topological characteristics of the forwarding node. However, in a route discovery operation, if the geographic location of the destination node is known, the dissemination of the RREQ packets could be directed towards this location. Motivated by this, the second part of this research has proposed a new probabilistic route discovery approach that aims to mitigate the routing overhead by limiting the dissemination of the RREQ packets towards the anticipated location of the destination nodes.

- The new approach, referred to as FF-AODV combines the functionalities of the fixed probabilistic as well as simple flooding based route discovery approaches. The FF-AODV assumes that a node does not move too far away and too soon from its neighbours. Therefore, using the routing history at mobile nodes for each source-destination pair, the FF-AODV divides the network topology into two logical zones, namely the *active* and *inactive* zones. The nodes in the active zones are privileged to forward the RREQ packets by assigning them a large forwarding probability which includes simple flooding, while the nodes in the inactive zones are less privileged by being assigned a low forwarding probability.

- Numerous simulation experiments have been conducted under different network working conditions to compare the performance of the proposed FF-AODV with that of the traditional AODV and its fixed probabilistic variant, FP-AODV. Several performance metrics have been considered in the analysis, including routing overhead, collision rate, network throughput and end-to-end delay. A wide range of system parameters, including network density, offered loads and node mobility have been considered. Simulation results have shown that in most cases considered, FF-AODV exhibits superior performance advantage in terms of routing overhead, average collision rate, network throughput and end-to-end delay compare with the traditional AODV and FP-AODV.

- In the fixed probabilistic route discovery, each node forwards an RREQ packet that is received for the first time according to a fixed forwarding probability. However, the network topology in MANETs is highly dynamic due to the movements of nodes in the network [37]. As a consequence, the node distribution is often random and changes frequently. Therefore, the forwarding probability should be set dynamically to reflect the local topological characteristics of a given node; e.g. whether the node is located in a sparse or dense region. Motivated by this observation, a new adjusted probabilistic route discovery algorithm, which has been referred as AP, has been suggested. The AP adjusts the forwarding probability at a node based on its 1-hop neighbourhood information. To obtain accurate and up-to-date neighbourhood information at a node, periodic exchange of “hello” packets among neighbouring nodes, already implemented in the AODV has been used.

- Extensive simulation experiments have been conducted to compare the performance of the new AP-AODV against FF-AODV, the traditional AODV and the fixed probabilistic route discovery version of AODV. The performance impact of different network densities, offered loads and node mobility have been examined in the simulation experiments. The results have revealed AP-AODV exhibit superior performance advantage in terms of routing overhead, collision rate, normalised network throughput and end-to-end delay compared with FF-AODV, the traditional AODV and the fixed probabilistic version of AODV (FP-AODV).

- While the adjusted probabilistic route discovery approach reported in Chapters 5 rely on predetermined forwarding probabilities and only the neighbour density, the final part of this thesis has introduced a mathematical expression which dynamically calculates the forwarding probability at a node using its local node density in addition to the covered neighbour set. In the new algorithm has been referred to as dynamic probabilistic route discovery (DPR for short).

- The performance of DPR-AODV has been compared with those of self pruning (SP-AODV), FP-AODV and AODV. The performance impact of a wide range of system parameters, including network density, offered loads, and node mobility have been examined. The results have shown that DPR-AODV outperforms the other four protocols in most circumstances.

7.3 Directions for Future Work

Several interesting issues and unsolved problems that require further investigation have emerged in the course of this research. These are briefly outlined below.

- This thesis has presented extensive performance analysis of probabilistic broadcast algorithms based on reactive routing, e.g. AODV and DSR, as the base routing protocols. It would be an interesting prospect to examine the effects of probabilistic broadcast algorithms on the routing table advertisements in proactive routing protocols, such as OLSR [9], and hybrid routing protocols, such as ZRP [40].

- The random waypoint mobility model [109] has been extensively used in this thesis to simulate node mobility and its impact on the performance of probabilistic route discovery. Although this particular mobility model has been widely used in the literature [77, 106, 115], there are several other models which have recently been proposed [26, 27, 110], and which account for different motion patterns. For instance, the community based mobility model [110] models human movements within communities and among different communities, the Manhattan mobility model [27] models vehicular mobility on structured roads in a city, and the Group mobility model [26] models a motion pattern similar to military combat zones, e.g. the motion of a military infantry commander and his/her battalion. A possible continuation of this research would be to examine probabilistic route discovery for other mobility models.

- The performance analysis of probabilistic route discovery has been conducted assuming CBR traffic that relies on UDP. A natural extension of the research work would analyse the performance behaviour of the proposed probabilistic routing algorithms for other traffic types such as VBR and those that rely on TCP.

- Most existing studies including the ones described in this thesis have relied on simulations in order to conduct the performance analysis of algorithms proposed for MANETs. However, simulation cannot cover all possible scenarios (e.g. MANETs with a large number of nodes) due to time and complexity constraints. As such, a natural extension of the research efforts described in this thesis would be to develop analytical models that define the interactions between the important system parameters and their effects on the performance of the probabilistic route discovery algorithms.

- Even though simulation is a valuable tool in evaluating the performance of a MANET system, it often requires certain simplifying assumptions in order to keep the complexities of the various models (e.g. radio propagation models or mobility models) at a manageable level. As a result, the model may fail to capture all the important factors that might affect the performance of the system. So far, there has been little activity in the deployment and performance measurements of actual MANET systems. Provided adequate computing resources are made available to materialise an actual MANET configuration in the future, it would be useful to conduct real experimental measurements and verify the simulation results reported in this thesis. Apart from instilling confidence in the existing work, the results collected from such deployments could be particularly valuable for the realistic calibration of future simulation models.

Appendix A

A.1. Performance Comparison of Probabilistic Route Discovery in terms of Network Density

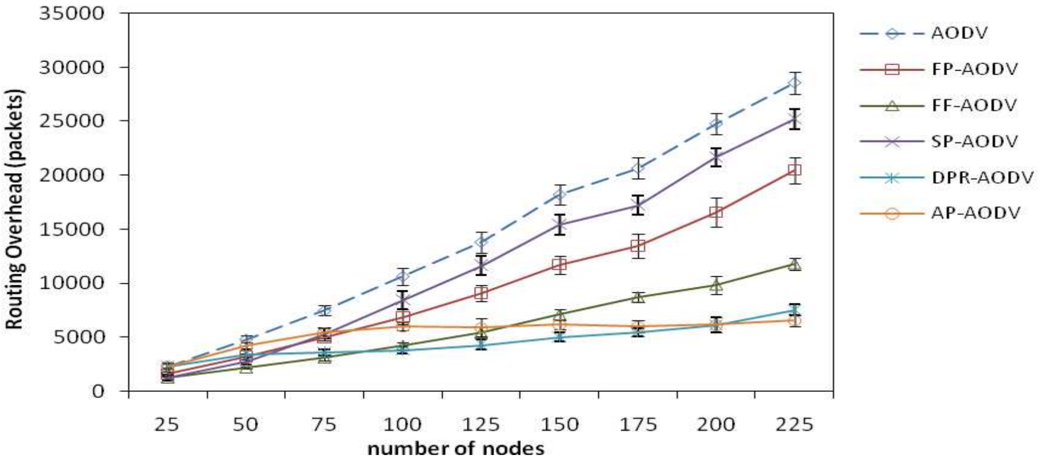


Figure A. 1. Routing overhead in terms of packets versus number of nodes placed over a 1000m x 1000m area.

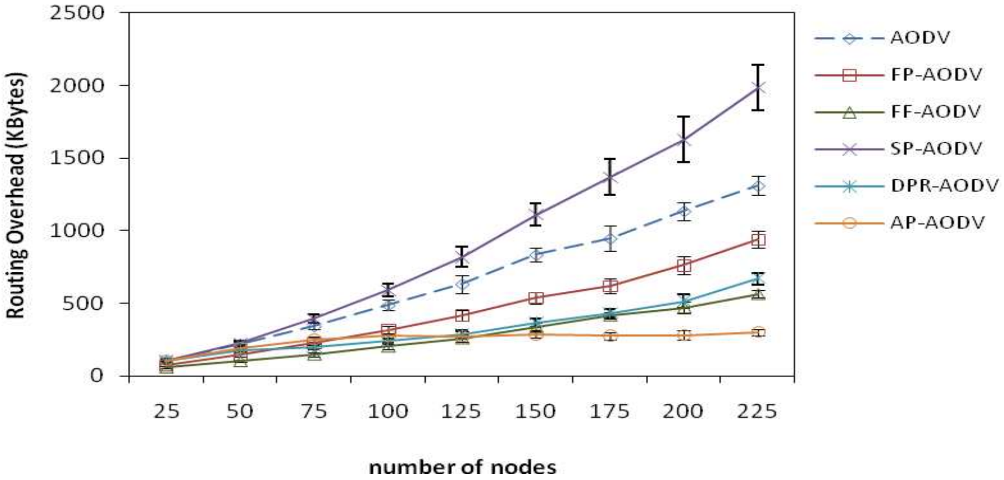


Figure A. 2. Routing overhead in terms of bytes versus number of nodes placed over a 1000m x 1000m area.

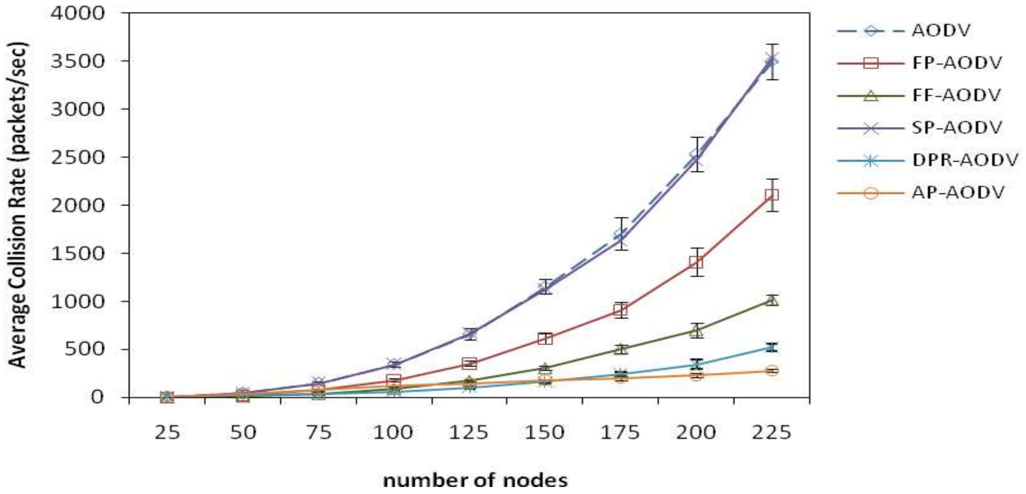


Figure A. 3. Average collision rate versus number of nodes placed over a 1000m x 1000m area.

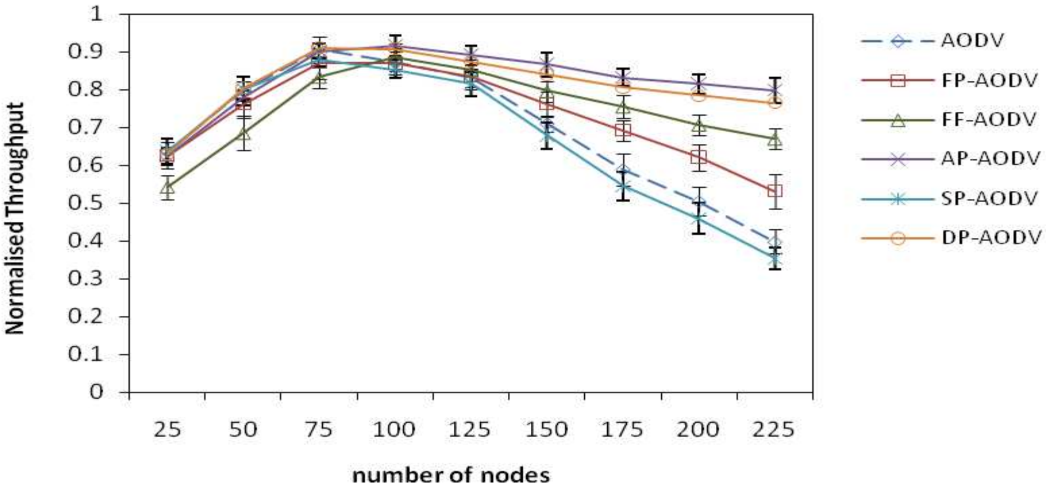


Figure A. 4. Normalised network throughput versus number of nodes placed over a 1000m x 1000m area.

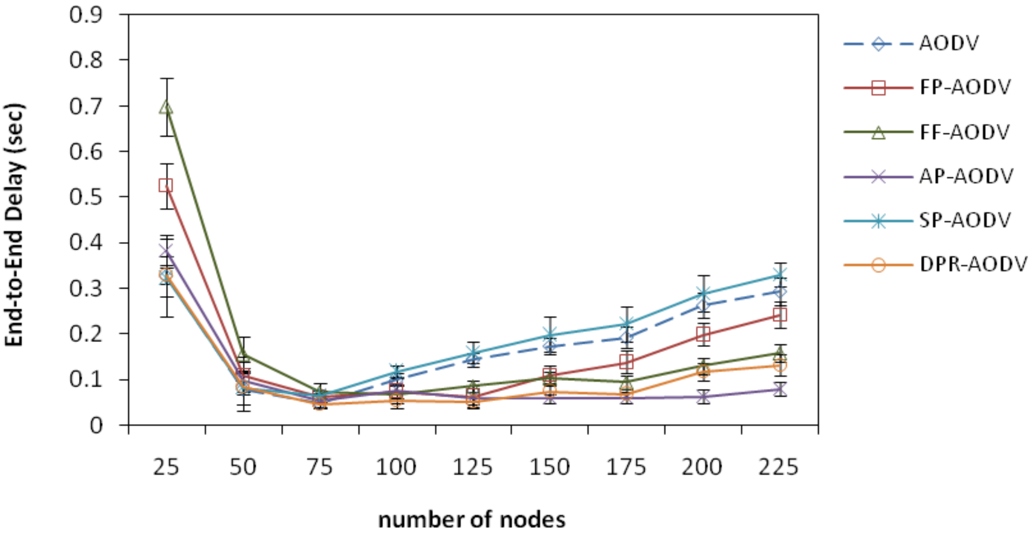


Figure A. 5. End-to-end delay versus number of nodes placed over a 1000m x 1000m area.

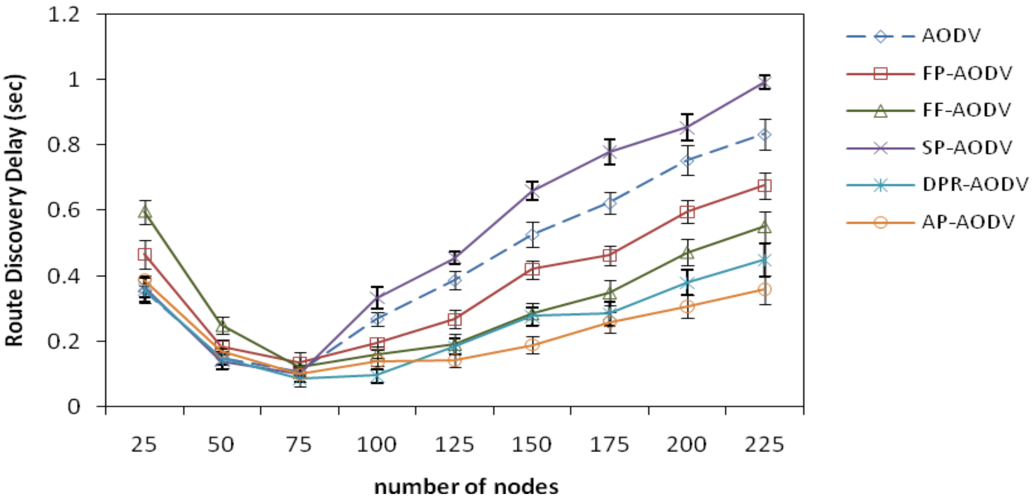


Figure A. 6. Route discovery delay versus number of nodes placed over a 1000m x 1000m area.

A.2. Performance of Comparison of Probabilistic Route Discovery in terms of Offered Load

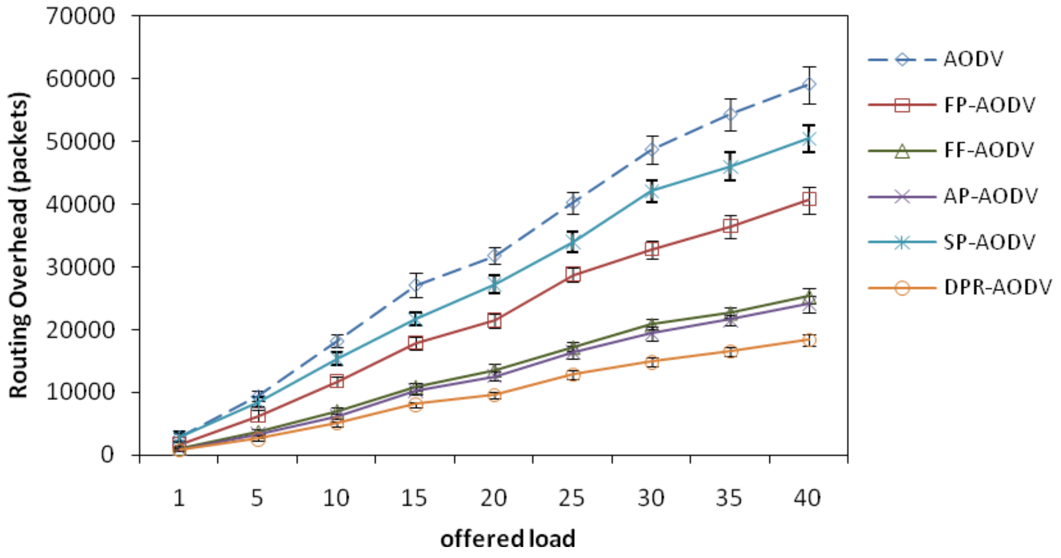


Figure A. 7. Routing overhead in terms of number of packets versus offered load for a network of 150 nodes placed in a 1000m x 1000m area.

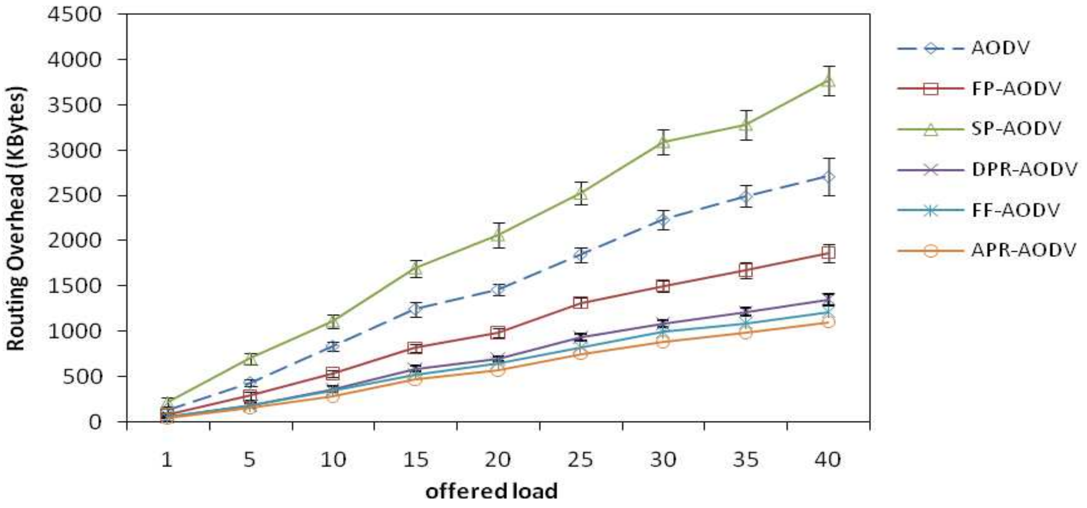


Figure A. 8. Routing overhead in terms of bytes versus offered load for a network of 150 nodes placed in a 1000m x 1000m area.

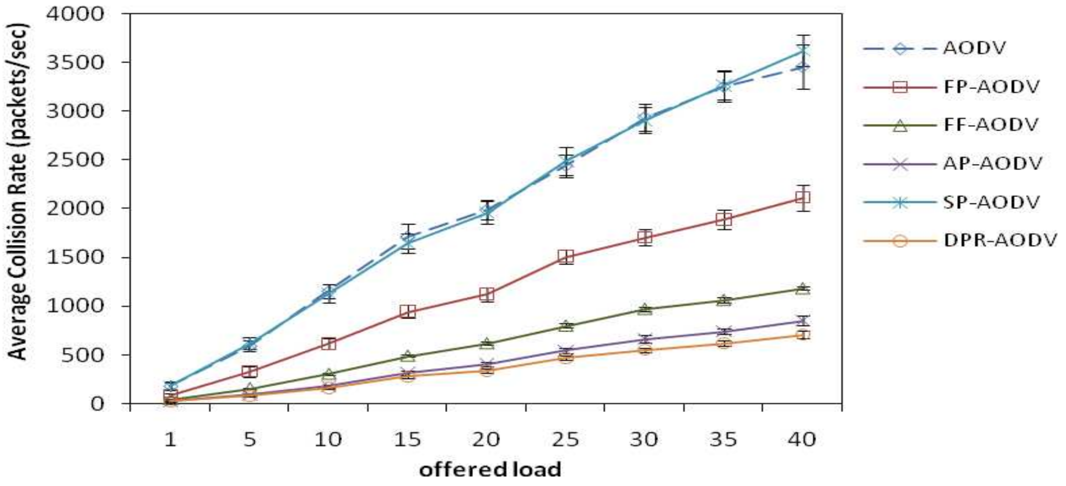


Figure A. 9. Average collision rate versus offered load for a network of 150 nodes placed in a 1000m x 1000m area.

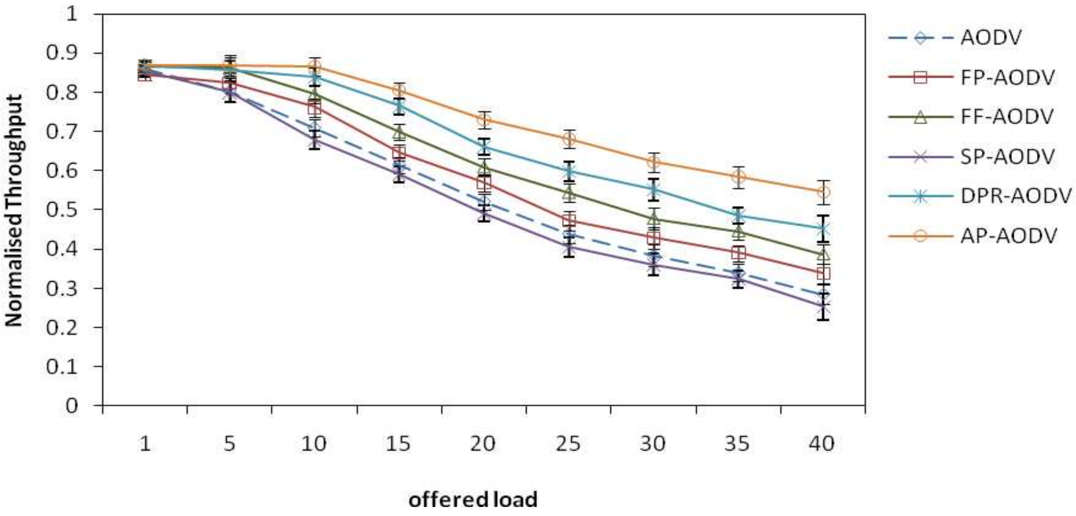


Figure A. 10. Normalised throughput versus offered load for a network of 150 nodes placed in a 1000m x 1000m area.

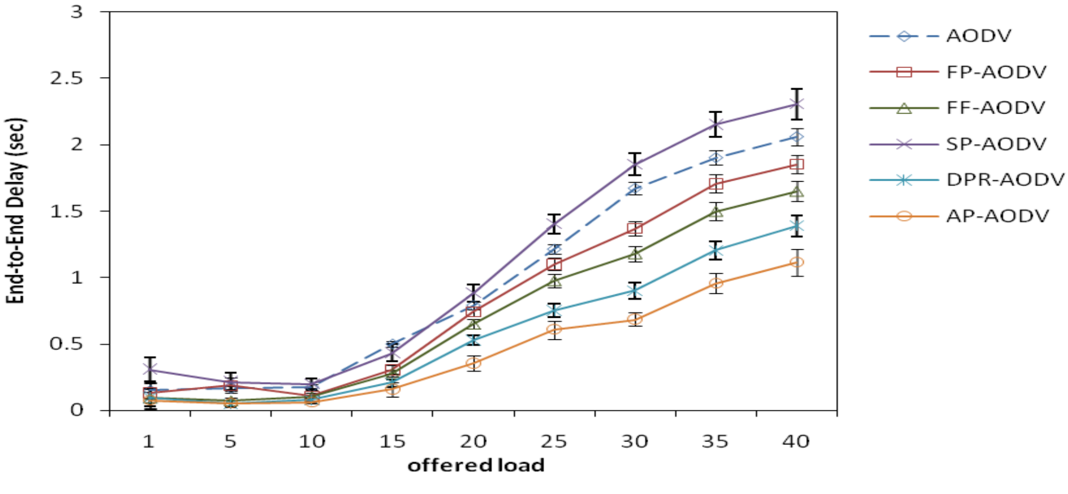


Figure A. 11. End-to-end delay versus offered load for a network of 150 nodes placed in a 1000m x 1000m area.

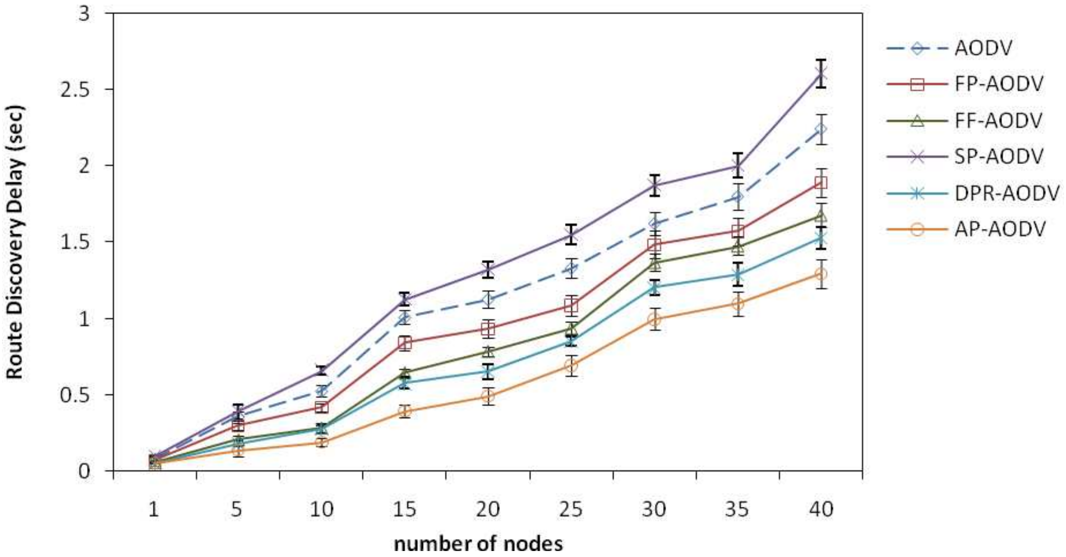


Figure A. 12. Route discovery delay versus offered load for a network of 150 nodes placed in a 1000m x 1000m area.

A.3. Performance of Comparison of Probabilistic Route Discovery in terms of Mobility

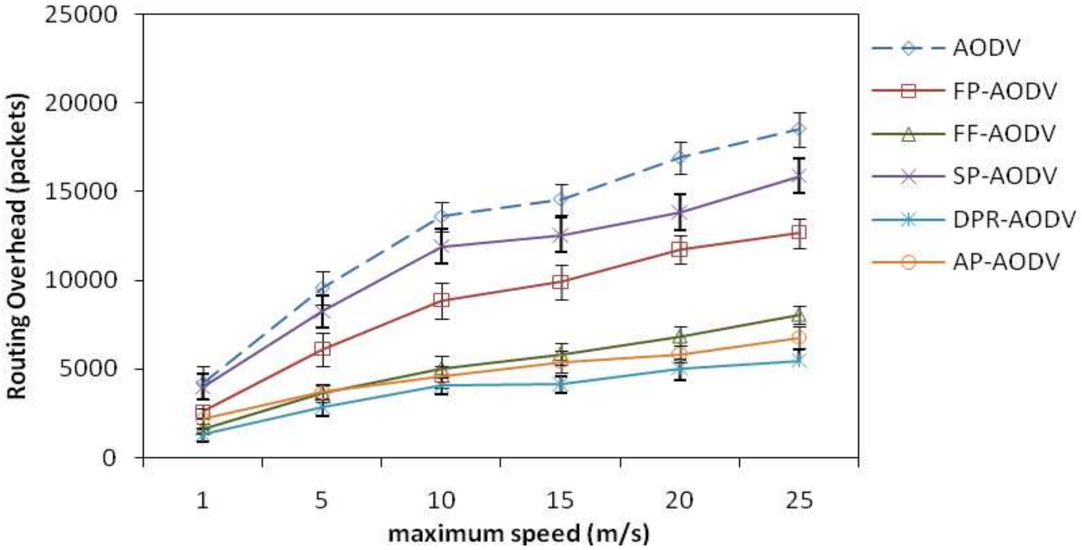


Figure A. 13. Routing overhead in terms of number of packets versus maximum node speed for a network of 150 nodes placed in a 1000m x 1000m area.

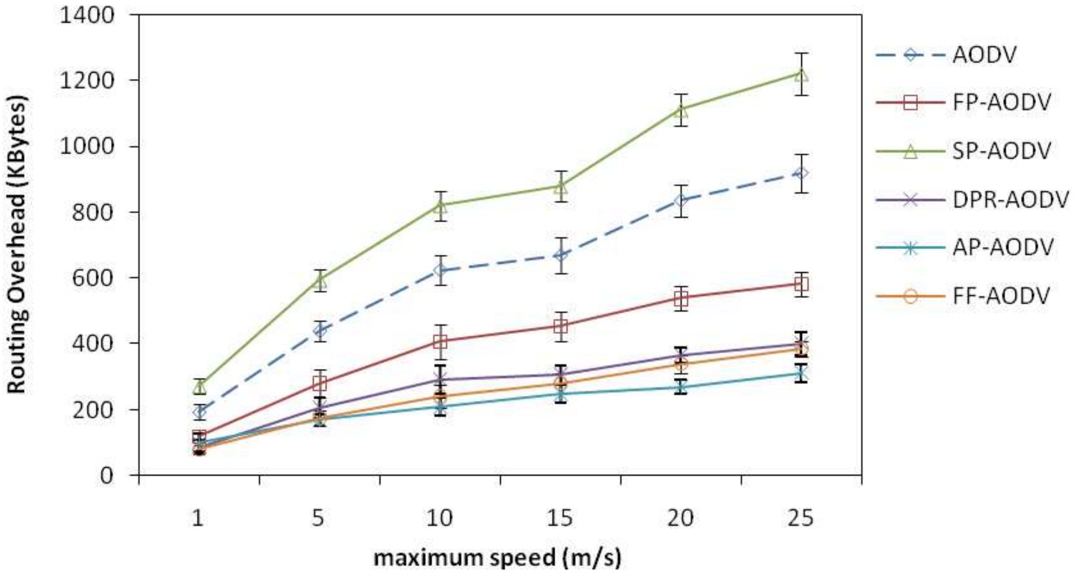


Figure A. 14. Routing overhead in terms of bytes versus maximum node speed for a network of 150 nodes placed in a 1000m x 1000m area.

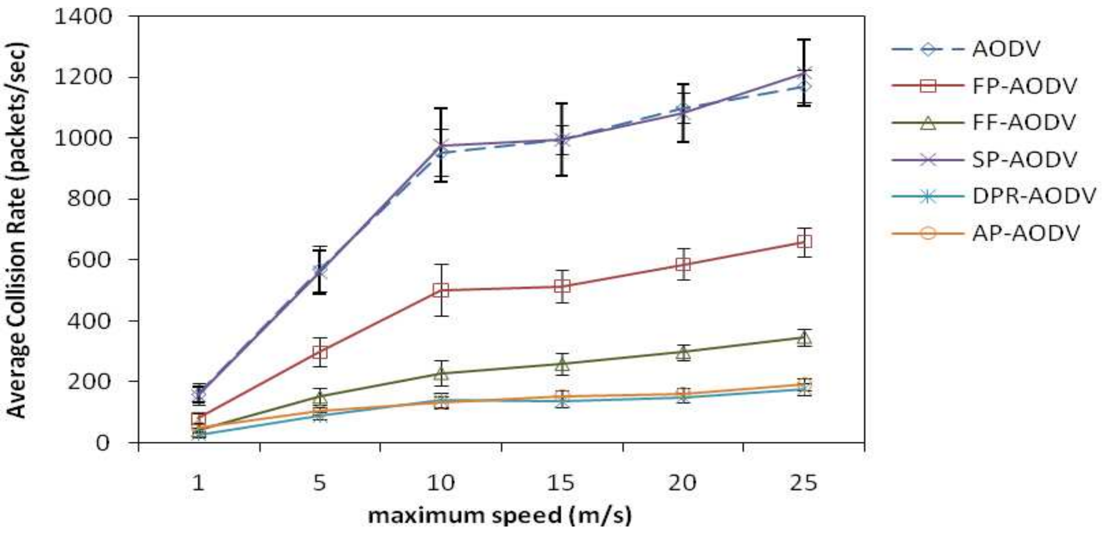


Figure A. 15. Average collision rate versus maximum node speed for a network of 150 nodes placed in a 1000m x 1000m area.

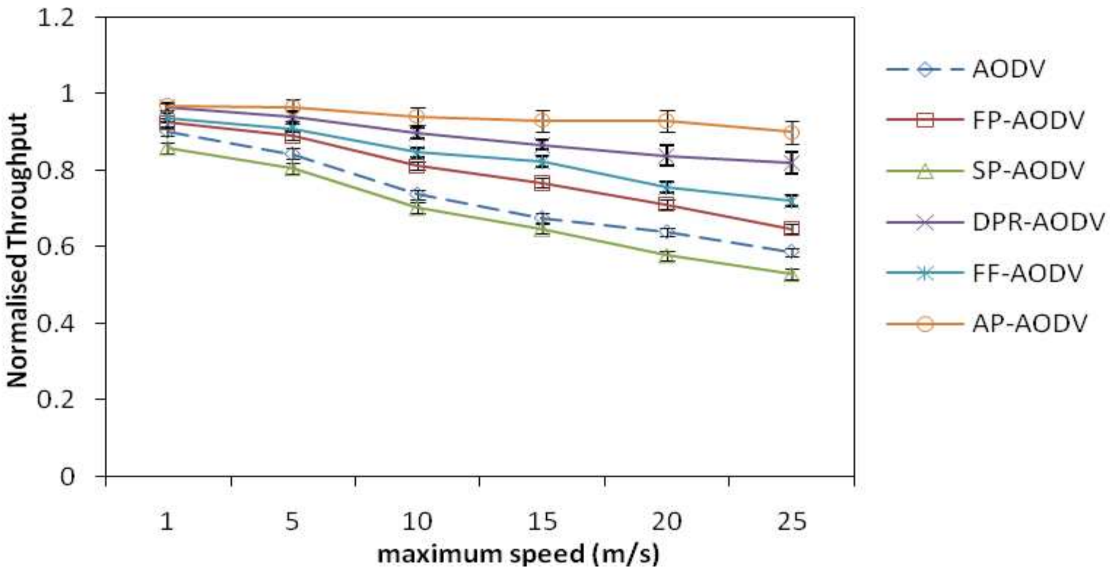


Figure A. 16. Normalised throughput versus maximum node speed for a network of 150 nodes placed in a 1000m x 1000m area.

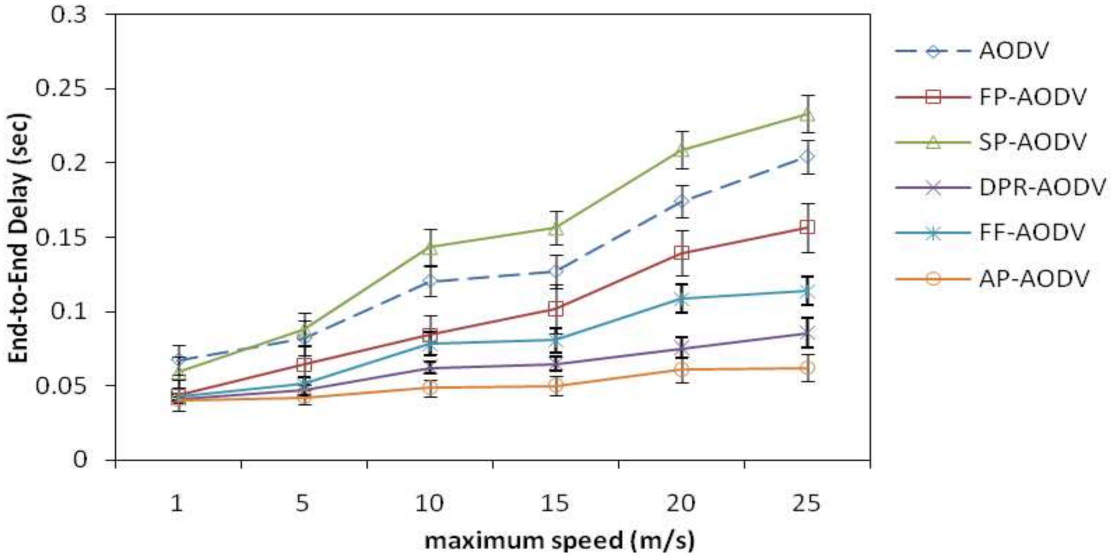


Figure A. 17. End-to-end delay versus maximum node speed for a network of 150 nodes placed in a 1000m x 1000m area.

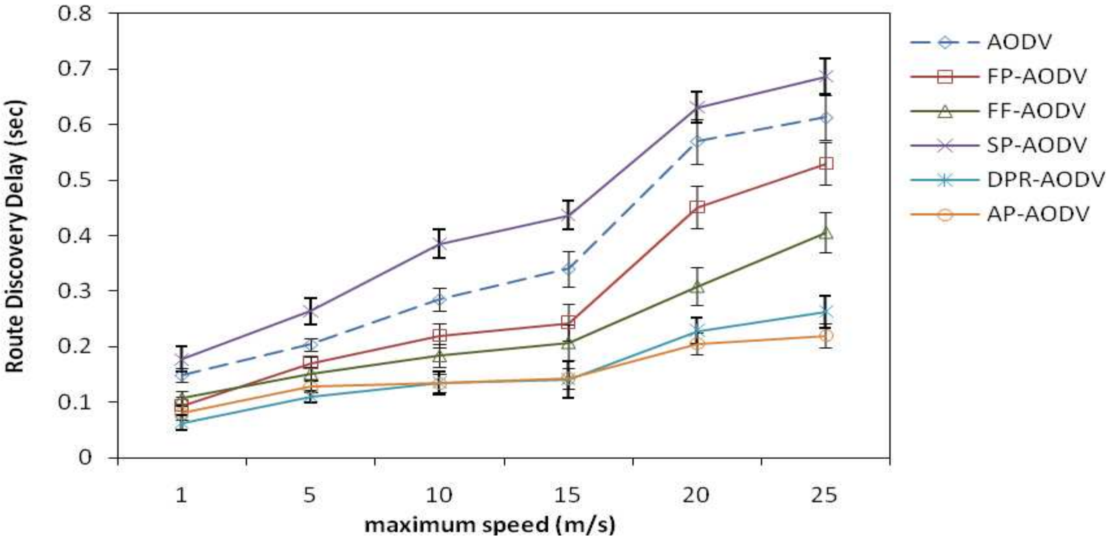


Figure A. 18. Route discovery delay versus maximum node speed for a network of 150 nodes placed in a 1000m x 1000m area.

Appendix B

Publications during the Course of this Research

- J. Abdulai, M. Ould-Khaoua, L.M.Mackenzie, Adjusted Probabilistic Route Discovery in Mobile Ad Hoc Networks, *Journal of Computers and Electrical Engineering*, vol. 34, Issue 1, pp. 168-182, January 2008.

- J. Abdulai, M. Ould-Khaoua, L.M.Mackenzie, M. Aminu, Neighbour Coverage: A Dynamic Probabilistic Route Discovery for Mobile Ad Hoc Networks, *Proceedings of International Symposium on Performance Evaluation of Computer and Telecommunication Systems, (SPECTS' 2008) IEEE,* pp.165-172, 2008.

- M. Aminu, M. Ould-Khaoua, L.M. Mackenzie, J. Abdulai, An Adjusted Counter-Based Broadcast Scheme for Mobile Ad Hoc Networks, *Proceedings of the Tenth International Conference on Computer Modelling and Simulation(EUROSIM/UKSIM 2008), 1-3 April 2008, University of Cambridge, UK*. pp 441 – 446, IEEE Computer Society Press, 2008.

- S. Al-Humoud, L.M. Mackenzie, M. Ould-Khaoua, J. Abdulai, RAD Analysis of Adjusted Counter-Based Broadcast in MANETs, *The 24th UK Performance Engineering Workshop, (UKPEW'08), Imperial College London*, pp. 300–310, July 2008.

- M. Aminu, M. Ould-Khaoua, L.M Mackenzie, J. Abdulai, Performance Evaluation of an Efficient Counter-Based Scheme for Mobile Ad Hoc Networks based on Realistic Mobility Model, *Proceedings of the 2008 International Symposium on Performance Evaluation of Computer and Telecommunication Systems(SPECT'08), Edinburgh, UK, IEEE*, pp. 181-188, June 2008,

- S. Al-Humoud, L.M. Mackenzie, M. Ould-Khaoua, J. Abdulai, Threshold Analysis of Adjusted Counter-Based Broadcast in MANETs, *Proceedings of Second UKSIM European Symposium on Computer Modelling and Simulation (EMS'2008*), pp. 500-55, 2008.

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- J. Abdulai, M. Ould-Khaoua, L.M. Mackenzie, Improving Probabilistic Route Discovery in Mobile Ad Hoc Networks *of 32nd IEEE Conference on Local Computer Networks (LCN 2007),* IEEE Computer Society Press. pp. 739-746, 2007

- M. Aminu, M. Ould-Khaoua, L.M. Mackenzie, J. Abdulai, Optimizing Counter-Threshold-Value for Counter-Based Broadcast Scheme in MANETs, *Proceedings of the 8th Annual PostGraduate Symposium on the Convergence of Telecommunications, Networking & Broadcasting, (PGNET 2007)*, Liverpool John Moores University, UK, pp. 241-246, 28-29 June 2007. EPSRC, UK.

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- J. Abdulai, M. Ould-Khaoua, L.M. Mackenzie, M. Bani-Yassein, On the Forwarding Probability for On-Demand Probabilistic Route Discovery in MANETs, *Proceedings of 7th Annual PostGraduate Symposium on the Convergence of Telecommunications*, *Networking and Broadcasting (PGNet 2006)* pp. 120 – 125, 2006.

- J. Abdulai, M. Ould-Khaoua, L. M. Mackenzie, M. Bani-Yassein, Efficient Forwarding Probability for On-Demand Probabilistic Route Discovery in MANETs, *Proceedings of 22nd UK Performance Engineering Workshop*(UKPEW 2006) pp. 9-15, 2006.

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