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Game Theoretic Approach in Routing Protocols for Wireless Mobile Ad Hoc Networks

by

Mohammad Naserian

A Dissertation

Submitted to the Faculty of Graduate Studies through the
Department of Electrical and Computer Engineering in Partial Fulfillment
of the Requirements for the Degree of Doctor of Philosophy at the
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Declaration of Co-Authorship and Previous Publication

I. Co-Authorship Declaration

I hereby declare that this thesis incorporates material that is result of joint research, as follows: This thesis also incorporates the outcome of a joint research undertaken in collaboration with Mohammed Tarique under the supervision of professor Kemal Tepe. The collaboration is covered in parts of Chapter 3 of the thesis. In all cases, the key ideas, primary contributions, experimental designs, data analysis and interpretation, were performed by the author, and the contribution of co-authors was primarily through the provision of discussing the simulation results.

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Thesis Chapter	Publication title/full citation	Publication Status
Chapter 3	Mohammad Naserian, Kemal Tepe, Tarique Mohammed, "On the connectivity of nodes in wireless ad hoc and sensor networks", <i>In the Proceedings of IEEE Canadian Conference on Electrical and Computer Engineering, Saskatoon, Canada, pp. 2073-2075.</i>	Published
Chapter 4	Mohammad Naserian, Kemal Tepe, Tarique Mohammed "Routing Overhead Analysis for Reactive Routing Protocols in Wireless Ad Hoc Network", <i>In the Proceedings of IEEE International Conference on Wireless and Mobile Computing, Networking and Communication (WIMOB), Montreal, Quebec, Canada, pp. 87-92, August 2005.</i>	Published
Chapter 5	Kemal Tepe, Mohammad Naserian, Tarique Mohammed, "A New Hierarchical Architecture for Wireless Ad Hoc Network", <i>In the Proceedings of Wireless 2004, Calgary, Alberta, pp. 246-254.</i>	Published
Chapter 5	Mohammad Naserian, Kemal Tepe, Tarique Mohammed "HDSR: Hierarchical Dynamic Source Routing for Heterogeneous Wireless Mobile Ad Hoc Networks", <i>In the Proceedings of the 10th IFIP International Conference on Personal Wireless Communications (PWC), Colmar, France, pp. 125-132, August 2005.</i>	Published
Chapter 6	Mohammad Naserian, Kemal Tepe, "Game Theoretic Approach in Routing Protocol for Wireless Ad Hoc Networks", <i>submitted to Elsevier Journal of Ad Hoc Networks.</i>	In press
Chapter 7	Mohammad Naserian, Kemal Tepe, "Game Theoretic Dynamic Probabilistic Forwarding in Wireless Ad Hoc Networks", <i>submitted to Elsevier Journal of Ad Hoc Networks.</i>	In press

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Abstract

Mobile Ad hoc Networks (MANETs) are becoming popular as a means of providing communication among a group of people. Because of self-configuring and self-organizing characteristics, MANETs can be deployed quickly. There is no infrastructure defined in the network, therefore all of the participating nodes relay packets for other nodes and perform routing if necessary. Because of the limitations in wireless transmission range, communication links could be multi-hop. Routing protocol is the most important element of MANET. Routing protocols for MANET can broadly be classified as proactive routing protocol and reactive routing protocol. In proactive routing protocols like Destination Sequence Distance Vector (DSDV), mobile nodes periodically exchange routing information among themselves. Hence proactive routing protocols generate high overhead messages in the network. On the other hand, reactive routing protocols like Ad hoc On-demand Distance Vector (AODV) and Dynamic Source Routing (DSR) work on-demand. Hence reactive routing protocols generate fewer number of overhead messages in the network compared to proactive routing protocols. But reactive routing protocols use a global search mechanism called “flooding” during the route discovery process. By “flooding” mechanism a source node can discover multiple routes to a destination. “Flooding” generates a large number of overhead packets in the network and is the root cause of scaling problem of reactive routing protocols. Hierarchical Dynamic Source Routing (HDSR) protocol has been proposed in this dissertation to solve that scaling problem. The DSR protocol has been modified and optimized to imple-

ment HDSR protocol. HDSR protocol reduces the “flooding” problem of reactive routing protocols by introducing hierarchy among nodes. Two game theoretic models, Forwarding Dilemma Game (FDG) and Forwarding Game Routing Protocol (FGRP), is proposed to minimize the ‘flooding’ effect by restricting nodes that should participate in route discovery process based on their status. Both FDG and FGRP protocols reduce overhead packet and improve network performances in terms of delay packet delivery ratio and throughput. Both protocols were implemented in AODV and the resulting protocol outperformed AODV in our NS-2 simulations. A thorough connectivity analysis was also performed for FDG and FGRP to ensure that these protocols do not introduce disconnectivity. Surprisingly, both FDG and FGRP showed better connectivity compared to AODV in moderate to high node density networks.

In memory of my respectful father,

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List of Abbreviations

ACK	Acknowledgement
AODV	Ad hoc On-demand Distance Vector
ARP	Address Resolution Protocol
BER	Bit Error Rate
CTS	Clear To Send
CSMA	Carrier Sense Multiple Access
CA	Collision Avoidance
CGSR	Clusterhead Gateway Switch Routing
CH	Cluster Head
CBR	Constant Bit Rate
CRP	Congestion adaptive Routing Protocol
CPU	Central Processing Unit
DARPA	Defense Advance Research Project Agency
DCA	Distributed Clustering Algorithm
DCF	Distributed Coordination Funcation
DHCP	Dynamic Host Configuration Protocol

DIFS	DCF Inter Frame Space
DMAC	Distributed Mobility Adaptive Clustering
DSDV	Destination Sequence Distance Vector
DSR	Dynamic Source Routing
FDG	Forwarding Dilemma Game
FGRP	Forwarding Game Routing Protocol
FN	Forwarding Node
FSR	Fisheye State Routing
FTP	File Transfer Protocol
GPS	Global Positioning System
GIS	Geographical Information System
HDSR	Hierarchical Dynamic Source Routing
IEEE	Institute of Electrical and Electronic Engineers
IETF	Internet Engineering Task Force
IERP	Interzone Routing Protocol
IARP	Intrazone Routing Protocol
IP	Internet Protocol
Kbps	Kilo bits per Second
LCC	Least Cluster Change
LAN	Local Area Network
LANMAR	Landmark Routing Protocol
LCA	Linked Cluster Architecture
LEAR	Localized Energy Aware Routing
MAC	Medium Access Control
MANET	Mobile Ad Hoc Network

MN	Mobile Node
NS	Network Simulator
NAM	Network Animator
OSI	Open System Interface
OTcl	Object Oriented Tcl
PDA	Personal Digital Assistant
PBOA	Progressive Back Off Algorithm
PDA	Personal Digital Assistant
RTS	Request To Send
RREQ	Route Request
RREP	Route Reply
RERR	Route Error
RAR	Retransmission Aware Routing
SIFS	Short Inter Frame Space
TCP	Transport Control Protocol
TBRP	Topology Broadcast based on Reverse-Path Forwarding
UCB	University of California at Berkeley
UDP	User Datagram Protocol
VINT	Virtual Inter-Network Testbed
WLAN	Wireless Local Area Networks
ZRP	Zone Routing Protocol

Chapter 1

Introduction

Wireless communication has become more and more popular in recent years. Today, cellular networks, satellite systems and wireless Local Area Networks (WLANs) are part of our daily life. In these kinds of wireless networks, there is a fixed infrastructure that establishes and maintains connections. There is another type of wireless network that has been under development, called the wireless ad hoc network, that is infrastructure-less, i.e. without a wired backbone. An ad hoc network is self-starting and self-maintaining, and can be formed on the fly. Wireless nodes can have mobility and can join or leave the network any time. Therefore, the network topology is changing dynamically. Ad hoc networks are very attractive if there is no existing network infrastructure or the current infrastructure is damaged. Some example applications are in a battle field, disaster relief, search and rescue operations as well as sensor networks. Generally, the Mobile Ad hoc Networks (MANET) could be a suitable solution for any application that requires a kind of temporary wireless network.

1.1 Applications of Ad Hoc Networks

Applications of wireless mobile ad hoc networks ranges from the military and disaster response applications to connecting a group of computers in a classroom. Some can be listed as following:

- **Sensor Networks**

Within the ad hoc networking field, wireless sensor networks assume a special role. A sensor network is composed of a large number of small sensor nodes which are randomly deployed inside an area where a phenomenon is being monitored [1] and [2]. Sensor devices are cheap to manufacture and each of them possesses identical capabilities. Such devices can be located into places like volcanic eruptions, chemical hazards, surfaces of planets, or generally where it is impossible or difficult for humans to enter. Such networks can then form a network of their own to collect data, compute, and acquire the desired information and relay them.

- **Emergency Services**

During times of emergency, when the existing infrastructure is damaged or out of service, there will be a loss of network connectivity. Emergency workers may need to share data with each other during their operation and they may also need some information from the wired network. Deploying a base station is not a feasible solution, as it may take several hours until a mobile base station can be made operational. In such cases, ad hoc networks remain the only possible solution for the network connectivity problems.

- **Home Networking**

Ad hoc networks can also be appropriate for applications in home networks where devices can communicate directly in order to exchange information.

- **Personal Communication**

Personal laptops, personal digital assistants (PDA), televisions, stereos, and other devices can form a MANET for multimedia communications.

1.2 Challenges in Deploying MANETs

There are many unique characteristics in ad hoc networks such as mobility, bandwidth constraint, error prone shared medium, congestion, and other resource constraints that do not exist in other networks. These characteristics, and the shared nature of the wireless channel, create some challenges for wireless ad hoc networks.

- **Mobility**

Participating nodes in a MANET can have mobility that could result in frequent route breakages, packet collisions, transient loops, stale routing information, and difficulty in resource reservation. An efficient routing protocol should be able to address all issues related to node mobility.

- **Scalability**

When the number of nodes increases, the number of routing messages in the network also increases. That increases the number of control messages in the network to the point where the network can not transfer data packets.

- **Energy Management**

In ad hoc networks, the mobile nodes operate on battery power. A mobile node in an ad hoc network not only generates its own traffic, but also forwards packets for other node's of the network. Therefore, loss of battery power will affect individual node as well as the network. When the battery of a node is exhausted, all of the routes that have been established through that node would no longer be valid. Nodes utilize their energy in the processing of the control messages from other nodes. That requires the mobile node to be active most of the time in order to listen to the channel.

- **Location dependent contention**

The load on a wireless channel varies with the number of nodes present in a given region. Contention for the channel becomes high when the number of nodes increases in the given region. The high contention for the channel causes a high number of collisions and a subsequent wasting of bandwidth. A good routing protocol should

avoid forming a high contention region in the network.

- **Wireless channel reliability**

Errors are higher due to the wireless medium and the multi-hop nature of the ad hoc networks. This degrades the end-to-end throughput significantly.

- **Quality of service**

Because of the lack of infrastructure, ad hoc networks are not very friendly towards applications that require stringent service requirements.

- **Security**

Traffic in an ad hoc network is highly vulnerable to security threats. Most network security solutions that rely on a Centralized Authority (CA) do not exist in an ad hoc network, which makes security in an ad hoc network a more challenging task. Shared wireless medium exposes the network to denial of service attacks.

1.3 Problem Statement

All of the routing protocols in wireless ad hoc network utilize some sort of flooding (data or control messages). For instance, in Ad Hoc On-Demand Distance Vector (AODV) and Dynamic Source Routing (DSR) protocols, Route Request (RREQ) messages are re-broadcasted by every node. The ultimate outcome of this re-broadcasting is “flooding” of overhead packets that consumes network’s bandwidth. Although some precautions, such as the “ring zero search” mechanism in [7] and [8], have been proposed in order to limit the flooding, flooding is still an issue in DSR and AODV routing protocols when the size of the network is large. When RREQ packets are received by the neighbors of a transmitting node, neighbors attempt to re-broadcast the RREQ packet in their own neighborhood soon thereafter. Because all neighbors contend with each other to get access to the wireless medium, this may increase number of collisions. It may also be likely that a node can receive multiple copies of the same RREQ packet from its neighbors that do not give any new information. Therefore, “flooding” generates a large number of redundant packets in the network that

consume network resources. Since flooding is a fundamental method in almost every routing protocol for wireless ad hoc networks, a more efficient flooding algorithm could significantly improve the performance of the routing protocol. However, reducing the number of redundant flooding messages may cause disconnectivity in the network. Therefore, a delicate balance must be maintained between routing overhead related to flooding and connectivity.

Some disadvantages of flooding are:

- Redundant re-broadcast: When a mobile node decides to re-broadcast a flooding packet, all of its neighbors may already have received that message from other nodes.
- Contention: After receiving a flooding packet by neighbors of the originator, those neighbors may severely contend with each other in order to get access to the medium to re-broadcast the flooding packet.
- Collision: Collisions are more likely to occur when all neighboring nodes attempt to re-broadcast at the same time.

Proposals to limit the “flooding” phenomenon in literature can be broadly classified as (1) location based schemes [26], (2) cluster based schemes [27, 28, 29, 30, 31, 32, 33] and [34], or (3) probability based schemes [35, 36, 37, 38] and [40]. Flooding in location-based schemes is performed according to the physical location of the nodes. In order to provide the location information, nodes are equipped with Global Positioning System (GPS). GPS requires additional hardware and software which increase the cost. That cost increase is not desirable for some applications such as sensor networks. In cluster-based method a group of nodes in close proximity form a cluster. In a cluster, there are three types of nodes: (1) the cluster-head (2) ordinary nodes, and (3) the gateway node. The cluster-head coordinates the communications of ordinary nodes. An ordinary node that is located in the radio range of two cluster-heads is called a gateway. Gateways pass data between clusters. Establishing and maintaining clusters requires additional overhead packets, which consumes additional network resources. Cluster-head and gateway nodes should dedicate all of their resources for the cluster members.

In a probabilistic scheme, a mobile node broadcasts a flooding packet based on a probability $p < 1$. The simplest approach in this class is pure probabilistic flooding, in which nodes that receive a broadcast packet retransmit that packet with probability p or discard (drop) this packet with probability $(1 - p)$ [39] and [36]. Through extensive simulations, it was shown in [36] that a simple probabilistic forwarding used up to 35% fewer overhead packets than flooding and could improve the performance of AODV even in small networks of 150 nodes. A critical value for forwarding probability depends on the number of neighbors of a node. As the number of neighbors of each node increases, the critical value of p should decrease [37]. The major problem of probabilistic schemes is that the probability at which a node should rebroadcast is not universal, but specific to network topology and there is no analytical formula to obtain that probability, p . In some studies, node density, or the number of neighbors, has been used in a function to calculate forwarding probability [41, 42, 43] and [44]. Zhang and Dharma [45] introduced a dynamic probabilistic schemes where every node calculates p based on the node density and the number of broadcasts of the same flooding packet. Forwarding is performed after a random delay, which increases the latency.

Another problem of reactive routing protocols such as DSR or AODV, is congestion. Nodes located around the center of the network carry more traffic compared to other nodes located around the perimeter of the network [46] making a part of the network more congested. Congestion information, obtained from queues of the network interfaces, have been used to improve ad hoc routing protocol [47] and [48]. Mobile nodes have limited battery capacity; and battery exhaustion is one of the reasons of node failure. In some applications replacing or re-charging the battery is not feasible. Limiting the flooding messages will help the nodes to save energy and extends the network life. Because of the multi-hop nature of the communication links in ad hoc networks, individual node failures may affect the network performance. Energy aware routing protocols were proposed to save energy in mobile nodes. These protocols can be classified as: (1) transmit power control [49, 50, 51, 52, 53] and [54], (2) load distribution [55] and [56], and (3) sleep/power down [57] and [58]. In the transmit power control approach, the wireless nodes' transmission power is controlled

to maintain a connected topology while saving energy. Selecting a route that minimizes the total energy consumption is the main objective of this approach. In the load distribution approach, network traffic is distributed among the nodes in order to increase the life of the network nodes. In sleep/power-down approaches, nodes have the option to switch to sleep mode in some time period to save energy. Some energy aware routing protocols incur additional overhead packets in the network that degrade the performance [52]. Therefore, there is always a trade off for these type of protocols between the energy saving and the performance. Recently, it has been suggested that a fixed protocol stack like Open System Interface (OSI) model is not suitable for ad hoc networks. An interaction among protocol layers, called the Cross Layer, is essential to optimize the performance [59, 60, 61, 62, 63, 64] and [65]. The authors of [63] proposed a cross layer design concept that improves network performance significantly by using cross layer information interaction among physical, MAC and network layers. Interaction between the physical layer and the MAC layer has been investigated in [62] to achieve automatic transmission rate adaptation that improves spectral efficiency and minimizes packet delay. In [65], the joint effect of physical and MAC layers on power efficiency and the appropriate transmission power level was investigated. An energy efficient scheme based on cross layer design was introduced in [61]. Authors of [64] proposed a cross layer routing protocol. They used physical layer Signal to Interference and Noise Ratio (SINR) and MAC layer delay in routing decisions. Choosing appropriate routing decisions at the network layer affects the performance of the MAC layer and the physical layer. The authors of [64] suggested that cross layer interactions among those three layers are essential for making efficient routing decisions. We use the cross layer information in Chapter 7 to select the forwarding nodes.

1.4 Contributions

This dissertation addresses the problem of efficient reactive routing protocol for wireless ad hoc networks through limiting the “flooding” effect by introducing hierarchy among the network nodes. The performance of the routing protocols for ad hoc network deteriorates with the increasing the network size and node density (scalability). In this dissertation, we

address the scalability problem in AODV and DSR routing protocols by modifying these protocols. We first show that the severity of the flooding phenomena in reactive routing protocols with a mathematical model and NS-2 simulations. Our mathematical model, verified through NS-2 simulations, shows that any reactive routing protocol is sensitive to the increase of size and number of nodes in the network. We show that reactive routing protocols are not scalable. Also the performance of the reactive routing protocols deteriorate with increasing traffic. The first proposed routing protocol to improve the scalability is called the Hierarchical Dynamic Source Routing (HDSR) protocol [75]. The Dynamic Source Routing (DSR) protocol is modified to implement the HDSR protocol. In the HDSR protocol, network nodes are classified into Mobile Node (MN) and Forwarding Node (FN). MN can only be the source or the destination. FN participates in the packet forwarding operation. Because only forwarding nodes (FN) participate in the route discovery phase of the protocol, a large number of overhead packets are eliminated. That is why there are less contention and collisions caused by overhead packets generated during the route discovery process. Therefore, network resources such as bandwidth and battery power are used more efficiently in HDSR protocol compared to DSR protocol. That enables better utilization of shared wireless medium, hence transmission of more data packets instead of overhead packets. After receiving request packet from a source node, a few of the neighboring nodes, of the source, which are FNs, re-broadcast the request message, which reduces the chance of packet collision and reduce network overhead. FNs are randomly distributed and pre-selected in the HDSR protocol, which is the case for heterogeneous networks. We utilize game theory as a decision making tool in dynamically selecting FNs based on the desired network performance. FDG and FGRP are the proposed game theoretic hierarchical protocols. A Neighbor Discovery Protocol (NDP) is proposed to determine the number of neighbors for each node without additional overhead. Game theory is used in forwarding decisions. Forwarding Dilemma Game (FDG) is a simple protocol that uses proposed NDP to identify the number of players of the forwarding game. The outcome of the forwarding game is the forwarding probability that the node would use to forward the flooding packet.

Forwarding Game Routing Protocol (FGRP) utilizes cross layer information in a defined

availability parameter inside the utility function of the nodes. Here the proposed NDP is also utilized with some modifications. In FGRP, the strategy of the players of the forwarding game is their forwarding probability. The strategy selected by other neighbors (players) is also included in the FGRP utility function. Availability parameter makes FGRP model flexible to different applications. In FDG model, the forwarding probability is dictated only by the number of players of the game (node density). While in FGRP, the strategy (forwarding probability) is selected based on node's availability, other nodes participation and node density.

At a glance, the proposed HDSR, FDG and FGRP protocols have the following unique advantages compared to other 'flood' minimizing protocols:

- No additional hardware (i.e., GPS) is required.
- No additional control message is required. Existing control messages such as RREQ packet has been used.
- Proposed protocols work on-demand.
- Routing overhead is reduced. Therefore, network resources such as energy and bandwidth are saved.

FDG can be integrated with any routing protocol that implements "flooding". In addition to the above advantages, FDG has also the following improvement:

- FDG is aware of node density by utilizing NDP.
- FDG protocol performs well in low and high node densities.
- Connectivity of the nodes is not compromised by limiting the flooding.

FGRP brings addition improvement by utilizing the cross layer information:

- FGRP is aware of node density by utilizing NDP.
- FGRP protocol performs well in low and high node densities.

- Connectivity of nodes is not compromised by limiting the flooding.
- Cross layer information such as congestion, residual battery level can be utilized to implement FGRP protocol to tailor the system for desired performance.
- The FGRP protocol ensures energy consumption distribution among nodes in the network.
- The FGRP protocol uses node energy efficiently. Hence network life is maximized.

1.5 Thesis Organization

In this dissertation, we propose algorithms that limit the packet flooding in ad hoc network. An overview of the ad hoc networks and routing protocols is provided in Chapter 2. Since game theory will be utilized, an introduction to game theory is provided in Chapter 2 as well. Limiting the flooding packets can cause network disconnectivity and isolated nodes. That is why we first investigate connectivity conditions in Chapter 3 through extensive NS-2 simulations. In Chapter 3, we show that the probability that every node has at least one neighbor, namely local connectivity, is a fairly good approximation for the global connectivity. The result of Chapter 3 can be used by ad hoc network protocol designers in hierarchical protocols like the one proposed in Chapter 5.

A method for quantizing the overhead packets in an ad hoc network with reactive routing protocol is presented in Chapter 4. The result of Chapter 4 is helpful to validate the computer simulations. The results of the proposed model are compared with those of the NS-2 simulations; and they match quite well.

The HDSR protocol is introduced in Chapter 5. The advantages and disadvantages of HDSR protocol are explained in detail. A comparative performance analysis between the DSR protocol and the HDSR protocol is presented in Chapter 5. The forwarding node selection in HDSR is random.

The decision to forward a flooding packet, based on the outcome of the FDG game, is proposed in Chapter 6. A wireless node in FDG has a strategy set $S = \{Forward, Not Forward\}$.

To limit the number of flooding packets, probability of selected strategy is calculated based on the mixed strategy Nash equilibrium of the game. A novel Neighbor Discovery Protocol (NDP) presented in Chapter 6 provides the number of players of the FDG game. We will show in Chapter 6 that FDG applied to AODV improves the scalability performance of the AODV routing protocol.

A dynamic probabilistic forwarding protocol for wireless ad hoc networks based on game theory will be presented in Chapter 7. In FGRP, wireless nodes of the ad hoc network are the players of the game and the forwarding probability of the nodes is the strategy of the players. Each node has a utility that is a function of its strategy and its availability to forward packets for other nodes. Parameters such as energy, congestion and the distance from the source of the received packet can be included in a node availability parameter. A node enters the forwarding game upon receipt of a flooding packet. In Chapter 7 we show that utilizing FGRP improves the performance of AODV. The performance figures will be measured by varying three network parameters: scalability (node density), packet generation of source nodes, and mobility of nodes.

Chapter 8 will provide a summary of this work. Some future research directions is also discussed in Chapter 8 .

Chapter 2

Background

2.1 Routing Protocols for Ad Hoc Networks

The main purpose of a routing protocol is to create and maintain a routing table that contains information on how to reach a certain destination in the network. Nodes use this information to forward packets that they receive to other nodes. Routing is not a new issue in computer networking. Routing protocols such as distance vector routing (e.g. Routing Information Protocol; RIP [3] and [4]) and link-state routing (e.g. Open Shortest Path First protocol; OSPF [5]) have existed for a long time and are broadly used in wired networks. These routing protocols are not suitable to be used in mobile ad hoc networks for the following reasons: First, they were designed with a quasi-static topology assumption. In ad hoc networks, mobile nodes can join and leave the network at any time. Nodes are battery operated and may run out of power at any time. Therefore, the network topology changes frequently and those routing protocols may not reach a steady state and be able to construct routing tables. Second, those routing protocols were designed for wired networks with bidirectional links that may not be always the case in mobile ad hoc networks. Other than wireless channel, different radio range of wireless nodes could be the root cause of uni-directional links. Third, those routing protocols try to maintain routes to all reachable

destinations in the network, and that is not feasible in typical mobile ad hoc networks with large numbers of nodes, such as a large wireless sensor network. In MANETs, because of the shared wireless medium, broadcasting the routing information periodically would occupy bandwidth and reduce network throughput. Therefore, special routing protocols are needed for MANETs.

Since wireless nodes perform routing for other nodes of the network, the dynamic topology of the ad hoc network causes frequent route breakage. The shared wireless medium, high packet loss, inherent unreliability and high interference and noise contribute in the degraded performance of the routing protocol in MANETs. Nodes that are located in each other's radio range can not transmit at the same time because of the shared wireless medium and this limits the bandwidth and increases delay. Routing protocols provide self-organizing and self-configuring properties of the ad hoc network. That makes routing one of the most important elements of ad hoc networks. Specifications for many existing ad hoc routing protocols have been developed and prepared by the Internet Engineering Task Force (IETF) MANET working group [6]. That group has published drafts for the following ad hoc routing protocols:

- AODV (Ad hoc On-demand Distance Vector) [7]
 - DSR (Dynamic Source Routing) [8]
 - ZRP (Zone Routing Protocol) [9]
 - OLSR (Optimized Link State Routing) [10]
 - LANMAR (Landmark Routing Protocol) [11]
 - FSR (Fisheye State Routing) [12]
 - IERP (Interzone Routing Protocol) [13]
 - IARP (Intrazone Routing Protocol) [14]
 - TBRPF (Topology Broadcast based on Reverse-Path Forwarding) [15]
-

In literature, MANETs routing protocols are usually classified by the approach they use for acquiring and maintaining routes. Two main approaches used today are:

1. Proactive (table-driven) routing:

In this approach, routing protocol tries to keep a routing table with routes of the nodes in the network. Network topology changes are propagated in the entire network to ensure that all nodes update their routing tables. In proactive routing protocols, like Destination Sequence Distance Vector (DSDV) [16], routing information is periodically exchanged among the wireless nodes and a node would have a route to any destination in the network. DSDV routing protocol is based on the classic Bellman-Ford routing algorithm [17]. In DSDV, while network resources have been spent (i.e. used) to acquire routes, some of the routes may not be used for the life of the network. Exchanging routing information periodically generates huge number of overhead packets in the network, which makes the proactive routing protocols not suitable for MANETs especially in high mobility scenarios. The advantage of this approach is that routes are available all the time and there would not be any route discovery delay.

2. Reactive (on-demand) routing:

A route to a certain destination is acquired via a route discovery process when it is needed. When the route is found, it is maintained by a route maintenance process until it has been determined that the route is no longer needed. The advantage of this approach is the saving of network resources, as the periodic exchange of routing information is no longer necessary. The disadvantage is that the route discovery process could take some time, and this adds to the packet delay. For some applications, this may not be acceptable. There are also hybrid approaches that combine both the proactive and the reactive routing protocols together.

In this section, a brief overview of two popular routing protocols, AODV and DSR, is provided.

2.1.1 Ad hoc On-demand Distance Vector (AODV)

Ad hoc On-demand Distance Vector (AODV) [7] is one of the most popular routing protocols for ad hoc networks. AODV performs very well both during high mobility and high network traffic load, making it one of the most interesting candidates among the existing ad hoc routing protocols. AODV offers low overhead and quick adaptation to dynamic link conditions ([21] and [22]). Different AODV implementations, such as AODV-UU [23], have been developed. Three different types of message control packets are defined in AODV:

1. Route Request (RREQ)
2. Route Reply (RREP)
3. Route Error (RERR)

AODV is a reactive protocol where routes to destinations are acquired in an on-demand fashion. When a node needs a route to a destination, it broadcasts a RREQ packet. The RREQ packet is propagated throughout the network and every node that receives it sets up a reverse path, i.e., a route towards the requesting node. When the RREQ packet is received by the destination or a node with a (fresh) route, a RREP packet is sent back to the originator of the RREQ packet. The intermediate nodes utilize the reverse route that has been generated in the RREQ for forwarding RREP messages. If the route is provided by the intermediate nodes, the destination node never learns about a route back to the source node and does not have a route if it needs to communicate with the source node (e.g. to reply to a TCP connection request). To address this issue, the originator of a RREQ packet can set a gratuitous RREP flag in the RREQ packet to notify the intermediate nodes to send a gratuitous RREP to the destination node if they have a route. This way, the destination node learns the route to the source node. Routing table entries maintained by AODV nodes contain the following fields [7]:

- Destination IP Address
- Destination Sequence Number

- Valid Destination Sequence Number
- Interface
- Hop Count (number of hops required to reach the destination)
- Next Hop
- List of Precursors (described below)
- Lifetime (expiration or deletion time of the route)
- Routing Flags
- State (valid or invalid)

For route maintenance, every node monitors the status of the link to the next hop. This can be done by monitoring periodic HELLO messages (beacons) from other nodes or link layer notifications such as those provided by IEEE 802.11 [24]. A list of unreachable destinations is sent via a RERR packet to the neighboring nodes when a link failure is detected. Routes are only kept as long as they are needed. If a route is not used for a certain period of time, its corresponding entry in the routing table is deleted.

2.1.2 Dynamic Source Routing (DSR) protocol

The Dynamic Source Routing (DSR) [8] protocol is another reactive routing protocol that is based on source routing. Source routing means that every packet contains the route through which it should pass to reach its destination. This route is embedded in the header of the packet. There are two main mechanisms in DSR: (1) route discovery and (2) route maintenance. These mechanisms have been designed based on the following assumptions.

- Nodes of the network are willing to participate in network operation.
- Mobile nodes may move at any time in any direction without notice. It is assumed that the node's speed is moderate with respect to transmission latency and wireless transmission range.

- The network card of a mobile node can operate in 'promiscuous receive' mode. This mode causes the hardware to deliver every received packet to the network driver software without filtering based on link-layer destination address.
- Wireless links are bidirectional. It is assumed that Medium Access Control (MAC) layer utilizes a mechanism like four-way handshaking. The four-way hand shaking involves exchanges of Request to Send (RTS), Clear to Send (CTS), Data and Acknowledgment (ACK) packets between a transmitting and receiving mobile nodes.

If a node, called source, wishes to send some packets to another node, called destination, it first searches its route cache for a route to that destination. A route discovery mechanism to find a route to the destination is initiated if a route does not exist in the cache. In route discovery, the node transmits a route request (RREQ) packet that is received by other nodes that are located in its wireless transmission range. Each route request contains addresses of source and destination nodes, and a unique identification number (request ID). Each node that receives the RREQ appends its address to the header of the RREQ and re-broadcasts the RREQ if it is not the destination. If the receiving node is the destination of the RREQ, it sends a route reply packet (RREP) to the source node after copying the accumulated routing information located in the header of the RREQ to the header of the RREP. When the source node receives the RREP packet, it records the new route into its cache and utilizes that route to send data packets. Intermediate nodes that receive the RREQ more than once and have already forwarded would ignore subsequent RREQ's. Source and destination addresses and request ID help to identify a duplicate RREQ.

Network topology changes are detected by the route maintenance mechanism. If an intermediate node on the route detects a broken link, it initiates the route maintenance mechanism and sends messages to the source and other nodes that are on this route. Acknowledgment messages can be used to provide assurance about the link existence. MAC protocol acknowledgment messages can be utilized for this purpose. For instance, in the IEEE 802.11 Wireless LAN MAC layer [25], acknowledgments are provided for every packet (data or control). If a node does not receive any acknowledgment after sending a packet several times, it considers the link broken, and marks all the routes containing that link as

“invalid”. A route error RERR packet is broadcasted when a node discovers a broken link. Nodes that receive the RERR packet, update their route caches. When a RERR packet is received by the source node, a route discovery mechanism is initiated by the source node if there is no alternative route in the cache for that certain destination.

2.2 Network Simulator (NS-2)

Network Simulator(NS-2), an open source discrete event simulator, was developed at the University of California, Berkeley. NS-2 originated from Real Network Simulator [70] and was developed at Cornell University, Ithica, New York in 1989. Network Simulator evolved while it was supported by Defense Advanced Research Project Agency (DARPA) through the Virtual InterNetwork Testbed (VINT) project at Lawrence Berkeley National Laboratory (LBNL) in Berkeley, Xerox Palo Alto Research Center (PARC), University of California at Berkeley (UCB), and Information Science Institute (ISI) of the University of Southern California (USC). NS-2 includes contributions from researchers working at UCB, Monarch projects of Carnegie Mellon University (CMU) and Sun Microsystems. NS-2 is an appropriate tool to simulate and test the performances of network protocols. The simulator takes a network scenario as input, which consists of network topology, protocols, workload and control parameters. It produces performance results such as throughput, queuing delay and number of dropped packets. NS-2 can simulate Transport Control Protocol (TCP) and User Datagram Protocol (UDP), traffic source behavior such as File Transfer Protocol (FTP), Telnet, Web, Constant Bit Rate (CBR), router queue management mechanism such as Drop Tail, routing algorithms such as Dynamic Source Routing (DSR) protocol, Ad hoc On-demand Distance Vector (AODV), Destination Sequence Distance Vector (DSDV) and MAC protocol such as IEEE 802.11. Because NS-2 is open source, it provides the researcher the flexibility to modify the implemented protocols. This makes NS-2 a very powerful tool for research and development.

NS-2 code is written in C++ and Object Oriented Tcl (OTcl). OTCL is based on Tcl script language with object oriented extensions developed at MIT. Figure 2.1 shows a simplified model of NS-2. OTcl script consists of a simulation event scheduler, network

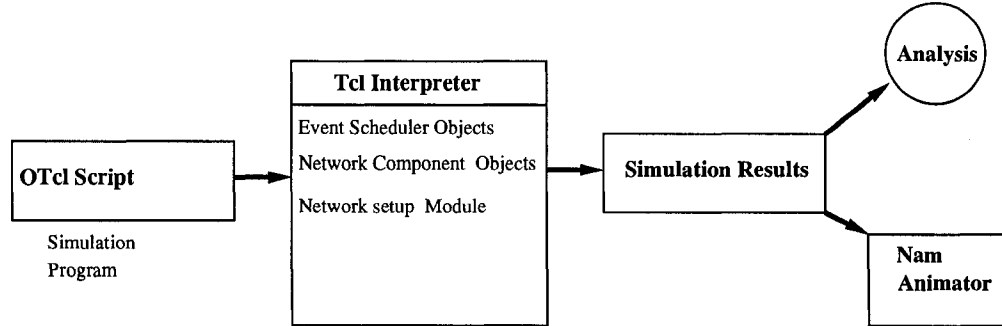


Figure 2.1: NS-2 model

component object libraries, and network setup libraries. The NS-2 users write programs in Tcl script to setup and run network simulations. Every packet generated in NS-2 has a unique identification (id). The record of every packet is stored in a trace file. Trace files contain information like time packet generation time, source ID, and packet arrival time at the destination. Network Animator (NAM) is an additional tool to NS-2 that depicts network activities graphically. Packet dropping, node movement, energy levels and other network parameters can be viewed in NAM.

The Monarch project of Carnegie Mellon University extended NS-2 to simulate wireless networks. The extended version of NS-2 provides new elements at the physical, link and routing layers to simulate wireless networks. An overview of a wireless network proposed by the Monarch project is depicted in Figure 2.2. Mobile nodes are independent of each other and a network interface connected to the common channel, is provided. Wireless channel carries packets between different mobile nodes. When a packet is transmitted, it reaches all nodes that have network interfaces connected to the same channel. A predefined power level is utilized in transmitting packets. The other mobile nodes receive that packet at a certain power level which is determined by radio propagation model. A packet received at a power level greater than a threshold value is acceptable. If the received power of the packet is smaller than the threshold value, the packet is lost.

The architecture of a mobile node in the NS-2 is shown in Figure 2.3. Network interface records the interface properties of the packet and invokes the propagation model upon

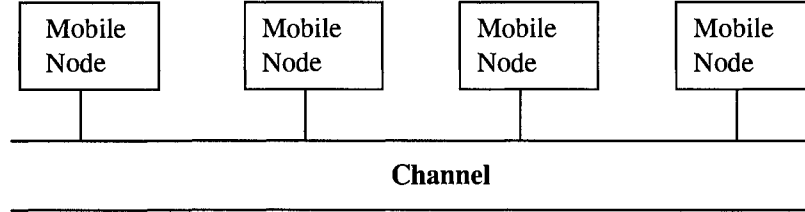


Figure 2.2: Mobile node model in the NS-2

receiving a packet from the channel. Interface properties and propagation model determine whether that mobile node can receive the packet successfully or not. A successfully received packet by the network interface is sent to the MAC layer. If the MAC layer verifies that the received packet is error free and collision free, the packet is then sent to the node's entry point. If the receiving mobile node is the final destination of the packet, the address multiplexer gives the packet to the port demultiplexer and the port demultiplexer hands it over to the sink. If the receiving mobile node is not the final destination, the address multiplexer will hand over the packet to the default port. The routing agent determines the next hop address that the packet should be forwarded to and sends the packet back down to the logical link layer. Once the hardware address is available, the packet is put into the interface queue. Then the MAC layer takes the packet from the interface queue and sends it to the network interface.

2.3 Simulation Model

In order to evaluate the performance of routing protocols proposed in this dissertation, NS-2 [71] simulations were performed. In all simulations, the effective transmission range of the wireless radio was 250 meters and MAC protocol was IEEE 802.11 with 2 megabits per second channel capacity. IEEE 802.11 MAC was in distributed coordination function (DCF) mode and used Request-To-Send (RTS) and Clear-To-Send (CTS) control packets [25] for unicast data transmission to neighboring nodes. The RTS/CTS exchanges precede the data packet transmission and implement a form of virtual carrier sensing and channel reservation

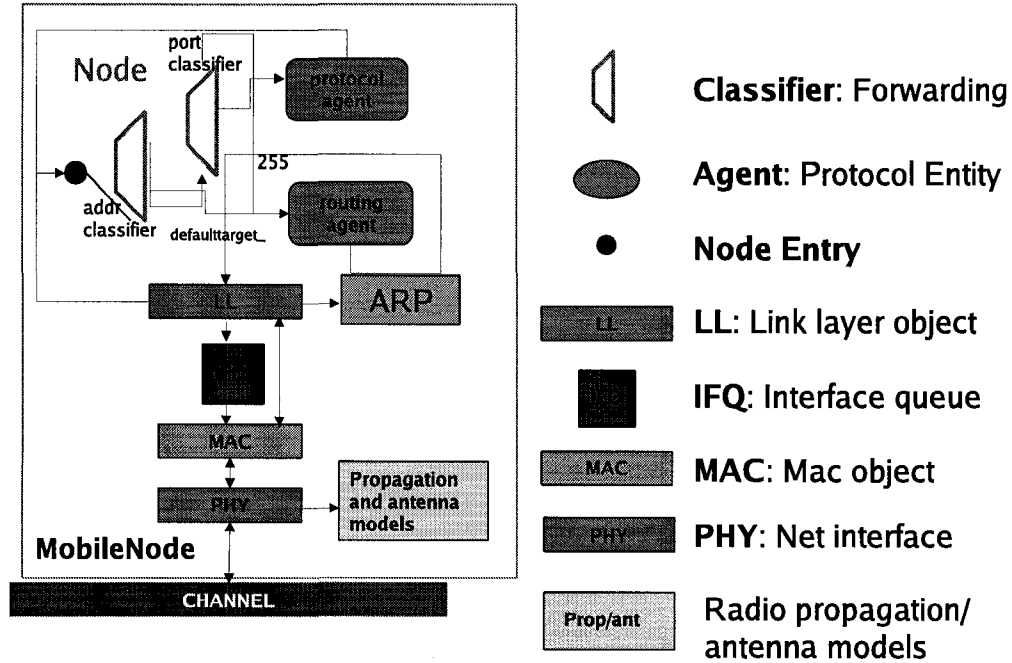


Figure 2.3: Portrait of mobile node in the NS-2

to reduce the impact of the hidden terminal problem. Data packet transmission is followed by an acknowledgment (ACK). In all of our simulations, two ray ground propagation model was utilized. In the simulation set ups, unless specified, wireless nodes are distributed randomly over a flat area according to the uniform distribution. To compare the performance of the proposed protocol, the following performance metrics were considered:

- **Throughput**

Throughput is measured as the number of bits of the successful received data packets at the destinations and reported values are the average throughput for the duration of the simulation time.

- **Average end-to-end delay per packet**

The end-to-end delay (in seconds) for successfully received packets.

- **Packet delivery ratio**

The ratio between the number of successfully received packets and the number of

generated packets by the CBR sources.

- **Normalized routing overhead**

The number of routing packets per one data packet that is successfully received at the destination.

2.4 Introduction to Game Theory

Application of game theory in ad hoc networks will be introduced in Chapter 6 and Chapter 7. In this section I briefly introduce elements of game theory. Game theory is a part of applied mathematics that describes and studies interactive and multi-person decision making problems. Decision makers follow certain well defined objectives and consider their knowledge or expectations of other decision makers. Many applications of game theory are related to economics. Game theory has been applied to numerous fields such as law enforcement, business management, power and stability in politics, models for bargaining, voting procedure, evolutionary biology and models of peace and war [76]. The field of game theory dates back to the early days of World War II, when British naval forces playing cat and mouse with German submarines needed to understand the game better so that they could win more often. They discovered that the right moves were not the ones pilots and sea captains were making intuitively. By applying concepts later known as game theory, the British improved their hit rate enormously. Their success against submarines led them to apply game theory to many other war activities. Thus, game theory was proven in practical life and death situations before it was actually laid out on paper as a systematic theory. Game theory can be used either to analyze an existing system, or as a tool when designing a new system. Existing systems can be modeled as games. The models can be used to study the properties of the systems. For example, it is possible to analyze the effect of different kinds of users on the system. Another approach is implementation theory, which is used when designing a new system. Instead of fixing a game and analyzing its outcome, the desired outcome is fixed and a game ending in that outcome is looked for. When a suitable game is discovered, a system fulfilling the properties of the game can be implemented. Game theory

has also been utilized in decision making [80] and [81]. There is a clear distinction between a game that involves multiple decision makers and an optimization problem, which involves only a single decision maker. A shopper at a grocery store performs optimization by trying to maximize satisfaction (utility) with the purchased items. One store may enter a pricing game with other stores to determine the prices for the items [82].

2.4.1 Classifying Games

There are three classes of games: games of skill; games of chance; and strategic games [80]. Games of skills are one-player games. Optimization problems are categorized in that class. The single player has complete control of the outcome of the game. Games of chance are one-player games against nature that is a second player. The player does not completely control the outcomes of the game and strategy selections do not lead to a certain outcome. Those type of games are usually involve risk and uncertainty. Strategic games are games with two or more players, not including nature. Each player has partial control over the outcome of the game. Strategic games are subdivided into two-player and multi-player games.

2.4.2 Strategic Game

A game has three elements:

1. A finite set of players $n \geq 2$.
2. The pure strategy space S_i for each player i
3. Utility (pay off) function, u_i , for every player. The utility function u_i depends on i 's strategy and strategies selected by other players.

The players other than some given player i are referred as "player i 's opponents". They are denoted by $-i$ and their strategy can be denoted as S_{-i} .

2.4.3 General Terms and Definition

When players of the game try to increase and maximize their payoff they are called *rational* players. In cases where the players are computers and machines, the rationality assumption always holds. If players have knowledge about each other's moves the game has *perfect information*. Games in which players make simultaneous moves (i.e. choose their strategies at the same time) are called *static games* and have always imperfect information. If strategy is played in a certain order, the game is referred to as *dynamic* or *extensive form* game. If the player's interest coincide, the game is called a *cooperative game*. Strategic games where the players's interests are in conflict with each other are called *zero-sum* games. In *zero-sum* games, the sum of the payoff of the players is constant or equal to zero. In a *zero-sum* game, a player can not increase his or her utility without hurting other players.

2.4.4 Nash Equilibrium

Nash Equilibrium is the most commonly used solution concept in game theory. Here we use the notation and definition provided in [77] and [78].

Definition:

In the n -player game $G = \{S_1, S_2, \dots, S_n; u_1, u_2, \dots, u_n\}$, the strategies $(S_1^*, S_2^*, \dots, S_n^*)$ are a Nash equilibrium if, for each player i , S_i^* is player i 's best response to the strategies specified for the $n - 1$ other players, $(S_1^*, \dots, S_{i-1}^*, S_{i+1}^*, \dots, S_n^*)$: Any choice of strategies for all players is said to be a Nash equilibrium, if no player has an incentive to deviate from that strategy in order to improve its utility. In other words, the utility of the players will not increase if they select a non-equilibrium strategy.

$$u_i(S_1^*, \dots, S_{i-1}^*, S_i^*, S_{i+1}^*, \dots, S_n^*) \geq u_i(S_1^*, \dots, S_{i-1}^*, S_i, S_{i+1}^*, \dots, S_n^*) \quad (2.1)$$

The strategy that provides a higher utility regardless of other players action, is called *dominant* strategy. When players have no *dominant* strategy, playing a *mixed strategy* may be considered, where each of the various pure strategies is played with some probability. In *mixed strategy*, players select play each strategy with some probability.

2.5 Summary

In this chapter, Mobile Ad hoc Network (MANET) is described. It is shown how MANET differs from a traditional wired network, and why a good routing protocol is important for MANET. The operations of proactive and reactive routing protocols have been explained. “Flooding” problem of reactive routing protocol has been defined and explained. An introduction to game theory was also provided. We will use game theory in Chapter 6 and 7 to solve the flooding problem in routing protocols of ad hoc networks.

Chapter 3

On the Connectivity of Nodes in Wireless Ad Hoc and Sensor Networks

The transmission range of the nodes in ad hoc networks affects the connectivity and routing overhead. Therefore, in the process of selecting the transmission range, knowledge about the connectivity of the network is crucial. We consider an ad hoc network with n nodes that are randomly located in a region of known dimensions. We create a model for the relationship between the number of nodes, n , and the transmission range so that the resulting network topology is connected with high probability. We utilize NS-2 to investigate the effect of transmission range, the number of nodes, and the dimensions of the network on the connectivity.

3.1 Introduction

In this chapter, we investigate a very fundamental and important property of wireless multi-hop networks, namely their connectivity. Whereas in wireless networks with fixed infrastructure (e.g., cellular telecommunication networks or wireless LANs), it is sufficient that each mobile node has a wireless link to at least one base station, the situation in a

decentralized ad hoc network is more complicated. To achieve a fully connected ad hoc network, there must be a wireless multi-hop path from each mobile node to all other mobile nodes. The connectivity therefore depends on the number of nodes per unit area (node density) and their radio transmission range. Each single mobile node contributes to the connectivity of the entire network. In an ad hoc network, if the transmission power of a node is increased, a higher transmission range is achieved and therefore, more other nodes may be reached through a direct link. On the other hand, if we reduce the transmission power of a node, the node may become isolated without any link to other nodes. Selecting a higher transmission range causes more routing overhead and more interference to other nodes and therefore reduces the overall capacity of the network. Gupta and Kumar [66] consider random deployment of the nodes inside a disk with a unit area. The authors show that in order to have a asymptotic connectivity there is a critical transmission range for the nodes $O(\sqrt{\frac{\log n}{n}})$, where n is number of nodes in the unit area. In [68] the minimum node degree (the probability that every node has at least k neighbors) is introduced and the k -node connectivity has been investigated. Authors of [67] provide bounds for critical transmitting range for connectivity in wireless ad hoc networks. In this chapter, we answer to the following questions: For a given area A , how many sensor nodes, n , with what radio transmission range, r_0 , is required to achieve a network with a global connectivity with a probability p ? How large must the transmitting range, r , be to ensure that the resulting network is connected with high probability? We investigate the global connectivity of the network by extensive NS-2 [71] simulations.

3.2 Background and Simulation Environment

A node is called isolated when there is no other node in its wireless transmission range. The existence of isolated nodes is an undesirable characteristic of a wireless network. When the wireless transmission range of the nodes is constant, increasing the number of nodes in a network with constant size will raise the probability of connectivity. Figure 3.1 shows results from NS-2 simulations for connectivity of the network with constant area. When the number of nodes is increased from 70 to 150, the network connectivity moves from 25

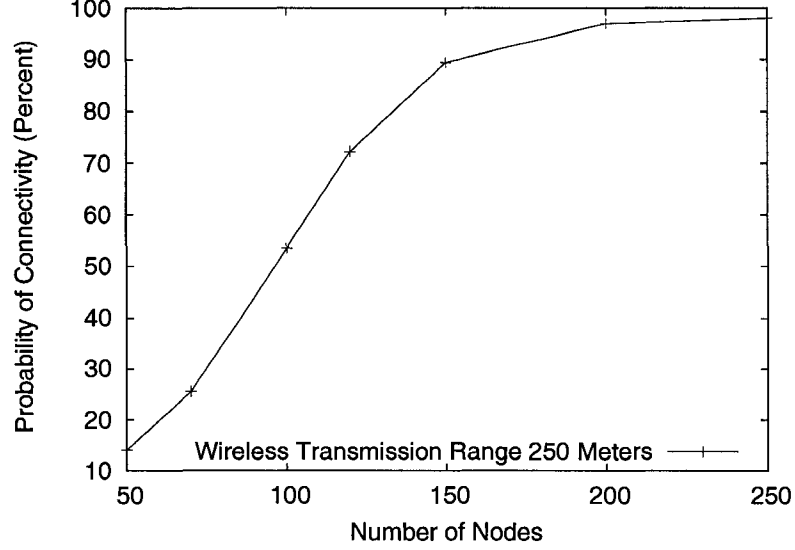


Figure 3.1: Increasing the number of nodes

to 90 percent.

Let us consider a set of n nodes, each with a wireless transmission range of r_0 , that are randomly distributed in an area A ($A \gg \pi r_0^2$), probability of having no isolated node in the network can be written as [68] and [69] :

$$P(\text{No isolated Node}) = (1 - e^{-\rho\pi r_0^2})^n, \quad (3.1)$$

where $\rho = \frac{n}{A}$ is the node density. From the above equation, if we want to be sure that with a probability of at least p , no node in this ad hoc network is isolated, we must set the wireless transmission range of the nodes at least equal to:

$$r_0 = \sqrt{\frac{-\ln(1 - p^{\frac{1}{n}})}{\rho\pi}}. \quad (3.2)$$

Equation (3.1) yields the probability that every node in the network has at least one neighbor. We refer to this as the probability of local connectivity. We define the probability of global connectivity as the probability that every node in the network can have a single or multiple path communication link with any randomly chosen destination. Unfortunately, no

exact formula for the probability of global connectivity is known. We would like to measure the minimum wireless transmission range of the nodes so that the network is connected with probability p . Another goal is to verify the validity of Equation (3.1) as a lower bound for global network connectivity in a practical situations. We use extensive simulations with NS-2 network simulator. We assume that the path loss in the access medium is described by the following expression:

$$P_r = \gamma \frac{P_0}{r^\alpha}, \quad (3.3)$$

where γ is a constant and P_0 is the transmitted power and α is medium loss exponent where $\alpha \geq 2$. DSR [8] is used as the routing protocol in our simulations and we run a range of simulations by varying the wireless transmission range of the nodes from 150 to 500 meters. We run the simulations in a way that source node i originates 100 data packets with the rate of 4 packets per second which then tries to send data packets to a randomly chosen destination j . In all scenarios the nodes are static and uniformly distributed in the rectangular area and there is only one source-destination pair. We define the function $Con(i, j)$ as follows:

$$Con(i, j) = \begin{cases} 0; & \text{If no path between node } i \text{ and } j \text{ exists} \\ 1; & \text{Otherwise} \end{cases}. \quad (3.4)$$

Since the route cache of the source node i is empty, a route discovery function of the routing protocol is called to find a route for the data packet. If a route is found to forward the data packets with the assigned transmission range, the path for the selected pairs of source-destination is considered to be connected (e.g. $Con(i, j) = 1$). If the route discovery part of the routing protocol fails to find a path $Con(i, j) = 0$. In order to increase the statistical accuracy of the results, simulations are repeated 1000 times with different random seeds and different node distribution patterns. The reported probability of connectivity is the average value of $Con(i, j)$ functions.

3.3 Simulation Results

We would like to show that the local connectivity equation not only is a lower bound for the global connectivity, but also can be used as an approximation. We created scenarios in the NS-2 to test this idea. In the area of 2000 by 2000 meters, 100 and 150 wireless nodes are randomly distributed in separate scenarios with differing transmission range. Figure 3.2 compares the result of the NS-2 simulations and probability of having no isolated node (local Connectivity) described by Equation (3.1). As it can be seen from that figure, for the case of 150 nodes the local connectivity and global connectivity (determined from the NS-2) are completely matched when the wireless transmission range of nodes are greater than 200 meters.

In order to estimate the critical transmission range, we created scenarios in which different numbers of nodes are randomly scattered in networks within a constant area (e.g. 2000 by 2000 meters and 3000 by 3000 meters). Simulations are repeated with increasing wireless transmission range of the nodes (from 100 to 500 meters). The results are depicted in Figures 3.3 and 3.4. If global connectivity of 80% is needed for the network of size 2000 by 2000 meter, the wireless transmission range of nodes (sensors) must be set to 250 meter when there are 150 nodes and it must be set to 200 meter when there are 200 nodes. These figures also highlight the fact that the probability of connectivity decreases with increasing transmission range in dense networks. When the number of nodes are high (e.g. 200-300) in the designated area, the high transmission range of the nodes (e.g. 400 or 500 meter) yields lower probability of connectivity compared to lower transmission ranges (e.g. 250 or 300 meter). We monitored the routing overhead for these scenarios when the connectivity is greater than 80 percent. Figure 3.5 depicts the routing overhead for a 2000 by 2000 meter network. Although the connectivity is the same for all cases, the routing overhead for a 300-node network is two times greater than that of a 150-node network.

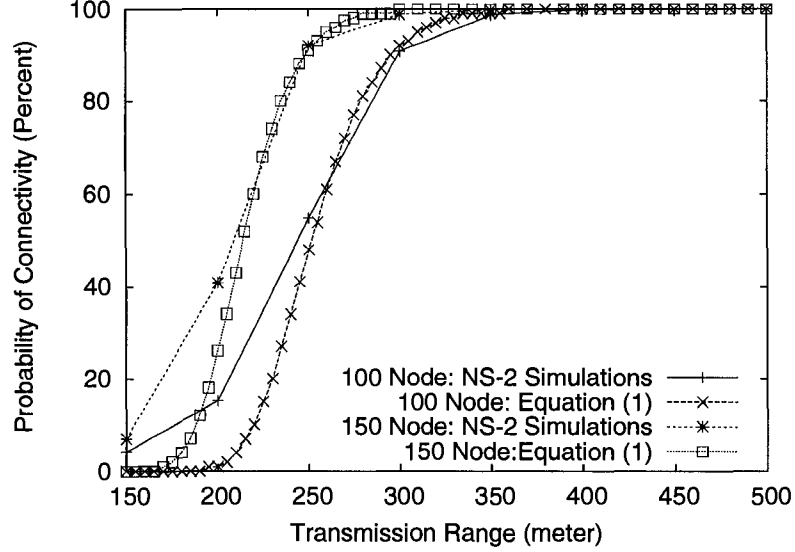


Figure 3.2: NS-2 simulation result for connectivity compared with probability of having no isolated node from Equation (3.1).

3.4 Summary

We used extensive NS-2 Simulations to obtain the global connectivity of the network with different transmission range of the nodes. We also showed that the probability that every node has at least one neighbor, referred as local connectivity, is a fairly good approximation for the global connectivity. We observed that in highly dense networks, if the wireless transmission range is set very high, the global connectivity will deteriorate. The result of this chapter can be used by ad hoc network protocol designers in developing hybrid or hierarchical protocols like the one proposed in [75]. The results of this chapter, can be a guide for the rest of this dissertation. We would like to keep the network connectivity the same when the routing protocol is modified. In other words, a routing protocol should not compromise the connectivity in order to save energy or reduce routing overhead.

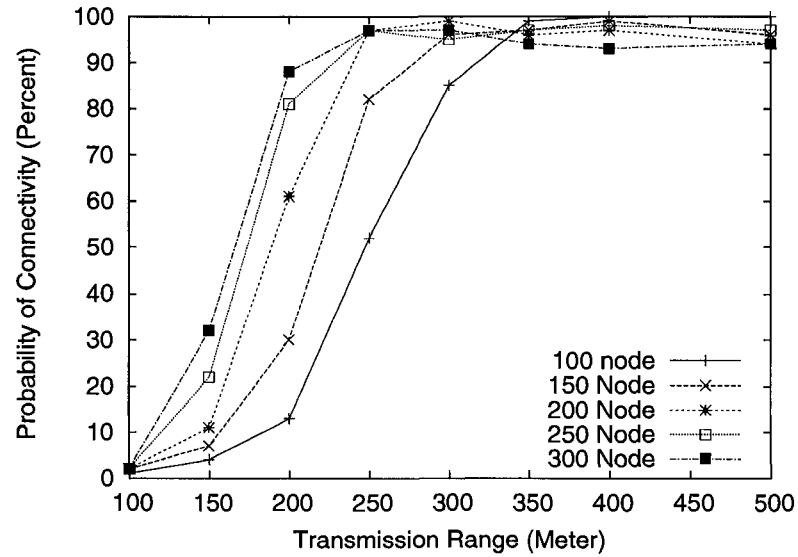


Figure 3.3: Probability of connectivity of the network with area of 2000 by 2000 meters with different number of nodes.

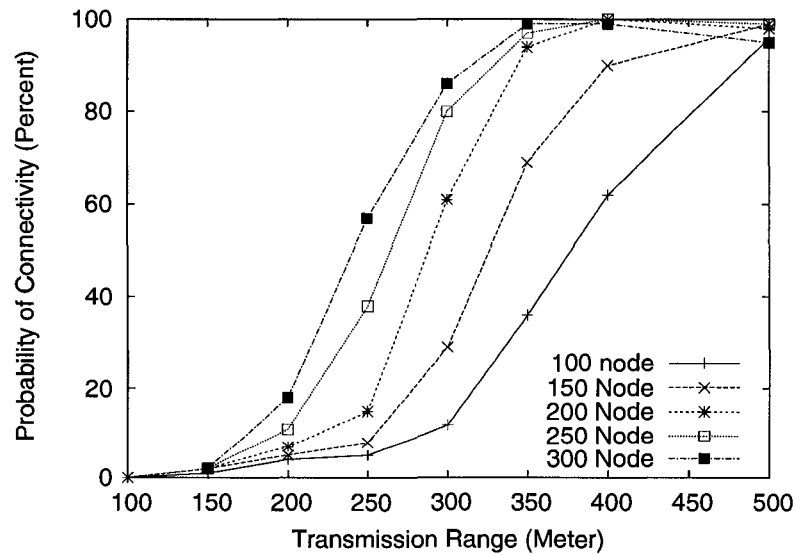


Figure 3.4: Probability of connectivity of the network with area of 3000 by 3000 meters with different number of nodes.

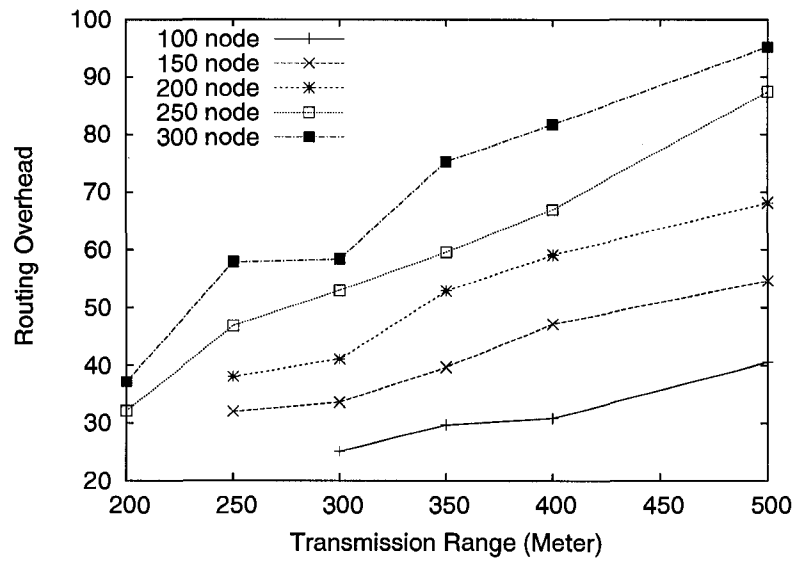


Figure 3.5: Routing overhead for the scenario of Figure 3.3.

Chapter 4

Routing Overhead Analysis for Reactive Routing Protocols

Although several routing protocols have been proposed that can be used in mobile ad hoc networks, there has been very little formal analysis of communication overhead or, more specifically, routing overhead for these procedures. This chapter provides a new mathematical framework for quantifying the overhead of reactive routing protocols such as Dynamic Source Routing (DSR) and Ad hoc On-Demand Distance Vector Routing (AODV) in wireless ad hoc networks with random locations of the nodes. The analysis was compared with the simulations, and these were found to match. The results of this study can be used to predict scalability properties of routing protocols.

4.1 Introduction

In this chapter, we investigate routing overhead in reactive routing protocols. In reactive routing protocols the node that needs a route to a destination floods the network with broadcasting route request messages. Since radio propagation is omni-directional and the physical location of a node may be covered by the transmission ranges of several other

nodes, many rebroadcasts are considered to be redundant. Although this method of routing provides multiple paths, it will occupy bandwidth and makes the ad hoc network unscalable. Scalability is an important problem in ad hoc networks. The number of nodes and the size of the network affect the network performance. The more crowded the network is, the more serious the contention is and there are more redundant broadcasts. When the hosts are mobile, the broadcasting is expected to be performed more frequently due to link breakage.

The authors of [72] used the Manhattan grid with uncertain (unreliable) nodes to quantify the routing overhead. The nodes were located at the intersection of the grid. Although the topology of random ad hoc networks is much different from that of a Manhattan grid, this kind of approach provides insight into routing overhead.

In this chapter, we are interested in finding an analytical model for the routing overhead in reactive protocols in ad hoc network with random locations of the nodes. By constructing such a model we will be able to predict the behavior of the routing protocol in different scenarios without doing the time consuming computer simulations, which can be sometimes impossible for large scale networks. This model is also helpful to validate the results of computer simulations for ad hoc network scenarios. The result of this research can be useful for mobile ad hoc network protocol designers in the evaluation of scalability limits of the protocols.

Our observations showed that there are two important network parameters that contribute to the routing overhead:

1. The number of neighbors of any node,
2. The number of hops from source to destination.

Number of neighbors depends on the node density in the network. Due to considerations such as radio power limitation, channel utilization, size of the network, and power-saving concerns, a mobile node may not be able to communicate directly with the other hosts in a single-hop fashion. In this case, a multi-hop scenario occurs where the packets sent by the source node are forwarded by several intermediate nodes before reaching the destination.

Therefore, the second important source of the routing overhead is the number of intermediate nodes, or number of hops. Obviously, we can observe the case of the combination of these two sources where the intermediate nodes may also have neighbors that broadcast the routing packets. The combination of these three effects contributes to routing overhead in the network the most. We should emphasize that routing overhead due to network congestion and route error packets are not the target of this study.

4.2 Routing Overhead Analysis in Ad Hoc Networks

In our observations, routing overhead in ad hoc networks originates from two major sources: (1) number of neighbors, and (2) number of hops. “Neighbors” of a wireless node is defined as nodes that are in wireless transmission range of that node and participate in route discoveries originated or broadcasted by that node. The authors of [39] have shown that if there are k nodes in the wireless transmission range of node X , the expected additional coverage that node X gains from the k^{th} node is below five percent if $k \geq 4$. They also showed that contention is expected to be higher as k increases and the probability of all nodes experiencing contention increases quickly over 0.8 as $k \geq 6$.

Another parameter that affects the routing overhead is the number of hops that a packet travels through until it reaches the destination. The number of hops is related to the size of the network and wireless transmission range of the nodes.

In order to investigate the effects that number of neighbors and hops have on routing overhead, we conducted two experiments with NS-2 [71]. In this chapter, Dynamic Source Routing (DSR) is used as the routing protocol in the NS-2 simulations. The simulations are run in a way that the source node originate only one data packet. Since the route cache of the source node is empty, route discovery function of the routing protocol is called to find a route for the data packet. In the next subsections, the impact of those two parameters on routing overhead will be discussed.

4.2.1 Effect of Number of Neighbors

We created a simulation scenario where there is a pair of source and destination nodes (SN and DN), and an intermediate node (IN), that relays the data packet from the source node to the destination node. Figure 4.1 shows such a scenario. The destination node is not in the wireless transmission range of the source node. The intermediate node is located between the source and destination. We created some arbitrary randomly distributed nodes in the wireless transmission range of the source node, called neighbors. We should emphasize here that only one neighbor will participate in the data packet relaying and that is the intermediate node. Although other neighbors won't participate in data packet relaying, they will take part in the route discovery process and flooding of the *route request* (RREQ) packets. We increased the number of neighbors of the source node and recorded the number of routing overhead packets. Results are reported in Figure 4.2, which shows that overhead grows linearly with increasing number of neighbors of the source.

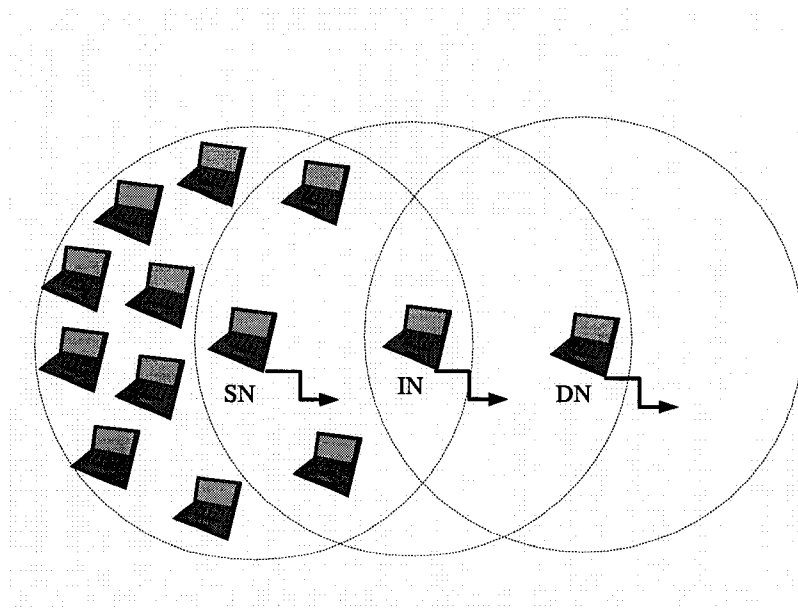


Figure 4.1: Effect of the number of neighbors

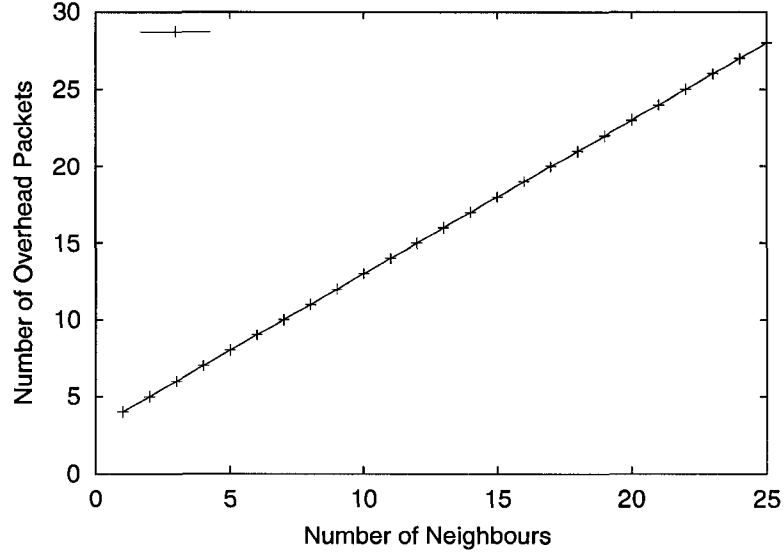


Figure 4.2: Routing overhead versus number of neighbors

4.2.2 Effect of Number of Hops

The number of hops is directly related to the size of the network and the location of the source and the destination. In order to test the effect of the number of hops on the overhead, we created a scenario with a chain of wireless nodes. The source and the destination are located at the ends of that chain. Figure 4.3 shows such a scenario with three intermediate nodes. We increased the number of intermediate nodes from no intermediate node to fifteen intermediate nodes. We reported the number of overhead packets versus the number of hops in Figure 4.4, which shows a linear relationship between the number of overhead packets and the number of hops. In that particular case, the number of overhead packets, O , is given by $O = 2l$, where l is the number of hops. In this experiment, the intermediate nodes do not have neighbors other than the next or previous intermediate node. The effect of the number of hops on the routing overhead becomes more important when the neighbors of intermediate nodes are present. We will investigate this problem in the following section.

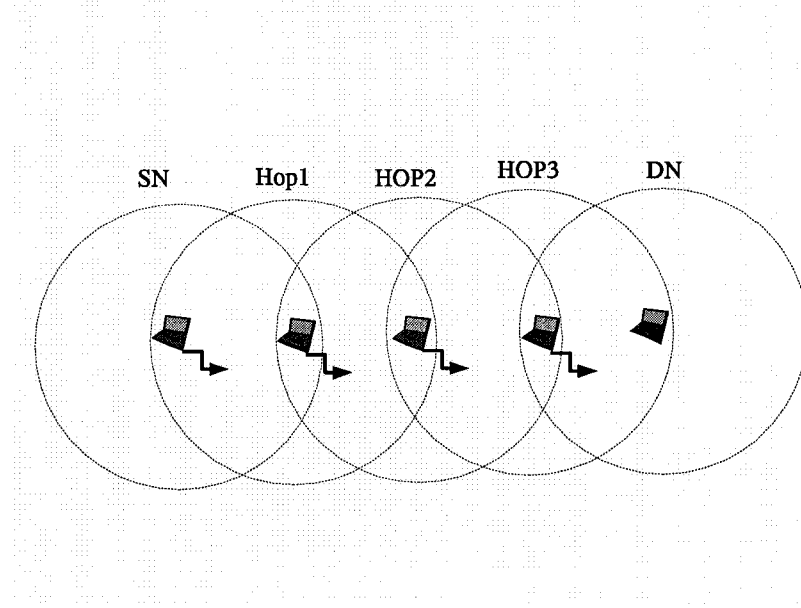


Figure 4.3: Effect of number of hops

4.3 Mathematical Analysis of Routing Overhead

Earlier, with our simulations, we showed that there are two parameters that affect the routing overhead. Those are number of neighbors and number of hops. In this section, we will find routing overhead using a probabilistic model. The physical distance between any two communicating nodes of the network will determine the number of hops required for relaying the data packets from a source to a destination.

Let's assume a wireless ad hoc network with n wireless mobile nodes that are uniformly distributed in a field of size $a \times b$ square meter. The wireless transmission range of nodes are equal and is r meters. Dimensions of the network are a and b meters where $a, b \gg r$. The location of the source node S can be considered anywhere in the field. We can calculate the probability that an arbitrary node A is located in the wireless transmission range of node S or the probability that an arbitrary node A can hear node S is p , and this is given by

$$p = \frac{\pi r^2}{ab}. \quad (4.1)$$

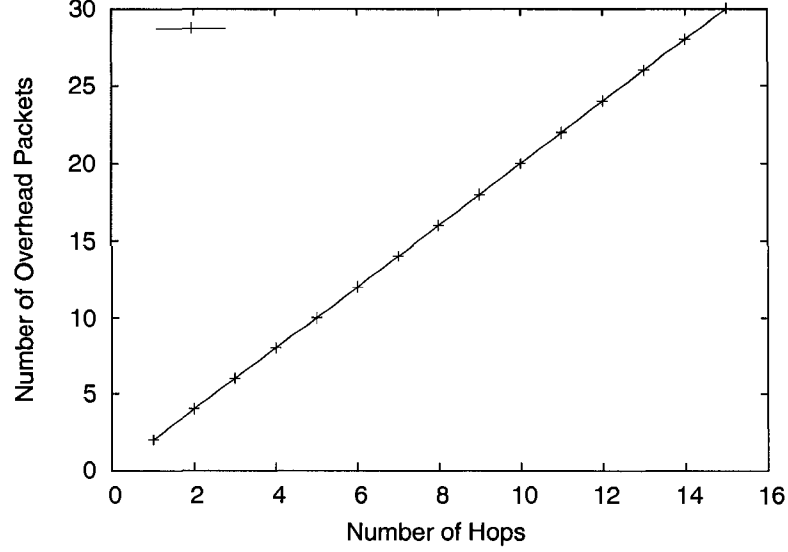


Figure 4.4: Routing overhead versus number of medium nodes (Hops)

In the above equation, the border effect is ignored. If we distribute $(n-1)$ nodes in addition to node S in the field, the probability that node S has k neighbors can be written by

$$P_K(k) = \binom{n-1}{k} p^k (1-p)^{n-1-k}. \quad (4.2)$$

In Equation (4.2), k is the binomial random variable. Since S is arbitrary and can be any node in the network, $E[k]$ will represent the average number of neighbors for any node in the network. Hence,

$$E[k] = (n-1)p. \quad (4.3)$$

Now we would like to focus on the number of hops or intermediate nodes required to relay a packet from source S to destination D . In order to reach this goal, it is sufficient to find the Euclidan distance d between any two arbitrary nodes S and D . The number of hops, l , will be

$$l \simeq \left\lceil \frac{d}{r} \right\rceil, \quad (4.4)$$

where the $\lceil \cdot \rceil$ is the ceiling operator. Assume that the coordinates of node S and D are (x_1, y_1) and (x_2, y_2) , respectively. Random variables x_1, x_2 and y_1, y_2 are independent and

uniformly distributed between $[0, a]$ and $[0, b]$, respectively. The random variable d defines the distance between the nodes S and D , and can be written in terms of x_1, x_2 and y_1, y_2 as:

$$d = \sqrt{(x_1 - x_2)^2 + (y_1 - y_2)^2}. \quad (4.5)$$

We denote $x = x_1 - x_2$ and $y = y_1 - y_2$. Since x_1, x_2 and y_1, y_2 are uniform random variables, the probability distribution function (PDF) of x, y can be obtained by

$$f_X(x) = \begin{cases} \frac{1}{a} - \frac{|x|}{a^2} & -a < x \leq a \\ 0 & \text{Otherwise} \end{cases}, \quad (4.6)$$

and

$$f_Y(y) = \begin{cases} \frac{1}{b} - \frac{|y|}{b^2} & -b < y \leq b \\ 0 & \text{Otherwise} \end{cases}. \quad (4.7)$$

Now we have $d = \sqrt{x^2 + y^2}$, where the PDF of x, y is known. If we denote $z = x^2, w = y^2$ then PDFs of z and w can be obtained as follow:

$$f_Z(z) = \begin{cases} \frac{1}{a\sqrt{z}} - \frac{1}{a^2} & 0 < z \leq a^2 \\ 0 & \text{Otherwise} \end{cases}, \quad (4.8)$$

and

$$f_W(w) = \begin{cases} \frac{1}{b\sqrt{w}} - \frac{1}{b^2} & 0 < w \leq b^2 \\ 0 & \text{Otherwise} \end{cases}. \quad (4.9)$$

With some manipulation, we can obtain PDF of random variable $u = d^2$ from random variables z and w . Since z and w are independent the PDF of u can be obtained by:

$$f_U(u) = f_Z(z) * f_W(w), \quad (4.10)$$

where $*$ is the convolution operator. From that we can obtain the PDF of d , and it is given by:

$$f_d(x) = \begin{cases} 2x \left[\frac{\pi}{ab} - \frac{2x}{ab^2} - \frac{2x}{ba^2} + \frac{x^2}{a^2b^2} \right] & ; \quad 0 \leq x \leq b \\ \frac{2x}{ab} \left[\frac{\pi}{2} - \arcsin\left(\frac{\frac{x^2}{2} - b^2}{\frac{x^2}{2}}\right) \right] - \frac{4x}{ab^2} \left[x - \sqrt{x^2 - b^2} \right] - \frac{2x}{a^2} & ; \quad b \leq x < a \\ \frac{2x}{ab} \left[\arcsin\left(\frac{a^2 - \frac{x^2}{2}}{\frac{x^2}{2}}\right) - \arcsin\left(\frac{\frac{x^2}{2} - b^2}{\frac{x^2}{2}}\right) \right] + \frac{2x}{a^2b^2} (a^2 + b^2 - x^2) - \\ \frac{4x}{ab^2} (a - \sqrt{x^2 - b^2}) + \frac{4x}{ba^2} (\sqrt{x^2 - a^2} - b) & ; \quad a \leq x < \sqrt{a^2 + b^2} \end{cases} \quad (4.11)$$

From Equation (4.11), the expected value of d , $E[d]$, can be calculated as

$$E[d] = \int x f_d(x) dx. \quad (4.12)$$

The expected value of the number of hops, $E[l]$, is

$$E[l] = \lceil E[d]/r \rceil. \quad (4.13)$$

Where r is the wireless transmission range of the nodes.

We would now like to calculate the average number of overhead packets in terms of the average number of neighbors and the average number of hops for one communication link. The routing overhead consists of two parts *route request* (RREQ) and *route reply* (RREP). When a node receives a RREQ in order to eliminate duplicate RREQs, it will check the *request id* and the originator address of that request. The nodes also keep a record of the recently received RREQs. Therefore in the worst case scenario when all nodes of the network are connected together and there are no nodes, the number of the RREQ packets propagated in the network for one communication pair will be $(n - 1)$ when n is the number of nodes in the network. In order to reduce the number of times that a single request is broadcasted by different nodes, there is a parameter in the header of the RREQ packet which will inform the receiver about the maximum number of times that this request

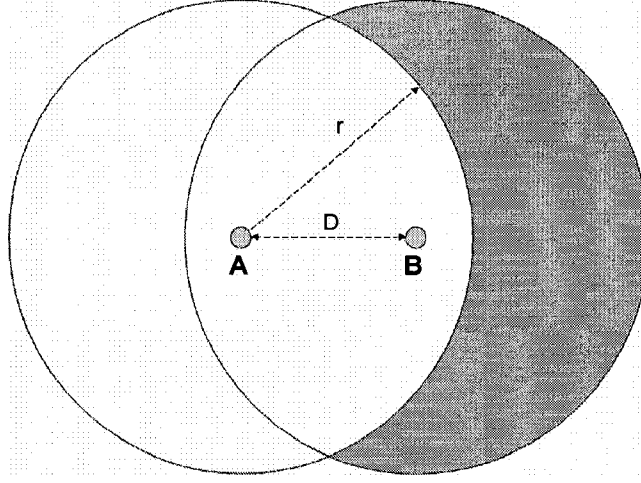


Figure 4.5: Effective neighbors in a two-hop-scenario

can propagate. This maximum number is increased by one if the originator does not hear anything back. So on average the RREQ packets will propagate up to the depth of $E[d]$ in the network. All the nodes that are in this area will broadcast the request propagated by the initiator.

Previously, we said that the average number of neighbors for any node in the network is $(n - 1)$. Since each node broadcasts the request only once, we would like to eliminate the common neighbors. Figure 4.5 shows a simple scenario with two hosts. Nodes A and B have $(n - 1)p$ neighbors on average but there are also common neighbors. We refer to the area that is covered by the transmission range of nodes A and B as S_A and S_B respectively. The common neighbors will be located in the area of $S_A \cap S_B$. If we consider D as the distance between the two nodes (centers of the circle), the intersection area of S_A and S_B is given by [39]:

$$INTC(A, B) = 4 \int_{\frac{D}{2}}^r \sqrt{r^2 - x^2} dx. \quad (4.14)$$

We would like to know the average amount of the area $INTC(S_A, S_B)$. Since the location of

B is random inside A 's transmission range, the average value can be obtained by integrating the above value over the circle of radius x centered at A for x in area $S_A \cap S_B$,

$$E[INTC(A, B)] = \int_0^r \frac{2\pi x \cdot INTC(A, B) dx}{\pi r^2} \approx 0.59\pi r^2. \quad (4.15)$$

According to the above equation, the probability that the second hop has common neighbors with the first node on average is $0.59p$. The common neighbors broadcast the RREQ packet when they hear the packet first from A , and according to the routing protocol they will not re-broadcast. If we subtract the common neighbors from the average number of neighbors $(n - 1)p$, we will find the effective number of neighbors for the second hop B , which will participate in broadcasting and we denote that by k_2 . Therefore we can always write the average number of effective neighbors for the arbitrary second hop B as:

$$E[k_2] = 0.41p(n - 2). \quad (4.16)$$

In other words, the probability of finding new neighbors for node B is $0.41p$.

In order to find the total number of broadcasts, we need to sum the number of neighbors at each hop. We assume that every RREQ will be broadcasted on average to a depth; and expected value of depth is $E[l]$ or the average number of hops.

It is shown in [39] that the extra coverage area will be less than $0.05\pi r^2$ when the number of neighbors is greater than 4. According to [39], for 3, 4 and 5 neighbors, the extra coverage will be 0.19, 0.09 and 0.05 of the original coverage area, respectively. This means that in order to find the number of propagating requests we count the number of neighbors of the originator plus the number of neighbors of the neighbors of the originator up to the depth of $E[l]$. Since increasing the number of neighbors, more than four on average, does not affect the coverage area, we only consider four neighbors of the originator. These four arbitrary nodes would provide more extra coverage for the originator and consequently create connection to other nodes that are far from the transmission range of the originator. For the second and higher tiers of the neighbors of neighbor we consider only 3 neighbors that provide extra coverage with the area of 0.19, 0.09 and 0.05 of the original coverage area. For simplification, the additional coverage index when there are i nodes in the transmission

range of the originator is denoted as C_i . With the above explanations, $C_1 = 0.41$, $C_2 = 0.19$, $C_3 = 0.09$, and $C_4 = 0.05$. N_1 is considered as the number of neighbors of the originator, or first tier neighbors. We can write:

$$N_1 = (n - 1)p. \quad (4.17)$$

N_j is defined as the number of effective neighbors of the j th tier. We can write N_2 and N_3 as follow:

$$N_2 = \sum_{i=1}^4 (n - N_1 - i) p.C_i, \quad (4.18)$$

$$N_3 = 4 \times \left[\sum_{i=2}^4 (n - N_1 - N_2 - i + 1) p.C_i \right]. \quad (4.19)$$

In third tier and larger, it is considered that there are three neighbors on average that provide the extra effective coverage.

Since on average the RREQ travels to the depth of $E[l]$ in the network until it reaches the destination, the number of neighbors for the $E[l]^{th}$ tier can be written as:

$$N_{E[l]} = 4 \times 3^{E[l]-1} \left[\sum_{i=2}^4 \left((n - 1 - i) - \sum_{j=1}^{E[l]-1} N_j \right) p.C_i \right]. \quad (4.20)$$

From the above equations, the expected value of the total number broadcasts of the RREQ in the network can be found.

$$E[Broadcasts] = \sum_{i=1}^{E[l]} N_i, \quad (4.21)$$

where N_i is the number of neighbors in the i th tier that are in connection with the next tier. Equation(4.21) can be used as a lower bound of overhead due to the number of RREQs in ad hoc networks when an on-demand routing protocol is adopted.

Another part of the routing overhead is the RREP packets. Once the destination receives the RREQ, it will send a RREP packet back through which the RREQ has traveled. The destination may receive a number of requests and it will reply to all of them. We would

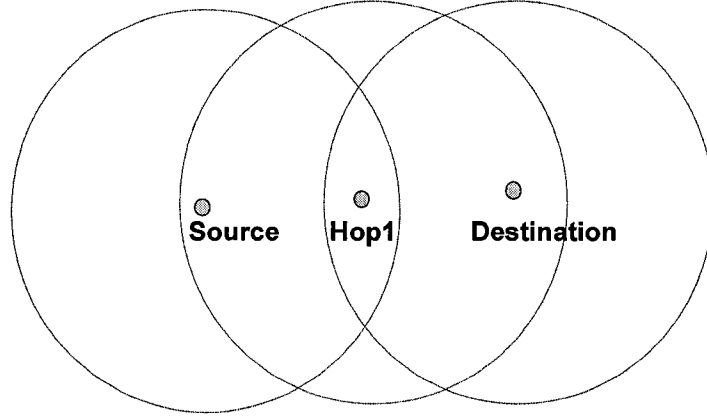


Figure 4.6: Two hop scenario for estimating the number of RREP packets

like to have an estimation of the number of RREP packets. The number of RREP packets depend on the number of neighbors that are located at the intersection of the wireless transmission range of the destination node and intermediate hops. Consider the two hop scenario of Figure 4.6. The average number of RREP messages will be equal to the expected value of the number of common neighbors among Source, Hop1 and Destination. The area that these common neighbors are located can be approximated by the area of the transmission range of Hop1. From this figure, we can write the expected number of replies from the destination to the source, as follows:

$$E[Rep] = (n - 4)p + 2. \quad (4.22)$$

Generally, the expected number of RREP packets can be written as:

$$E[Rep] = \begin{cases} E[l] + \frac{E[l]}{2} (n - E[l] - 2) p & ; \quad E[l] \text{ is Even} \\ E[l] + INT\left(\frac{E[l]}{2}\right) (n - E[l] - 2) p + 0.41p (n - E[l] - 2) & ; \quad E[l] \text{ is Odd} \end{cases} \quad (4.23)$$

Equation (4.21) and (4.23) quantize the average number of RREQ and RREP packets for one communication link. The combination of these two equations will constitute the routing overhead, which can be used in the study of reactive routing protocols for ad hoc networks. When the link between the source and the destination breaks, the route discovery part of the routing protocol will be called and models of Equation (4.21) and (4.23) can be used for estimating the routing overhead of finding a new link. For the calculation of the total overhead of the network in mobile scenarios we only need to add the frequency of the link breakage to the above model.

4.4 Numerical and Simulation Results

In order to verify our analysis, we conducted a set of experiments with the NS-2 network simulator. We considered an area of 1000 by 1000 meters and we changed the number of nodes from 20 to 120 in that area. The location of the nodes in all scenarios are chosen according to a uniform distribution. A single connection is established between two arbitrary nodes. In that connection, only one data packet is transmitted from the source to the destination. In order to have statistically accurate results, we repeated the simulations five thousands times with different network topologies of all the nodes, and the reported results are the average of those five thousands simulations. Figures 4.7 and 4.8 compare the number of RREQ and RREP packets from NS-2 simulation results and those of our analysis for the same network. Since our analysis does not take the collision and repeated requests into account, it can be considered as a lower bound for the routing overhead. That is also the reason that the NS-2 simulations results are slightly higher than our calculated

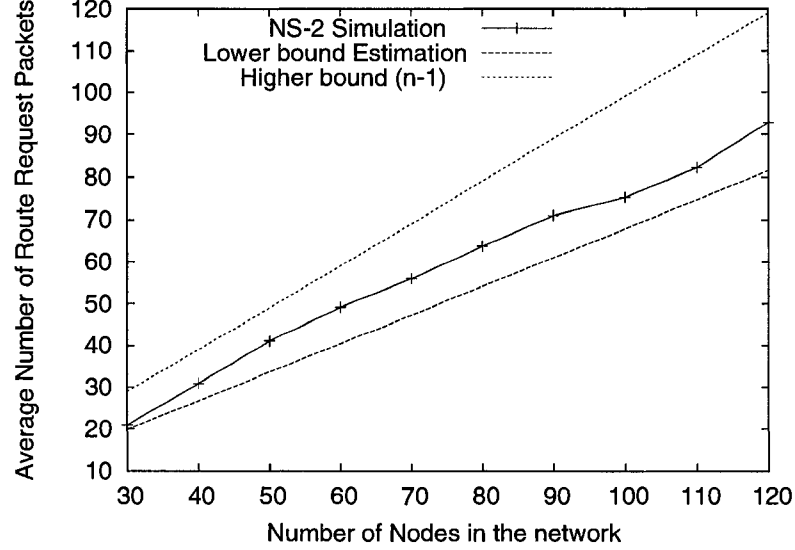


Figure 4.7: Comparison of analytical estimation and simulation of RREQ packets for one communication link

results. Figure 4.9 depicts the estimation of the total routing overhead of the network based on Equations (4.21) and (4.23) and the results of the NS-2 simulations. As can be seen, our estimation of the routing overhead is very close to the NS-2 simulation. We should emphasize here that the proposed results are for one and every communication link with the assumption that nodes do not have any routes in their cache.

4.5 Summary

In this chapter, we presented a method for quantifying the overhead packets in an ad hoc network with reactive routing protocol where the locations of the nodes are random. The results of this chapter can be helpful in validating the computer simulations. The proposed model provides useful data for wireless ad hoc network protocol designers. The results of the proposed model is compared with the results of NS-2 simulations, these results appear to match quite well. In this chapter, it was shown that the routing overhead in reactive protocols increases with the number of nodes as well as with increase in the size of the

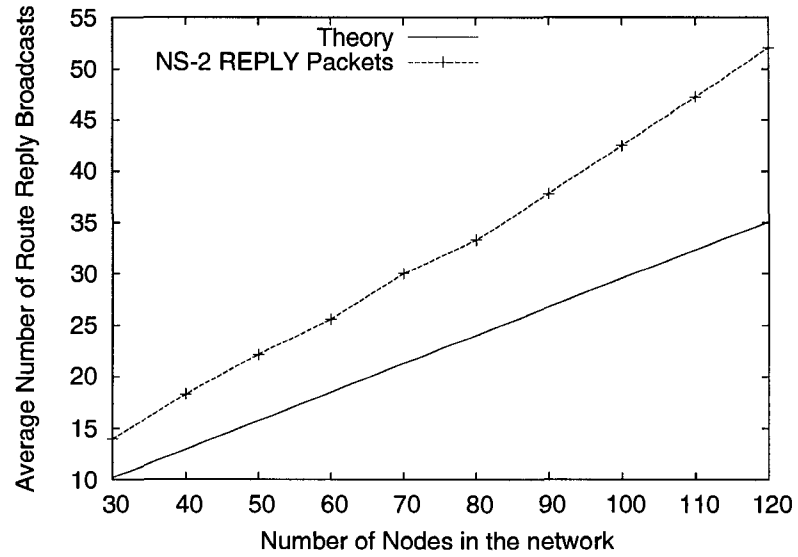


Figure 4.8: Comparison of analytical estimation and simulation of the number of RREP packets for one communication link

network.

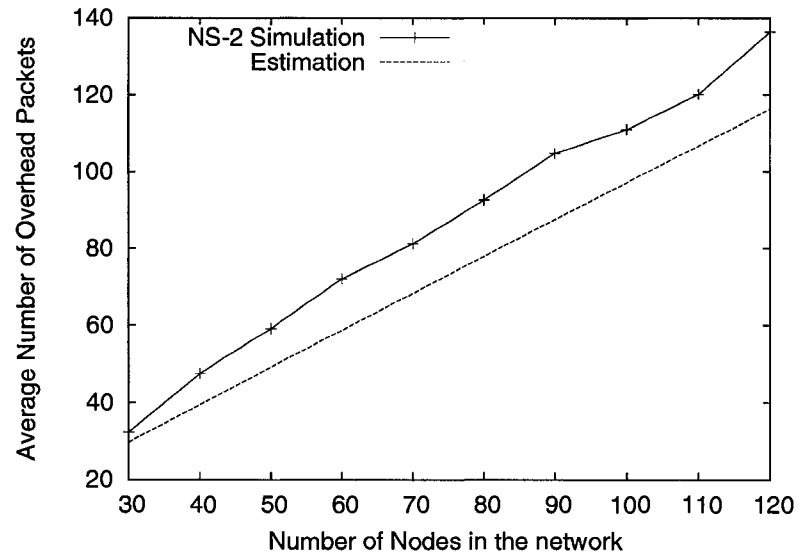


Figure 4.9: Total routing overhead; comparison of analytical results and NS-2 simulation

Chapter 5

HDSR: Hierarchical Dynamic Source Routing

5.1 Introduction

During the route discovery phase of an on-demand routing protocol, the source node floods the networks with route request messages, and all the neighboring nodes of the source node are obligated to rebroadcast the *route request* (RREQ) message to their neighbors and so on, until the destination node replies back to the source with routing information. Such flooding can consume significant amount of already scarce bandwidth of the wireless channel. One of the problems of reactive routing is the large end-to-end delay. That is because the routes are discovered (if they are not in the source nodes cache) after packets are generated. When that is coupled with flooding during route discovery phase, the end-to-end delays are larger than what a proactive routing can usually provide. These two problems may be acceptable for small networks, but when the networks get larger, they can significantly reduce the performance of the network, and they do not allow the network to scale well. That is why new solutions are needed to mitigate routing overhead and large end-to-end delays.

Our approach improving the performance of reactive routing, particularly in DSR, is to introduce hierarchy. The new protocol derived from DSR, called Hierarchical Dynamic Source Routing (HDSR), limits the number of nodes that participate in the route discovery of the protocol, which in turn reduces overhead and delay compared to DSR. Nodes that participate in route discovery, and eventually forward packets, are called Forwarding Nodes (FNs). Nodes that are the source and the destination are called Mobile Nodes (MNs). That architectural change provides HDSR to reduce the routing overhead significantly because the number of nodes that are involved in the route discovery is smaller and they can find and return routes faster to the source. That can reduce the end-to-end delay too. In addition to, MNs do not need to acquire and maintain any statistical information about the neighbors or do not need to send maintenance messages or location information about the neighbors. Such reductions could significantly save bandwidth of the network, hence improve the throughput of the network. Such changes were already implemented for AODV in [28], and yielding promising results.

In this chapter, we provide insight in overhead of on-demand routing protocols for random ad hoc networks, where nodes are randomly distributed in the network. That insight is important because we need to know what are the limits of HDSR when compared to DSR (in general, hierarchical compared to flat routing). Previously, estimating overhead in ad hoc routing was investigated by [72] and [74]. In [72], a topology model called Manhattan grid model was used to analyze the routing overhead. Although that study provides very good insights, the topology model is deterministic and may not capture effects introduced by random network. But in our work, we provide a framework for random networks, and our analysis is based on the random locations of the nodes. In [74], a hierarchical routing overhead has been analyzed but their results are not relevant to our case, because our hierarchical model is different from the models that are mentioned in that paper. For example, in [74] overhead due to cluster formation and cluster maintenance (e.g., “Hello messages” etc.) have been analyzed, which are not present in our work.

5.2 Description of HDSR

In the HDSR protocol, we classify the participating nodes of the network as Mobile Node (MN) and Forwarding Node (FN). We assign different functionalities to those nodes depending on what type of node they are. MNs initiate route discovery. FNs help them to find source route to the destination MN. The destination MN replies back through the FNs to source MN. Once a source discovers the routes, it starts sending packets to the destination. FNs assist the MN to forward packets to destination MN. Route discovery and route maintenance in HDSR are different from those in DSR.

When a source has data packet to send to a destination, if there no route in its route cache, it initiates a route discovery by transmitting a 'RREQ packet' as a local broadcast packet. Only FNs, which are within the range of the source can receive the broadcast packet. MNs that are also within the range of source and are not the destination of this packet, discard the broadcast message and do not broadcast further. Only the FNs re-broadcast the request to other FNs unless the destination MN receives this RREQ packet. The destination MN then replies back to the source MN through the FNs. After receiving the *route reply* (RREP) packet, the source MN records the source route in its cache and starts sending packets to the destination MN using the source route that it has just discovered.

Route maintenance is performed by FNs only. When the FN node detects that the next link from itself to the next MN or FN is broken, it updates its own route caches by marking all the paths that use the broken link as invalid and sends *route error* (RERR) message to the source MN and all other FN that uses the broken link for packet transmission. We will now explain how HDSR reduces overhead packet during the route discovery processes and prevent RREQ and RREP flooding.

Figure 5.1 shows how a route is discovered in HDSR. In this scenario, nodes 1, 2, 3, 5 and 6 are MNs and nodes 4 and 7 are FNs. Route discovery is initiated by MN-1 to find a source route to destination MN-8. MN-1 transmits the RREQ packet as a local broadcast message. MN-2, MN-3 and FN-4 are within the range of MN-1. MN-2 and MN-3 are restricted not to re-broadcast the RREQ further. They are not a forwarding node, and they are not the destination as well. Only FN-4 will rebroadcast the request packet after adding itself in the

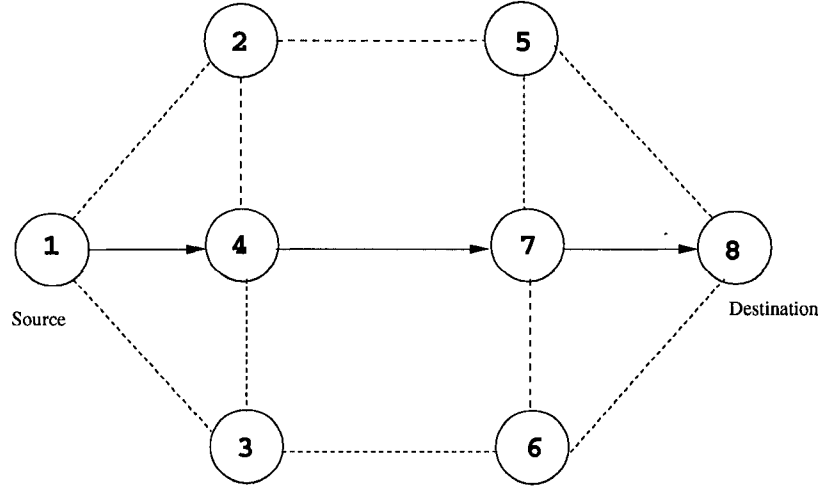


Figure 5.1: Limiting RREQ storming in HDSR

request packet. Only FN-7 will accept the RREQ packet, because it is the only FN within the range of FN-4. FN-7 rebroadcasts the request packet and the RREQ packet finally reaches the destination MN-8. MN-8 replies back to source node. Upon receiving the reply packet, source MN-1 records its route cache and starts sending packet through the source route it has just learned from the reply packet. In this case only three broadcast messages are generated. Redundant RREQ broadcasting by MNs except the source MN have been eliminated in HDSR, which saves bandwidth by reducing packet collision.

Figure 5.2 illustrates how RREP flooding is prevented in the HDSR protocol. In this case there is only one FN and all other nodes are MNs. Route discovery was initiated by MN-1 to find a source route to the destination MN-7. MNs 2, 4, 5, 6 and FN-3 are within the range of MN-1. Assuming that each MN and FN has a source route in its cache. For instance node 6 has an entry in its cache that indicates a route to node 7 through node 5. In DSR, when a nodes receives a RREQ to a destination and it has a route to that destination in its cache, it will reply to the originator of the RREQ and provides its cache information. In the HDSR protocol, only FN-3 will reply back to MN-1 in contrary to replying procedure used in DSR where all the MNs reply back to MN-1. All other MNs, which receive the RREQ message, will discard that RREQ message. MN-1 starts sending

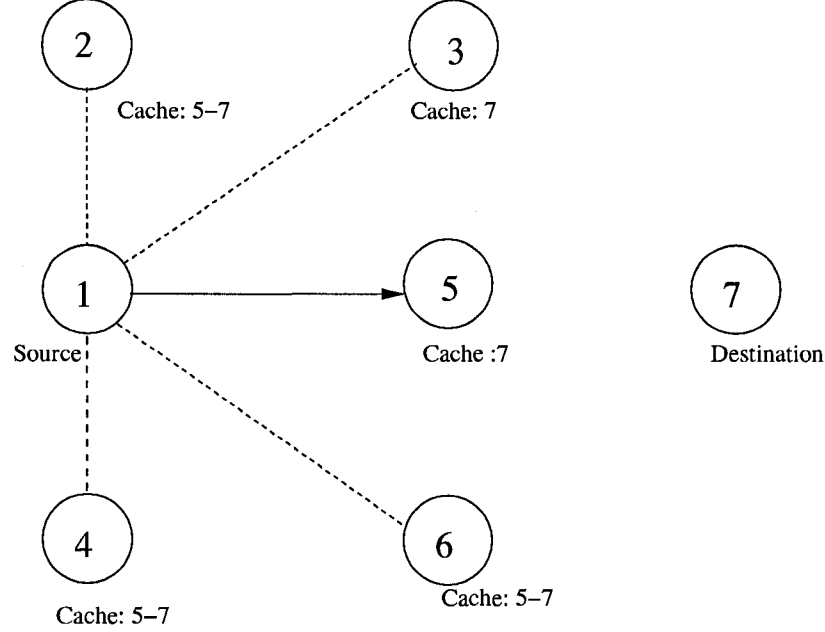


Figure 5.2: Limiting RREP storming in HDSR

packet to destination MN using the route 1-3-7. Thus RREP flooding is limited in HDSR when each node replies from its route cache.

5.3 Results for Static Scenarios

In this section, we present our simulation results for Static Scenarios. We kept node densities constant in the network when we increased the number of MNs in the network to measure the scalability of the routing protocols. For example, the area is 1500 by 500 meters when the number of MNs is 60, and it is 1500 by 750 meters when the number of MNs is 80. Traffic sources are Constant Bit Rate (CBR) with 512 bytes per packet. We varied the packet generation rate to measure the network performance under different traffic loads. The source-destination pairs are spread randomly over the network but the number of pairs are constant during each simulation scenario. Each CBR source starts randomly at the beginning 0 to 10 seconds of the simulation and each simulation runs 300 seconds. In order to increase the reliability of the simulations, each connection scenario is simulated

10 different times with new randomly selected node topologies, and reported results are the average of these 10 simulation. Testing the same connection scenario under different topologies also gives some indication about how HDSR will perform when the nodes are mobile. In HDSR, there are FNs in additions to MNs and locations of the FNs are chosen randomly as well. When we compare the performances of these two protocols, we reported number of mobile nodes in both cases but the number of FNs were reported separately in HDSR. We modified NS-2 source code to implement HDSR protocol. Our starting point was DSR protocol that was provided by NS-2. During this phase, we investigated all the functions that a mobile hosts need to do for implementation of DSR then we modified route discovery and route maintenance functions of DSR to create HDSR. In HDSR, all routing and forwarding functions are performed by FNs. MNs only implement routing functions if and only if they are either source or destination. For example, MNs initiate RREQ, reply to RREQs and accept RERR messages if they are either source or destination.

As we stated in the previous sections, one of the problems with DSR was generation of large number of overhead packets during the route discovery phase of the protocol. The number of overhead packets increases with the number of nodes in the network. The high number of overhead packets would cause higher end-to-end delay and lower throughput and delivery ratios. The HDSR and DSR protocols were tested in scenarios with differing traffic loads (i.e., packet generation rates). We wanted to test the metric performance such as throughput, delay and packet delivery ratios of HDSR and compare these with those of the DSR. We considered 40 MNs in the area of 1000 by 500 meters. All MNs are either source or the destination. In other words, there are 20 communication pairs in this network. There are additional 4 forwarding nodes (FN) in HDSR scenarios. Figures 5.3 to 5.7 are given to show the performances of these two protocols under differing traffic loads in the network with 40 MNs explained as above. Figure 5.3 shows the throughput of the network for packet generation rates. Networks with DSR routing protocol tend to get congested and unstable at lower traffics comparing with the same network while the HDSR has been chosen as the routing protocol. Although the throughput of the network with DSR is slightly higher at low rates, the DSR could only be operational and stable up to rates of 2 packet per second.

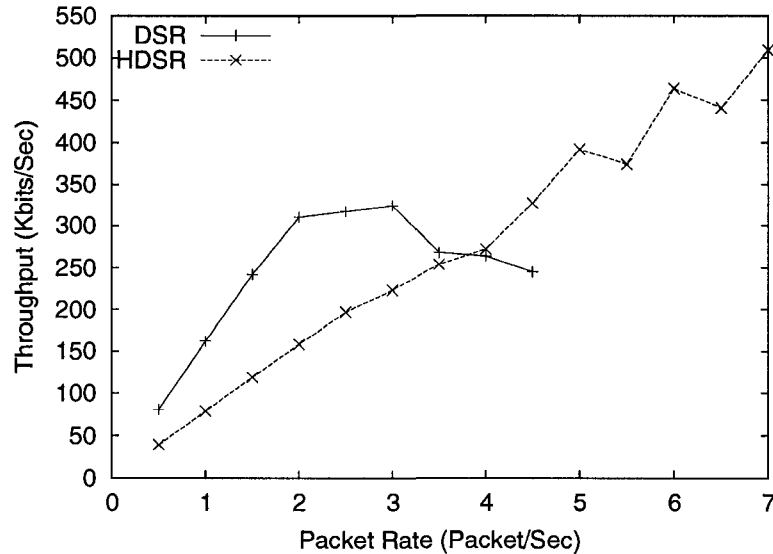


Figure 5.3: Throughput versus packet generation rate for 40 MNs scenarios

But HDSR performance increased constantly with increasing rates. The increased number of FNs in the system improved throughput but even with small number of FNs (4 FNs in these figures), HDSR easily outperformed DSR after 3 packet per second rates. The throughput of the network with HDSR reached a plateau of 500 Kbps and stayed there after any rate increase but for brevity these rates are not included in the plots.

Figure 5.5 shows delay performance of the same 40 MNs network. With HDSR, the average delay per packet was around 30% lower at very low traffics (i.e. packet per second) compared with DSR. DSR delay performance increases sharply when the packet generation rate passes 1.5 packet per second. At moderate and high traffic loads network with DSR routing protocol has delay per packet around 100 times more than that of the same network with implemented HDSR. Figure 5.7 shows the delivery ratios of the scenarios whose throughput and delay performances discussed above. As that figure reveals, the delivery ratio of the DSR drops to very low (close to zero) at low traffic loads, but at even relatively high traffic loads, the HDSR provides more than 40% delivery rates. The HDSR protocol provides consistently higher packet delivery ratio in all different packet generation rates.

To show the effect of increasing in the number of forwarding nodes in the HDSR protocol

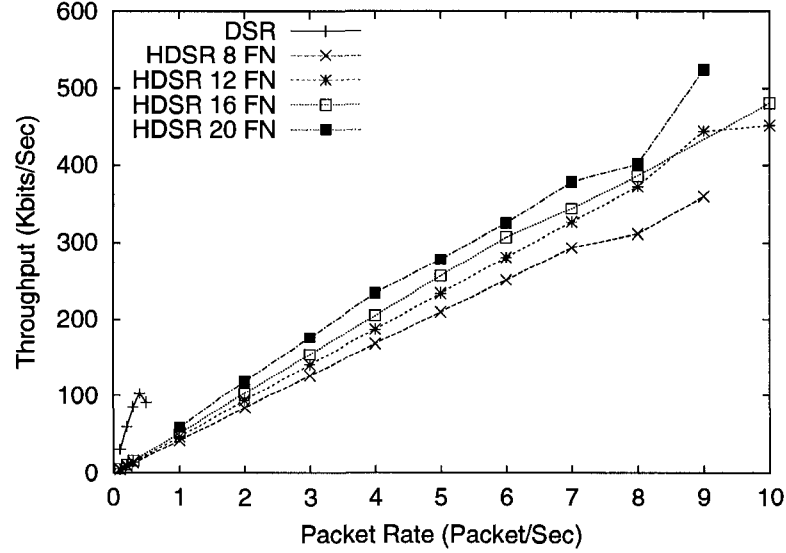


Figure 5.4: Throughput versus packet generation rate for 80 MNs scenarios

we also include the 80 mobile node network simulation results. We simulated the 80 mobile nodes in the area of 1000 by 2000 meter with differing the packet generation rate (offered load) and 20 communication pairs. For the HDSR scenario 8, 12, 16 or 20 FNs have been considered. The FNs and MNs are being uniformly distributed in the area of the network. The reported results are the average of at least ten simulation runs with different topologies of the MNs and FNs. Figures 5.4 to 5.8 are given to show the performances of HDSR and DSR protocols for the above explained 80 mobile node scenario. Here due to the higher size of the network and high number of sources, the throughput of the network with DSR routing protocol would not pass 100 Kbps, and due to very high number of routing packets the network will be congested at the very low packet generation rates (i.e less than one packet per seconds) as depicted in Figure 5.4. The higher number of FNs would provide more throughput and more routing overhead and higher delay. Figure 5.6 shows the average delay per packet of the 80 MNs network. As it can be observed, the delay per packet of the network with DSR protocol jumps very soon to the range of a couple of seconds. When HDSR was chosen as the routing protocol for the same 80 MNs network, the average delay per packet not only experienced an increase with the packet rate but also stayed in the range

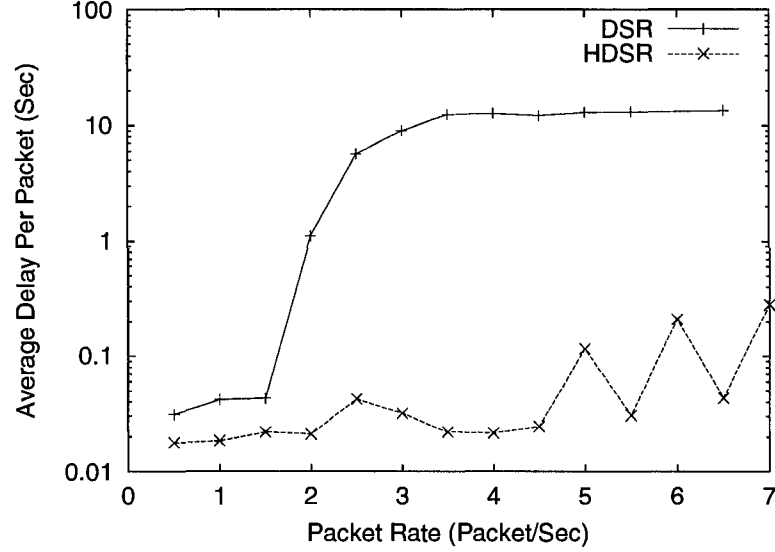


Figure 5.5: Average delay versus packet generation rate for 40 MNs scenarios

of milliseconds even with heavy traffic loads (i.e. packet generation rate more than 8 packet per seconds). Delay performance of HDSR with 8 FNs is half of the delay performance of HDSR with 20 FNs. The average delay with the small number of FNs in HDSR was lower compared to delay with large number of FNs. That result demonstrates correctness of our hypothesis that “limiting number of nodes that are involved in routing discovery reduces the delay” because with low number of FNs, route discovery phase takes less amount of time to return the routes. But we need to emphasize that large number of FNs has improved the throughput. We can say that there is a trade off between number of FNs and throughput and delay performances of the HDSR.

Figure 5.8 depicts the delivery ratios of the scenarios whose throughput and delay performances discussed above. As it can be seen, the delivery ratio of the network with DSR protocol drops at very low packet generation rate to less than 5%, while the delivery ratio of the network with HDSR routing protocol is above 50% at moderate loads and above 30% at heavy loads. Here it can be easily noticed that all three performance metrics are getting worse for DSR with packet generation rates more than 0.5 packet per second. Surprisingly, the delivery ratio of the lowest number of FNs scenario with HDSR was better than all the

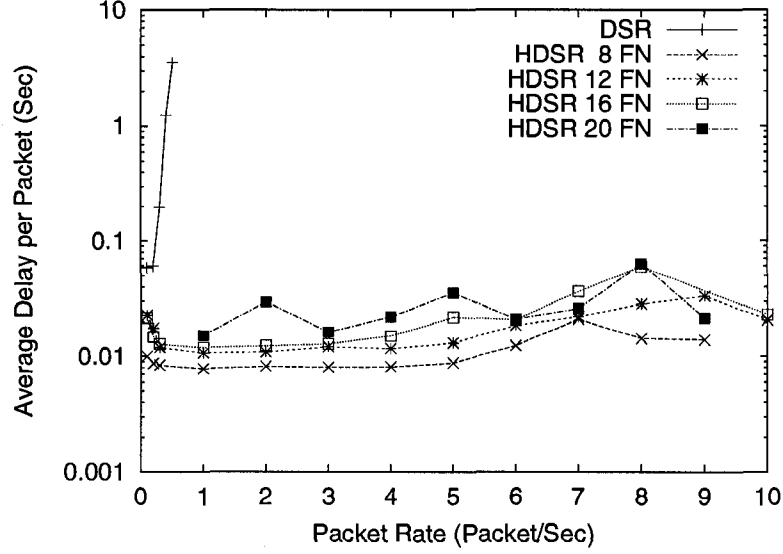


Figure 5.6: Average delay versus packet generation rate for 80 MNs scenarios

others. That suggests that HDSR even with small number of FNs can provide significant performance improvements.

After observation of the above improvements in performance metrics of the HDSR routing protocol, we would like to investigate the reasons of these improvements. Therefore we designed an experiment to monitor the routing overhead packets such as RREQ, RREP and RERR packets. Figures 5.10, 5.11 and 5.12 show the number of RREQ, RREP and RERR packets respectively when the packet generation rate increases for the same above scenarios. The addition of these three kind of packets makes the routing overhead shown in Figure 5.9. As it is depicted in Figures 5.10 and 5.11, the number of RREQ packets and RREP packets sharply increase when the packet generation rate is more than 2 packet per seconds. Since in DSR protocol all nodes who hear a request will send a reply back to the originator, the number of RREP packets is five times more than that of HDSR for heavier traffics. Due congestion problem in DSR, the number of RERR packets is much higher compared with that of HDSR for all different packet generation rates. For instance, the number of RERR packets in HDSR protocol is around five times at low rates and around hundred times at higher rates lower than that of DSR. Figure 5.13 shows the number of MAC layer frames

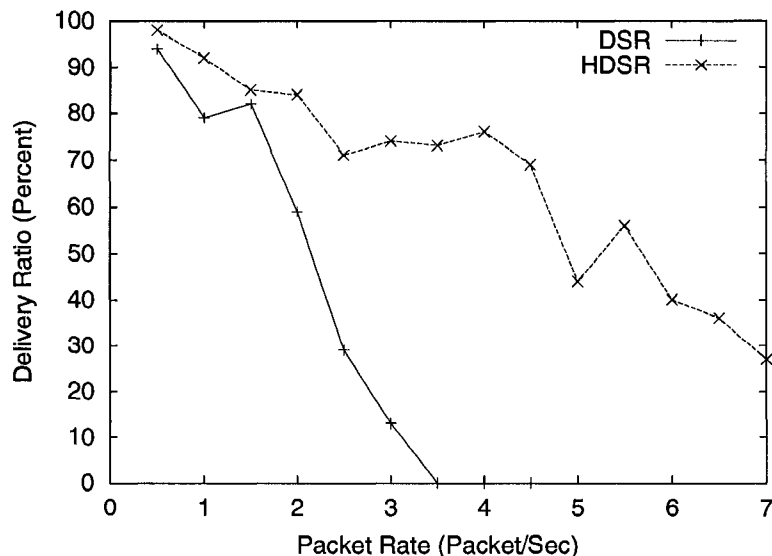


Figure 5.7: Packet delivery ratio versus data packet generation rate

(CTS, RTS, and ACK) in the 40 mobile node network for the whole simulation time. We should consider that although the size of these frames are small but they are consuming bandwidth and can be the source of higher delay in the routing protocols. The MAC load is much larger in DSR than that of HDSR.

In order to compare the scalability of the HDSR with DSR, experiments are designed by varying the number of nodes. Figure 5.14 and Figure 5.15 show results of those simulations related to the routing overhead and the average end-to-end delay versus different number of MNs in the network. In every scenario, all of the MNs are in communication and the node densities are the same. For instance for the 40 node network there are 20 communication pairs and so on. Since the DSR end-to-end delay is very high at even average packet rates, we chose the packet generation rate as one packet per second to have a better scalability comparison. The two figures clearly demonstrates that the HDSR significantly reduces the routing overhead and the average end-to-end delay compared to DSR if the number of nodes increases in the network. The overhead is relatively constant in HDSR but increases steeply in DSR with increase in the number of nodes. Overhead of DSR is 6 to 8 times more at 60 nodes, and 24 times more at 80 nodes compare to HDSR. We have seen similar patterns in

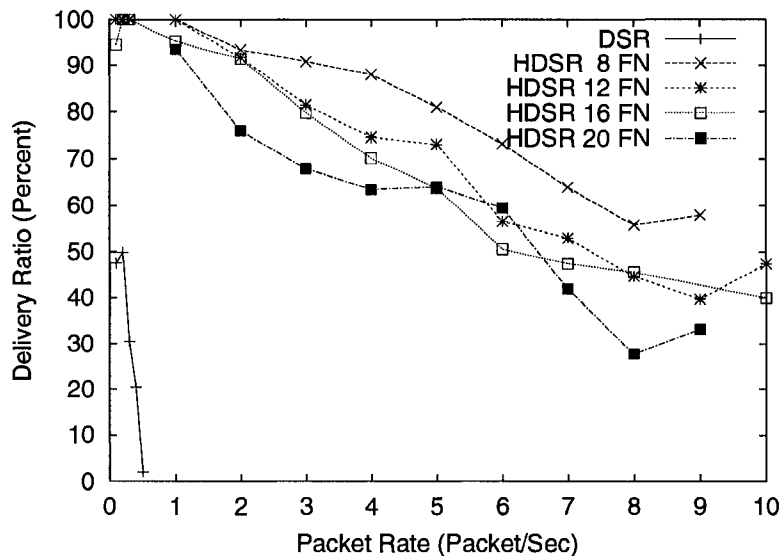


Figure 5.8: Packet delivery ratio versus data packet generation rate for 80 MNs scenarios

other simulation scenarios. The average delay per packet seemed to be higher in DSR in all cases. It is observed that the average delay with DSR protocol will critically increase when the number of mobile nodes increases to 80 while the HDSR protocol seems not to be very sensitive to the increase in the number of nodes.

5.4 Results for Mobile Scenarios

In this section, HDSR simulation results of scenarios with mobile nodes will be presented. Traffic sources are Constant Bit Rate (CBR) with 512 bytes per packet. The mobility model uses the Random Waypoint Model (RWM) in a rectangular field. In this model each node starts its journey from a random location to a random destination with a randomly chosen speed, which is uniformly distributed between 0-20 meter per second (m/s). When the mobile node reaches its destination it stays at that location for the period of a pause time, p seconds, and then it chooses another random destination and moves toward this new destination with a new randomly chosen speed. We vary the pause time p , which affects the mobility scenarios. Each CBR source starts randomly in the first ten seconds of the

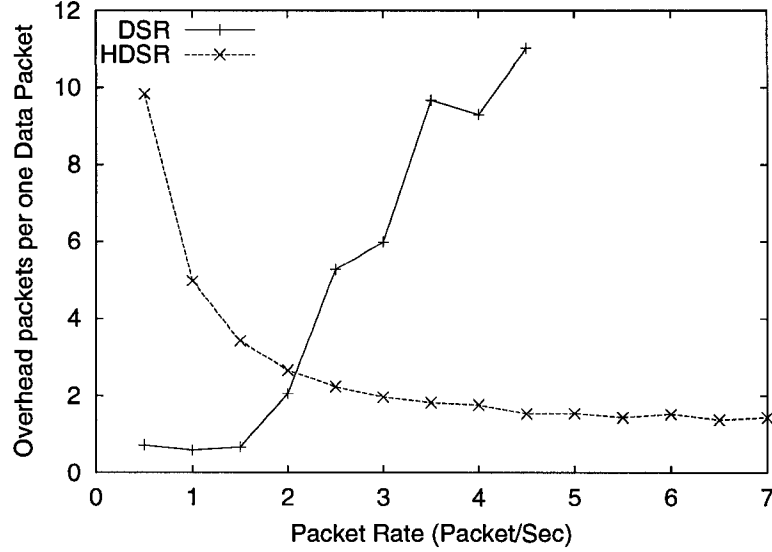


Figure 5.9: Routing overhead versus packet generation rate

beginning of the simulation and simulation runs for 600 seconds. In order to increase the reliability of the simulations, each connection scenario is simulated 10 different times with new topologies and different mobility scenarios. The reported results are the average of these 10 simulations. In order to obtain these new simulation environment, we modified the NS-2 source code to suit our needs, and at the same time implemented HDSR protocol and hierarchical architecture.

Figures 5.16, 5.17, and 5.18 show performances of simulations of 80 MNs scenarios versus the pause time of mobile nodes. The size of the rectangular area that mobile nodes are located is 1000 by 1000 meter. There are 20 CBR sources with data packet rate of 2 packets per seconds. In HDSR, there are 12 FNs in additions to MNs and locations of the FNs are chosen randomly as well. Figure 5.16 shows the routing overhead in HDSR and DSR. The overhead in HDSR is consistently lower than DSR in all scenarios, and for this scenario it is approximately 50 times lower. We repeated these experiments with differing number of nodes, and we found that overhead improvement in HDSR is higher when the number of nodes in the network grows. The difference between HDSR and DSR overhead increases when the mobility is higher (i.e., shorter pause times). Due to the higher number

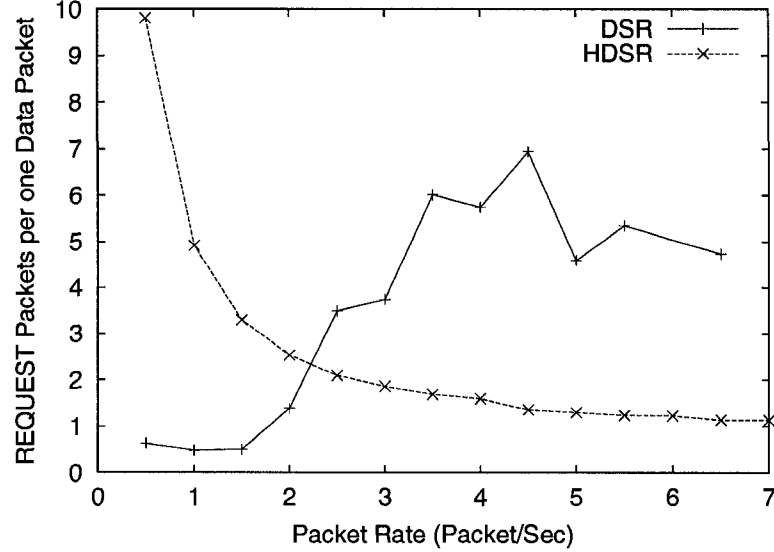


Figure 5.10: Number of RREQ Packets versus packet generation rate

of routing overhead packets, the network with DSR routing protocol has lower bandwidth for data packets, which we think adversely affects performance metrics in DSR compared with HDSR. For example, throughput of the network with HDSR is improved 3 times in high mobility and 20-30 percent in low mobility cases compared with that of DSR (Figure 5.17). In different scenarios, the throughput is always better with HDSR. The average end-to-end delay is also improved with HDSR. Figure 5.18 shows the average end-to-end delay of scenarios with 80 mobile nodes. In that case, the delay in DSR is 3 times higher than that of HDSR for very high mobility (i.e., pause time less than 50 seconds) and few tens of times in low mobility cases. Delivery ratios of HDSR was better than DSR too. We also repeated our simulations choosing scenarios similar to [21] and [22]. Figure 5.19 shows how HDSR saves overhead in a 50-node scenario, which results better throughput (Figure 5.20). The number of FNs in the network naturally affects the performance of HDSR. We varied the number of FNs in a 50 node network where the mobile nodes are moving with zero pause time. We observed that increasing the number of FNs in the network improves the throughput up to a certain point. After that point (9-11 FNs), increasing the number of FNs will increase the routing overhead and deteriorate the performance, which is depicted in Figure 5.21. That

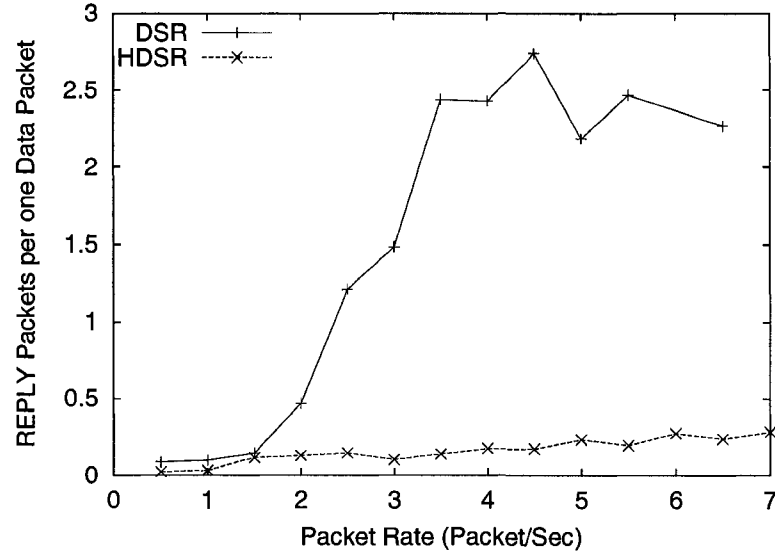


Figure 5.11: Number of RREP packets versus packet generation rate

is why we think that distribution of FNs in the network is important for optimization of the performance figures, but this study does not focus on the optimization problem.

5.5 Summary

In this chapter, a new routing protocol based on Dynamic Source Routing (DSR) for heterogeneous ad hoc networks was presented. HDSR limits the role of nodes during the routing discovery phase of the protocol, consequently increases the routing efficiency. We have shown via computer simulations that the HDSR improves network performance figures, namely throughput, delay and packet delivery ratio significantly. In HDSR protocol, introduced in this chapter, FNs are randomly distributed and pre-selected; which is the case for heterogeneous networks. But in Chapter 6 and Chapter 7, game theory will be used to select FNs dynamically based on desired network performance.

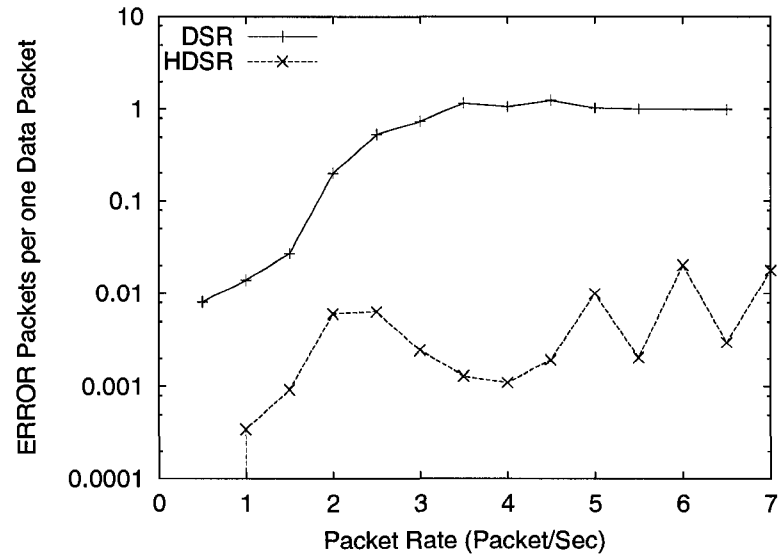


Figure 5.12: Number of Error packet generated versus packet generation rate

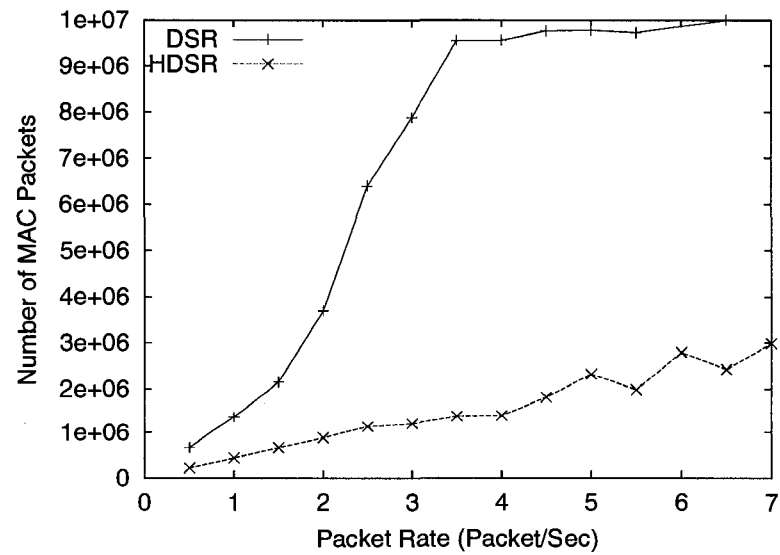


Figure 5.13: MAC load versus packet generation rate

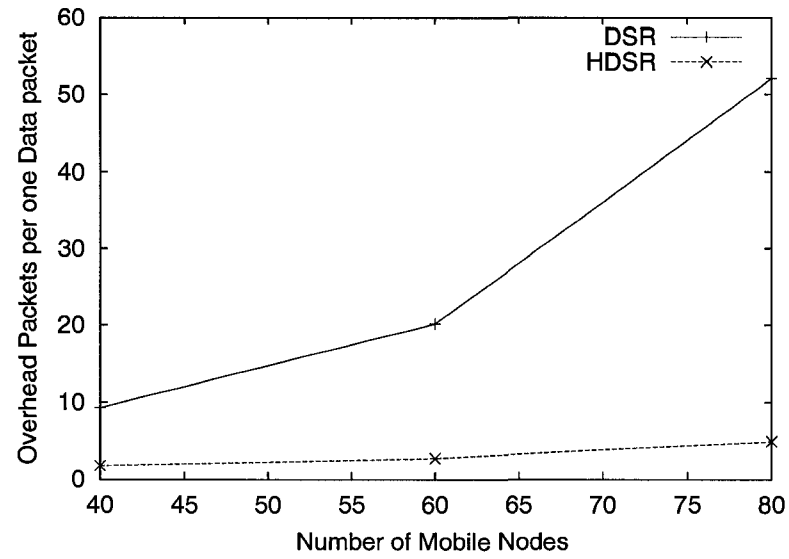


Figure 5.14: Routing overhead versus number of network nodes

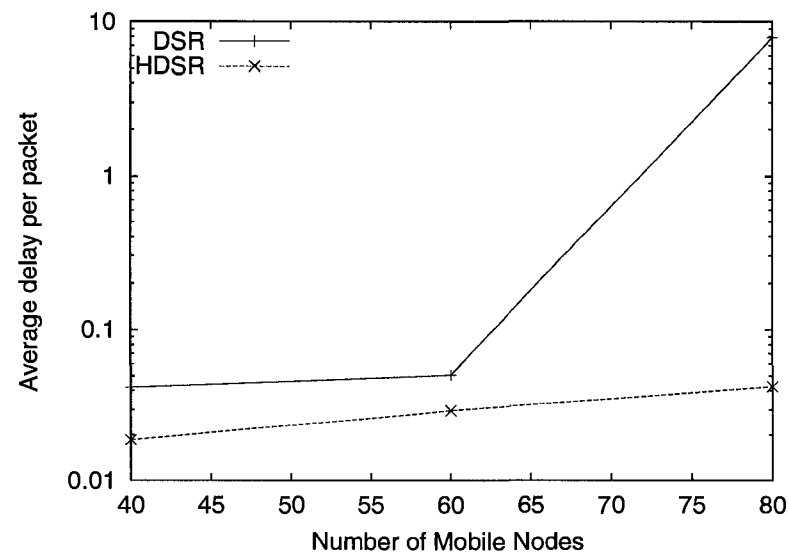


Figure 5.15: Average delay per packet versus number of network nodes

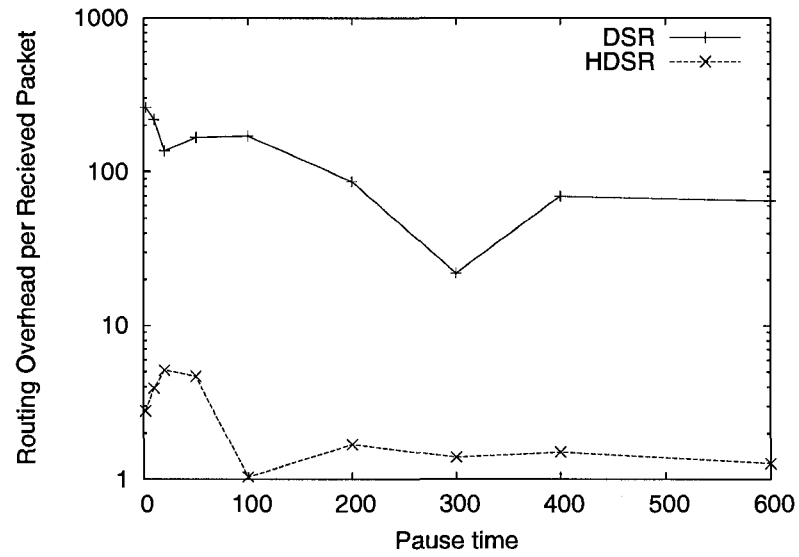


Figure 5.16: HDSR and DSR routing overhead comparison for 80 MN network

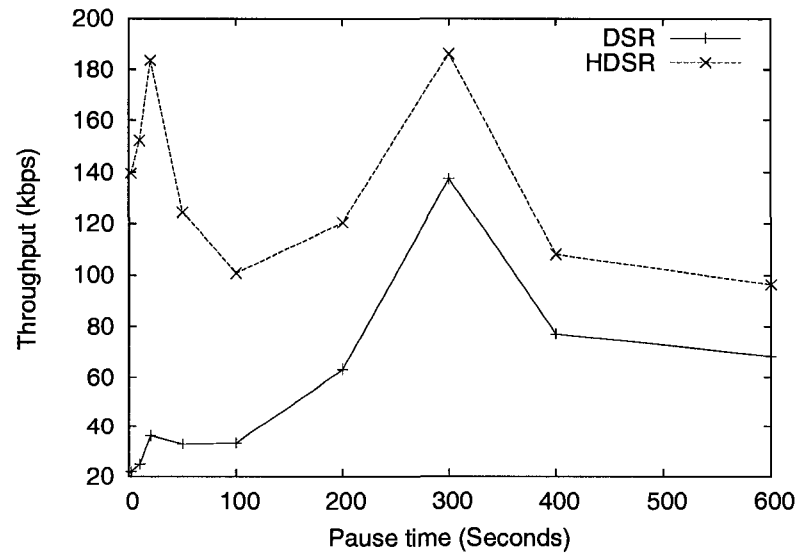


Figure 5.17: HDSR and DSR throughput comparison for 80 MN network

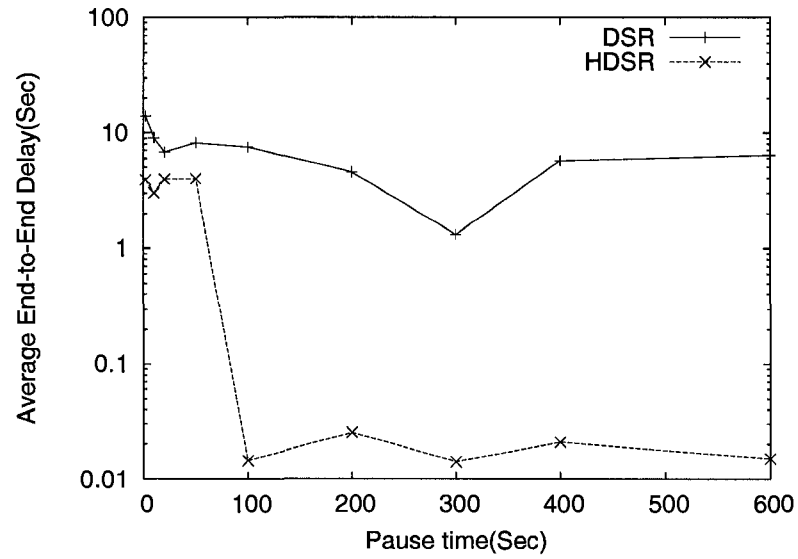


Figure 5.18: HDSR and DSR average end-to-end delay comparison for 80 MN network

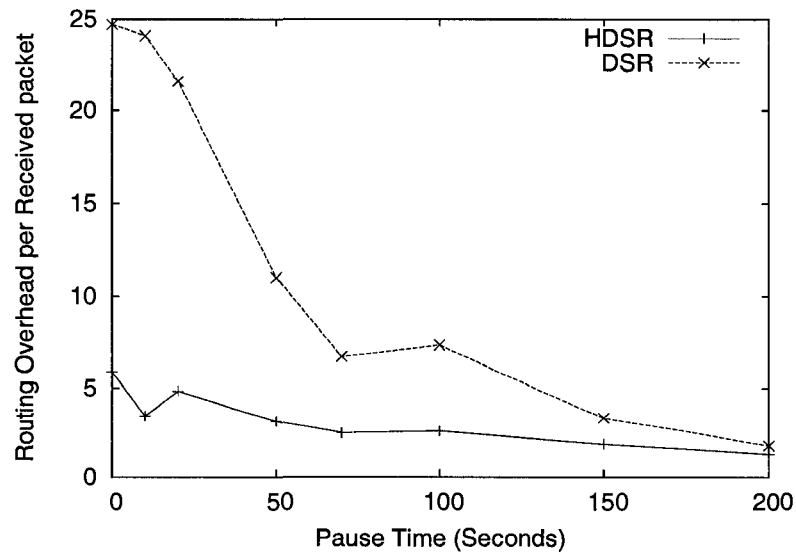


Figure 5.19: HDSR and DSR routing overhead comparison for 50 MN network

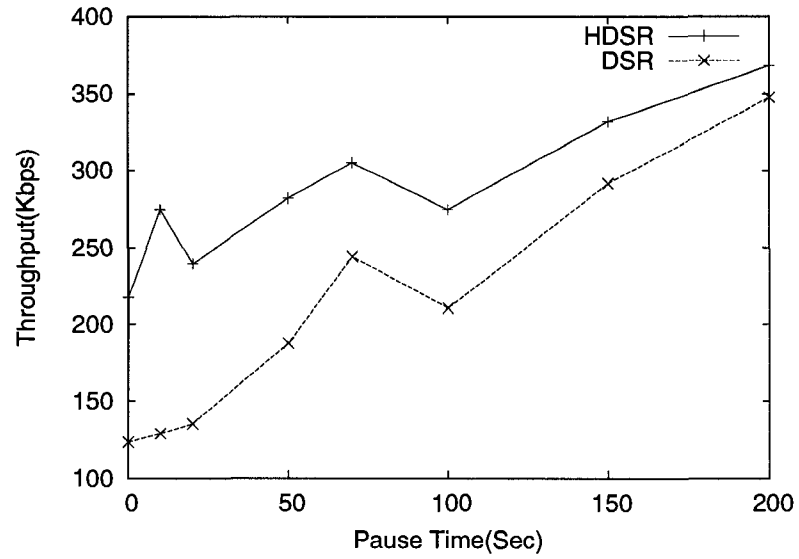


Figure 5.20: HDSR and DSR throughput comparison for 50 MN network

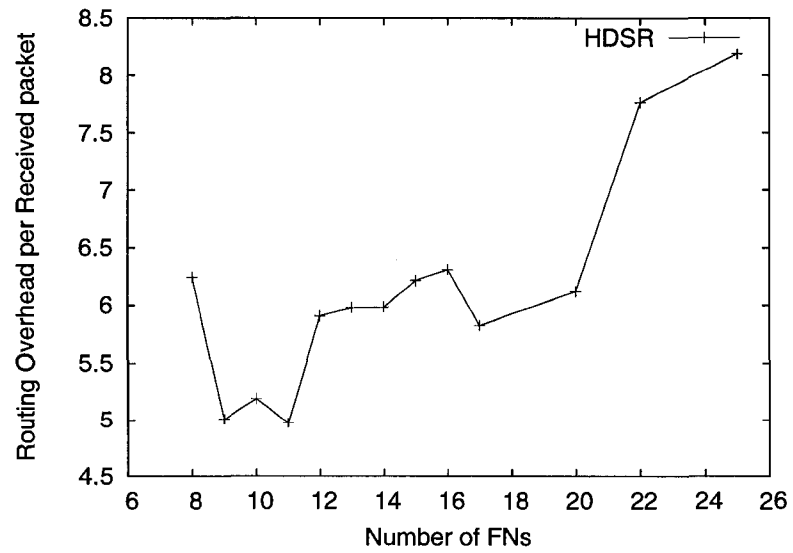


Figure 5.21: Different number of FNs for 50 MN network

Chapter 6

Forwarding Dilemma Game in Wireless Ad Hoc Networks

6.1 Introduction

In this chapter, we propose a mechanism to reduce flooding in the reactive routing protocols by applying game theory. Game theory is not new to the area of telecommunications and wireless networks. It has been used to model the interaction between users, to eliminate the selfish nodes and to coordinate nodes in ad hoc networks. The topology control problems in ad hoc networks were studied and modeled as non-cooperative games in [85]. In that model, network nodes get to choose their power level to ensure the desired connectivity. The model was divided into connectivity and reachability games. In the connectivity game, nodes choose power levels that sustain connection to other nodes while minimizing their costs. In the reachability game, each node tries to reach as many other nodes as possible, while minimizing its transmission range. A cooperation enforcement mechanism based on game theory was proposed in [86] and [87]. Those mechanism provide the study and analysis strategies for cooperation and packet forwarding enforcement among nodes. Basically, a node analyzes the past behavior of its neighbors as well as the availability of its resources

prior to choosing its next action. Additionally, the cooperation game was described and investigated in [86] as a repeated game for ad hoc networks with a tit-for-tat (TFT) strategy applying cooperation enforcement. It was shown that by implementing such a strategy in the ad hoc network, a node will not forward more packets than it sends on average. In [87], nodes of the network were classified based on their energy level. Normalized acceptance rate (NAR), the ratio of the number of forwarded packets by the node to the number of forward requests, was considered as an evaluation metric for every node. Generous tit-for-tat (GTFT) strategy was investigated in cooperating repeated game in [87] as well. It was proved that GTFT is a Nash equilibrium and converges to the rational and Pareto optimal NARs. In [95], a game theoretic framework based on the Nash bargaining game was introduced that solved the selfishness problem while reserving bandwidth in the forwarding node's neighborhood. The authors showed that Nash Equilibrium could be considered as a pricing scheme that provides optimality in bandwidth reservation and, that applying the game theoretic model efficiently eliminated selfish nodes. Saraydar, Mandayam, and Goodman considered the uplink power control problem in a single-cell code-division multiple-access (CDMA) wireless data system with N users [88]. They showed that the Nash equilibrium of the noncooperative power control game with pricing was a stable solution. In [89], they extended their work to a multi-cell environment. A game theoretic approach for the analysis of slotted Aloha with selfish users was proposed in [96]. It was shown that the performance of the selfish slotted Aloha system is near optimum, and the system performance is close to the best non-game theoretic systems. In [90], slotted Aloha with multi-packet reception was studied and it was proved that the stability of a slotted Aloha system with multipacket reception and selfish users is dependent on the transmission cost of a packet. It was also shown that the throughput of a MAC protocol with selfish users could be lower than that of other slotted Aloha implementations. A one-shot random access game was introduced [97] that analyzed the behavior of the nodes using the tools of game theory. It was shown that mixed strategy Nash equilibrium provided the focal equilibrium among $2^n - 1$ equilibrium points of the game, and that it had fairness property as well.

In this chapter, a game theoretic framework called Forwarding Dilemma Game (FDG) will be introduced where wireless nodes of the network are the players of the game. The game is played when a node receives a flooding packet from other nodes in the network. The player has two strategies to play: (1) forward the packet or (2) drop (not forward) the packet. The FDG has three components: (1) Number of players, N , the number of nodes that are receiving the flooding packet, (2) forwarding cost, and (3) network gain factor, G . Mixed strategy Nash equilibrium will be employed to provide the probability of forwarding the flooding messages. In order to enable nodes to discover the number of the players of the FDG game, a Neighbor Discovery Protocol (NDP) will also be introduced. In NDP, wireless nodes use either medium access messages or HELLO messages that are inherent in some of the routing protocols such as AODV and WRP [91]. In this chapter, FDG is implemented in AODV with existing HELLO messages where these messages are used for NDP with slight modification. FDG limits the number of nodes that participate in the route discovery of the protocol without disturbing the connectivity. By conducting connectivity tests, we verified that FDG not only improved connectivity in dense networks but also improved the network performance. This architectural change reduces the routing overhead significantly, helps nodes to find routes faster and reduces contention in the MAC layer. All of these would reduce the end-to-end delay of the data packets.

The rest of the chapter is organized as follows: Section 6.2 discusses the proposed Forwarding Dilemma Game. Section 6.3 presents the implementation of the FDG in AODV protocol. Section 6.4 investigates an optimum value for the network gain factor, G , through analysis and simulations. Section 6.5 presents the connectivity analysis results of FDG. Section 6.7 presents NS-2 simulation results for the proposed protocol and compares the results with those of AODV.

6.2 Forwarding Dilemma Game

In MANETs, the connection between the nodes is established by the flooding of data packets or control packets (route discovery part of the reactive routing protocol). In either case, flooding or re-broadcasting is the most reliable technique to transfer data packets to the

destination or find a route between source and destination. Figure 6.1 depicts a portion of a wireless ad hoc network where a source node, S , has a data packet to be sent to a destination node that is located outside of its wireless transmission range. Nodes that are located in the wireless transmission range of source node S are neighbors of S . If the routing protocol is simple flooding, S will broadcast the data packets and then these data packets are re-broadcasted by every neighbor of S , and every other node that receives them from the neighbors of S until they reach the destination. When reactive routing protocols such as DSR or AODV are utilized, instead of broadcasting data packets, S initiates a route discovery protocol that involves broadcasting smaller route request (RREQ) packets. The RREQ packets are rebroadcasted (i.e., flooded) by neighbors of S and any other node that receives the RREQ from neighbors of S . When the RREQ arrives at the destination node, the path is discovered from the route that RREQ traveled through to get to the destination. Then the destination node sends the discovered route to the source node using the route reply packet (RREP). When the source node receives the RREP, it starts sending data packets through the route that was returned by RREQ. If the network is dense, there will be a lot of redundant broadcasts of RREQ and RREP packets. That redundancy not only makes the route selection complicated but also degrades the overall performance of the network because of the shared wireless channel. In a shared medium, overhead packets increase delay per packet and the number of collisions which degrades the packet delivery ratio and throughput. Here, we investigate if a game theoretic packet forwarding model in a multi-hop network can be used to minimize the degrading effect of flooding in dense MANETs. Game theory has been widely applied in economics, social science, and biology [76, 77], and [78].

Here, a forwarding game is defined as:

$$G = \{N, (S_i)_{i \in N}, (U_i)_{i \in N}\}, \quad (6.1)$$

where N is the number of participating wireless nodes (players of the game), S_i is the strategy set, and U_i is the utility function for the node (player) i . Strategy S_i is the action set of the node i and $S_i = \{0, 1\}$, where $S_i = 1$ denotes that node i is forwarding while $S_i = 0$ denotes that node i is not forwarding the flooding packet. If the node chooses to

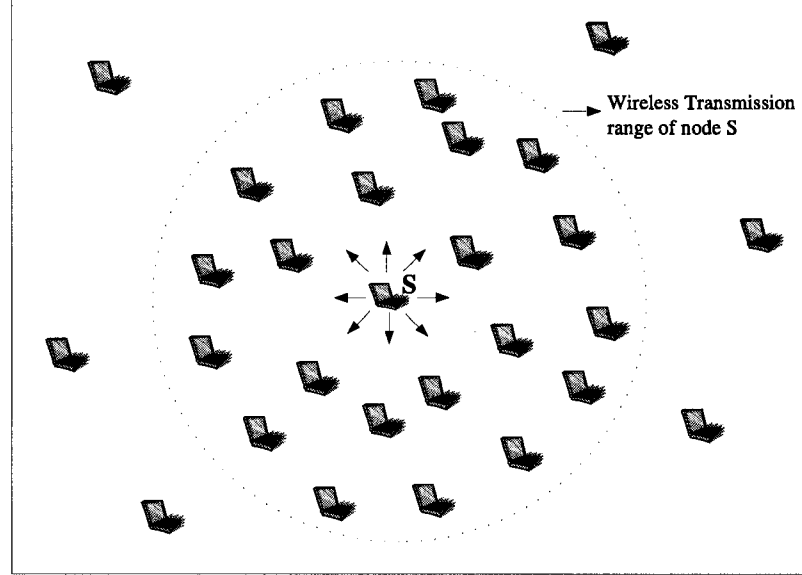


Figure 6.1: Forwarding game played among neighboring nodes of the source node S

forward, it is called a Forwarding Node (FN) or a Mobile Node (MN). Node i will receive utility U_i upon choosing a strategy. The game defined in Equation (6.1) is played whenever arbitrary node i receives a packet p_{jk} that is destined for node k from node j . Here node i needs to make a decision whether to forward p_{jk} or not. The number of players of the game is the number of nodes that receive p_{jk} in the same time slot as node i .

It is desirable that only a limited number of neighbors of the source node participate in forwarding. This strategy will improve resource utilization by reducing the number of overhead packets, which in turn improves the performance of the network. The problem is the selection of the necessary number of neighbors. This problem is similar to a situation in public economics where players would like to save their resources. Only some contributors are needed to bear the cost while the benefit is enjoyed by all players. In a voluntary contribution game, each person in a group must decide whether to make a costly contribution that is benefited by all the group members, or whether to rely on others' contributions. Diekman [98] and [99] introduced a game in which a collective good can be provided by a volunteer from a group of players. Here, Diekman's game is adopted to the game of

forwarding or not forwarding a flooding packet and is called Forwarding Dilemma Game (FDG). In this game, every node in the network has a cost for re-broadcasting packets for other nodes. Because of the forwarding cost in the model, neighbors will not forward the “flooding packet” right away, but expects other neighboring nodes to forward. Let $N > 1$ be the number of players. Arbitrary player i chooses between forwarding ($S_i = 1$) and not forwarding ($S_i = 0$). A node that forwards bears a cost of $f(c)$, where c is the forwarding cost and $f(\cdot)$ is a decreasing function. Utility G_i denotes the gain or benefit that node i receives if at least one of the players of the game spends forwarding cost and forwards the packet. A virtual currency, called nuglets, introduced by Buttyan and Hubaux [92] can be used to define gain G . Utility of node i in FDG is defined as

$$U_i(S) = \begin{cases} G_i - f(c_i) & \text{if } S_i = 1 \\ G_i & \text{if } S_i = 0, \text{ and } \exists S_j = 1 \text{ for some } j \neq i, \\ 0 & \text{if } S_j = 0 \text{ for all } j \end{cases} \quad (6.2)$$

where N players are neighbors of the originator of the flooding packet that are receiving the flooding packet in the same time slot. G_i and $f(c_i)$ are the utility and cost function for arbitrary node i , related to the flooding packet under process. The game has N equilibria, with exactly one forwarding node and $N - 1$ mobile nodes. There exists also a mixed strategy equilibrium. If arbitrary node i forwards the flooding packet with probability p_i , the expected utility of node i can be written as

$$E[U_i] = p_i (G_i - f(c_i)) + G_i \left((1 - p_i) \left(1 - \prod_{j \neq i} (1 - p_j) \right) \right). \quad (6.3)$$

The best response function for the players can be written as

$$\frac{\partial E[U_i]}{\partial p_i} = -f(c_i) + G_i \prod_{j \neq i} (1 - p_j). \quad (6.4)$$

Setting the derivative equal to zero, we get the following system of equations

$$f(c_i) = G_i \prod_{j \neq i} (1 - p_j). \quad (6.5)$$

If we denote $\lambda_i = \frac{f(c_i)}{G_i}$ and $q_i = (1 - p_i)$, the system of Equation (6.5) can be written as

$$\begin{cases} q_2 q_3 \cdots q_{N-1} q_N = \lambda_1 \\ q_1 q_3 \cdots q_{N-1} q_N = \lambda_2 \\ \vdots \\ q_1 q_2 \cdots q_{N-2} q_N = \lambda_{N-1} \\ q_1 q_2 \cdots q_{N-2} q_{N-1} = \lambda_N \end{cases} \quad (6.6)$$

If we multiply the above N equations, we can write:

$$(q_1 q_2 q_3 \cdots q_{N-1} q_N)^{N-1} = \lambda_1 \lambda_2 \cdots \lambda_{N-1} \lambda_N. \quad (6.7)$$

The forwarding probability of arbitrary node i , p_i , can be written by substituting Equation (6.6) in Equation (6.7):

$$p_i = 1 - \frac{\sqrt[N-1]{\prod_{j=1}^N \lambda_j}}{\lambda_i}. \quad (6.8)$$

The cost function $f(c)$ is considered a decreasing function to encourage nodes with lower cost to increase their forwarding probability. In the case where the gain and forwarding cost of the nodes are equal ($\lambda_1 = \lambda_2 = \cdots = \lambda_N$), Forwarding Dilemma Game (FDG) will be symmetric and can be depicted in a matrix form in Figure 6.2. Please note that source node S is not necessarily the originator of the packet and it could be any intermediate node that is forwarding a flooding packet, such as RREQ packets. Player one (row player) in the FDG game of Figure 6.2 is any node that has received a “flooding packet” and needs to make a decision to forward or not forward that packet based on the forwarding game. The column player of the forwarding game of Figure 6.2 are other $(N - 1)$ neighbors of S . If player 1 forwards, its utility will be $G - C$ regardless of the action of other neighbors. If none of the neighbors forwards, then all of them lose and receive a payoff of 0. It is assumed that $C < G$, so each node would prefer to forward if no other node does. But if one node is expected to forward, then each of the others would prefer to “free ride” and would not spend their energy and occupy unnecessary bandwidth.

		"N-1" Other Players	
		"All" Not Forward	At least "one" Forwards
Player 1	Not Forward	0	G
	Forward	G - C	G - C

Figure 6.2: Symetric Forwarding Dilemma Game (FDG) matrix.

Forwarding game depicted in Figure 6.2 has N equilibria, where only one node forwards and the other nodes do not forward. Since the players (nodes) make independent decisions, the strategy chosen by the players is unknown by others. On the other hand, since $G - C > 0$ and $G > G - C$, there exists no dominant strategy. In a symmetric mixed strategy Nash equilibrium for the forwarding game of Figure 6.2, let us denote the forwarding probability (probability that a player plays the "Forward" strategy) as p , consequently probability that a players plays the "Not Forward" strategy is $(1 - p)$. All of $(N - 1)$ other players will not forward with probability of $(1 - p)^{N-1}$. Therefore, we can write the probability of having at least one forwarding node out of the $(N - 1)$ neighbors as $1 - (1 - p)^{N-1}$. With that, the mixed strategy Nash equilibrium can be constructed as follows

$$G - C = G \left(1 - (1 - p)^{N-1} \right). \quad (6.9)$$

From the above equation, the probability of forwarding can be calculated as

$$p = 1 - \left(\frac{C}{G} \right)^{\frac{1}{N-1}}. \quad (6.10)$$

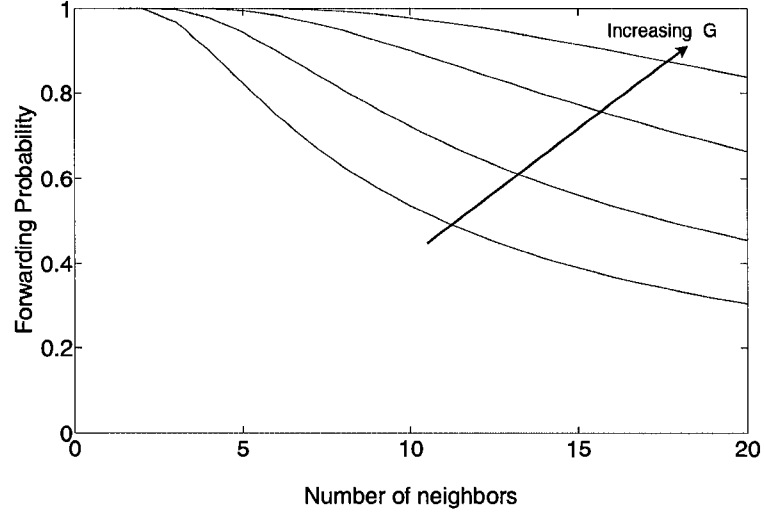


Figure 6.3: Forwarding probability changes with node density of the network and the defined gain G for the nodes, $C=1$

In Equation (6.10), since $C < G$, then $\frac{C}{G} < 1$. Therefore, the probability of forwarding for an arbitrary node decreases when the number of neighbors, N , increases. For example, in the limiting cases, while N is changing from 1 to infinity, the probability of forwarding will be changing from 1 to 0. Figure 6.3 depicts the forwarding probability that is given in Equation (6.10) with increasing number of neighbors of the source from 1 to 20 for different values of network gain, G . When the number of neighbors of the source is lower, the forwarding probability is higher. For example, for $N = 1$, regardless of the value of G and forwarding cost C , the forwarding probability will be 1. In a denser network, the number of neighbors of the source will be higher than 1, and every node will reduce its forwarding probability. For example, for $N = 20$, the forwarding probability can be between 0.3 to 0.8, as shown Figure 6.3, based on the parameter G that was defined for the network. This defines G as an important parameter that controls the decision process in the node, consequently routing overhead in the network. The critical selection of the value for G and its effect on network performance will be investigated in the following sections.

6.3 Implementation of Forwarding Dilemmas Game in AODV

In this section, the implementation of the Forwarding Dilemmas Game (FDG) into AODV routing protocol is explained. In the structure of AODV protocol, HELLO messages are periodically broadcasted by nodes and are used for link monitoring. When node A receives a HELLO message from node B , it discovers that node B is in its wireless transmission range and therefore its neighbor. On the other hand, not receiving a HELLO message from a node is interpreted as a broken link. In order to utilize AODV HELLO messages to obtain neighbor information for FDG, a neighbor discovery protocol (NDP) is introduced in Figure 6.4. In NDP, it is assumed that the links are symmetric. The source ID of the sender is deciphered from the header of the HELLO messages. Every node generates a time-stamped list of its neighbors (i.e, the source ID of the HELLO message that it has received). The neighbor list is updated periodically and outdated entries are removed. The number of neighbors of a node is the number of entries in the updated neighbor list.

In order to implement the FDG, the route discovery process and the structure of RREQ packets in AODV protocol is modified. An extra field is added to the RREQ to carry the number of neighbors of the source node. Figure 7.8 shows the modification in the route discovery process of AODV. When a source node generates a RREQ packet, in addition to its ID, it also inserts the number of its neighbors N into the RREQ packet. That is also done at the intermediate nodes. When the RREQ packet is forwarded by an intermediate node, the number of neighbors of the intermediate node as well as its ID is inserted into the related fields of the RREQ packet. When the RREQ is received by other nodes, the number of neighbors, N , of the originator (forwarder) of the RREQ can be discovered. Using N in Equation (6.10), the receiver of the RREQ can calculate the probability of forwarding for that RREQ. Then the forwarding probability is compared to a generated uniform random number to make the forwarding decision.

In AODV protocol, if the source node does not receive a RREP from the destination for any reason (e.g link quality), it initiates another RREQ. Nodes that did not forward the RREQ in the previous round increase their forwarding probability by 20 percent each time

```

1 ReceiveHelloMessage(*Packet Hello){
2   // Extracting the source of the packet
3   SourceID=Hello → src;
4   Call CreateNeighborList(SourceId);
5 }
6 CreateNeighborList(ThisNeighborId) {
7   //search the list and add it if it is not in the list.
8   if (SearchNeighborList(ThisNeighborId)=0) {
9     for i = 1 to ListSize
10    {
11      //Find the end of the list and add it there
12      if (NeighborList[i] → NeighborId = emty)
13      {
14        MyNeighborList[i] → NeighborId=SourceId
15        MyNeighborList[i] → Time=CurrentTime
16        break;
17      }
18    }
19  }
20 }
21
22 Bool SearchNeighborList(ThisNeighborId) {
23   for i = 1 to ListSize
24   {
25     if (NeighborList[i] → NeighborId ≠ ThisNeighborId)
26     {
27       //This was already in the list
28       MyNeighborList[i] → Time=CurrentTime
29       return 1;
30       break;
31     }
32     else {
33       return 0;
34     }
35   }
36 }
37 UpdateNeighborList(NodeId) {
38   //Entries older than ExpPeriod seconds are expired
39   Expired=CurrentTime-ExpPeriod
40   for i = 1 to ListSize
41   {
42     if (NodeId → MyNeighborList[i] → Time < ExpiredTime)
43     {
44       //remove this neighbor from the list
45     }
46   }
47 }
48 //This function is called when a node needs neighbors count
49 CountMyNeighbors(MyNodeId){
50   Call UpdateNeighborList(MyNodeId)
51   for i = 1 to ListSize {
52     if (MyNodeId → MyNeighborList[i] → NeighborId ≠ Empty)
53     NeighborCount ++;
54   }
55   return NeighborCount;
56 }
57
58

```

Figure 6.4: Integrating NDP with AODV

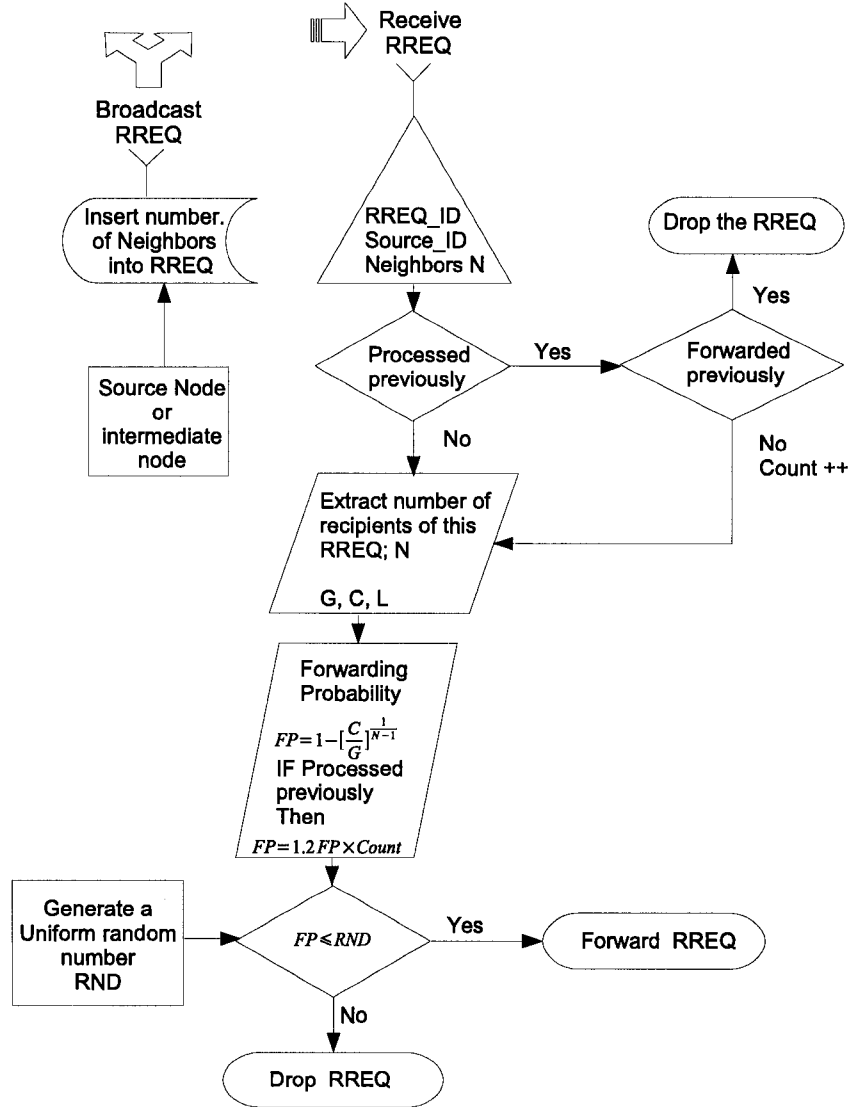


Figure 6.5: Flowchart: Implementing the Forwarding game protocol

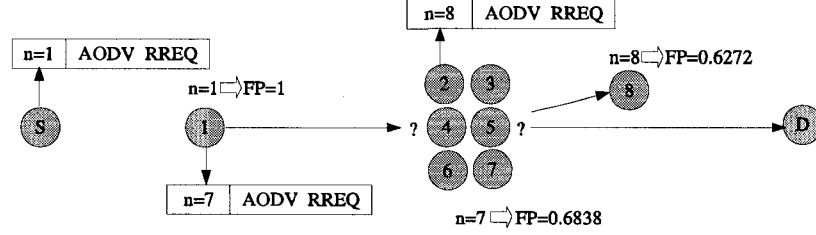


Figure 6.6: Simple topology, S and D are source and destination nodes

that they hear that RREQ is re-broadcasted by the source¹.

In order to explore the idea of the FDG, let's consider a scenario that is illustrated in Figure 6.6. Here, source node S has a data packet to be sent to a destination node D . Since S does not have a route for node D , it broadcasts a RREQ packet that contains the number of its neighbors in the neighbor field of the RREQ.

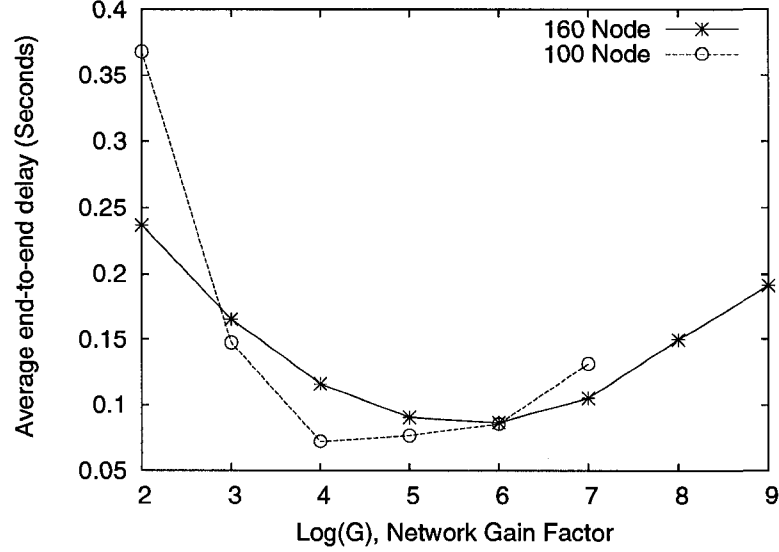
In this example node S has only one neighbor. Node S broadcasts the RREQ packet and this packet is received by node 1. Node 1 extracts the number of neighbors of node S from the neighbor field of the RREQ packet. Since $N = 1$, and the only recipient is node 1, the probability of forwarding is equal to one and the RREQ is forwarded by node 1. While node 1 is rebroadcasting the RREQ, it changes the neighbor field of the RREQ to 7. The broadcasted RREQ from node 1 is received by nodes 2, 3, 4, 5, 6 and 7. These nodes can find the number of the recipients of this RREQ packet (number of players of the game) by looking at the neighbor field of the RREQ packet. Each of these nodes calculates the forwarding probability similarly and will forward the RREQ packet with a probability of 0.6838. If the RREQ is forwarded, the neighbor field is also changed. In order to reach node D , only one node among nodes 2, 3, 4, 5, 6, and 7 is needed to forward the RREQ packet.

¹We performed extensive NS-2 simulation and concluded that the 20 percent increase in the forwarding probability in each round provides an efficient trade off between flooding and disconnectivity.

6.4 Disconnectivity versus Greedy Flooding: Optimum value for G

In the previous section, the forwarding dilemma game (FDG) and a mixed strategy Nash equilibrium as the solution of this game were explained. The probability of forwarding for every node, derived in Equation (6.10), depends strictly on the network gain parameter G . Without the loss of generality in this investigation, it is assumed that forwarding cost, $C = 1$. The investigation shifts to determining the range of values for parameter G , such that network connectivity is established with minimum routing overhead. When G is low, the forwarding probability is low, which might cause isolated nodes and disconnectivity in the network. In this case, the cost-gain ratio $\frac{C}{G}$ is not large enough to encourage selfish nodes to forward a packet for others. On the other hand, for high values of G , nodes increase their forwarding probability to obtain high utility value. When $G \rightarrow \infty$, the performance of the protocol would not improve by FDG. This case is called the greedy flooding. There is extensive research on the connectivity conditions of the network in literature. The critical power and the number of neighbors needed to obtain overall network connectivity by using stochastic modeling is analyzed in [93], which showed that the critical neighbor number (CNN) for connectivity is $k \log N$, with $0.074 < k < 5.1774$. Determining the minimum number of nodes that is required for full connectivity in a stationary network with uniform node spatial distribution is formulated in [94]. That formulation showed that in an ideal case, without inter-node interference, the minimum number of neighbors required for full connectivity is π . Under the guidance of the results presented in [93] and [94], it is considered that, on average, 4 neighbors for each node would be sufficient to establish connectivity among the nodes with high probability. If a node is processing a packet whose source has fewer than 4 neighbors, it should have the probability of forwarding, p , in the range of $0.9 \leq p \leq 0.99$. In other words, if q is the probability of not forwarding, then q is required to be in the range $0.01 \leq q \leq 0.1$. Hence, Equation (6.10) can be rewritten for q as

$$q = \left[\frac{C}{G}\right]^{\frac{1}{N-1}}. \quad (6.11)$$

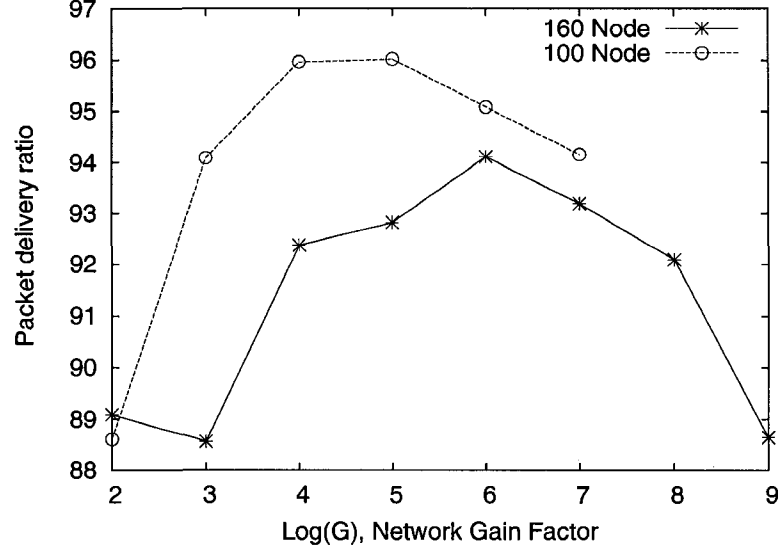
Figure 6.7: Average end-to-end delay versus network gain factor G

By taking the logarithm of both sides of Equation (6.11), the following will be obtained

$$(1 - N) \log q = \log(G). \quad (6.12)$$

Since it is required to have $0.01 \leq q \leq 0.1$ for $N \leq 4$, the network gain G should be in the range of $3 \leq \log(G) \leq 6$ to provide optimum operation. This range provides equitable trade offs between connectivity and network performance.

In order to verify the feasible values of G and to test the effect of G on network performance, a series of experiments are performed utilizing Network Simulator (NS-2) [71]. In the simulation, nodes are uniformly distributed in an area of 1000 by 1000 meters. The network gain factor G is varied in the simulations, forwarding cost C is set to 1 for all nodes. There are 60 sources with CBR (constant bit rate), where each is sending one 512 byte packet per second. The source nodes and their start time are randomly chosen. Simulations run for 200 seconds with modified AODV routing protocol with the FDG. In order to explore the effect of different node densities on the results, experiments with 100 and 160 nodes were performed as well. Figures 6.7 and 6.8 depict average end-to-end delay and packet delivery ratio of the network, respectively, for different values of network gain factor

Figure 6.8: Packet delivery ratio versus network gain factor G

G . For smaller values of G , the incentive to forward packets is minimal compared to the cost (e.g. $\log(G) < 3$). Since the forwarding probability calculated by the nodes is small, the chance that RREQ packets do not reach the destination in the first round is high. In that case, the RREQ packet is re-sent by the source, and the receiving nodes increase their forwarding probability by 10 percent. This explains higher than average end-to-end delay for smaller values of G (Figure 6.7). For $\log(G) \geq 6$, the average end-to-end delay starts to increase. This shows that due to high utility, nodes increase their forwarding probability up to a point where every node decides to forward RREQs. The simulation results confirm that the near optimum value for $\log(G)$ is in between 4 and 6.

6.5 Connectivity

Connectivity is a major concern in any routing protocol for ad hoc networks. Because FDG functionality is based on probability, one concern is that flooding messages may not be forwarded by some of the nodes. In FDG, if the source node does not receive a reply from the destination, the flooding packet will be rebroadcasted by the source. Neighbors that

have not forwarded the flooding packet in the previous rounds, increase their forwarding probability by 20 percent in each round.

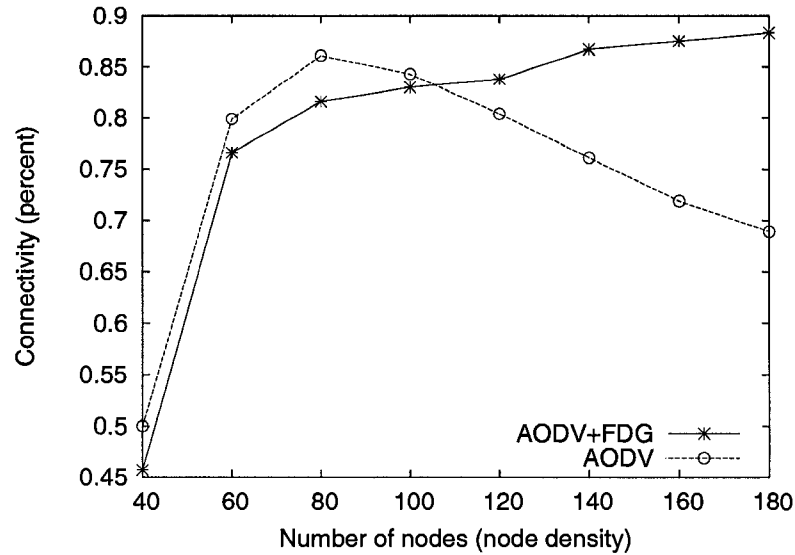


Figure 6.9: Connectivity versus number of nodes

A test was conducted to verify connectivity in FDG and compared with AODV results. In this test, source and destination nodes are positioned at two diagonal corners in a 1000 by 1000 meters field, while other nodes are uniformly distributed in the area and do not generate data packets. All of the nodes are static and there is no mobility. At the beginning of the simulation the source node generates only one data packet for the destination node. To discover the route, a RREQ packet is broadcasted by the source. If source does not receive a RREP from the destination within a certain time (30 msec in this setup), it broadcasts another RREQ up to a predefined number of times (4 times in our setup) [7]. If the data packet is not received by the destination within 4 seconds, this event is declared as disconnectivity, otherwise it is counted as connectivity. The number of nodes in the network were varied from 40 to 180 nodes, and simulations were repeated 1000 times for every scenario with different random seeds. The average of those simulations is shown in Figure 6.9. Disconnectivity is expected in low node density regardless of the routing protocol (e.g. 40 nodes). Connectivity in network with FDG was close to the one with

AODV in moderate node densities (60 to 100 nodes). Surprisingly, connectivity in the network with AODV dropped when the number of nodes in the network increased more than 80 nodes. This is related to the broadcast storm problem discussed previously. Our investigation showed that AODV with FDG not only matches the connectivity achieved by AODV alone but also improves connectivity in moderate to high node densities.

6.6 Performance Evaluation

Previously we claimed that implementing FDG in AODV improves the performance of the routing protocol. We conducted NS-2 simulations to verify our claim. In the simulations, the traffic sources were generated by Constant Bit Rate (CBR) sources with 512 bytes per packet and started randomly during the simulations and continued until the data packets were transferred. Source and sink nodes were chosen based on a uniform distribution at the beginning of each simulation. All the sources had a certain amount of data that needed to be transferred to the sinks. Nodes were randomly distributed in the area in each simulation and, therefore, their locations were different in every simulation. Five NS-2 simulations were run for every scenario, and the reported results for each scenario were the average of these simulation runs.

In order to show if FDG enhances the performance of the network at different node densities compared to AODV alone, the number of nodes in a 1000 by 1000 meter area were varied. The nodes were uniformly distributed in that area. The 60 communication pairs were remained the same for all scenarios. Therefore the results only reflect the change in node densities. The simulation time was 200 seconds and the data packet rate of the CBR was 1 packet per second for all scenarios. The number of wireless nodes varied between 130 and 250. Figures 6.10, 6.11 and 6.12 show normalized overhead, packet delivery ratio and average end-to-end delay per packet versus the number of nodes in the network, respectively. The routing overhead was lower in networks that employed AODV with FDG than AODV alone, because AODV with FDG selectively eliminated RREQ packets. The result reported in Figure 6.10 confirms that the normalized routing overhead was 2 to 3 times lower in AODV with FDG than AODV alone. Figure 6.11 shows the packet delivery ratios of the

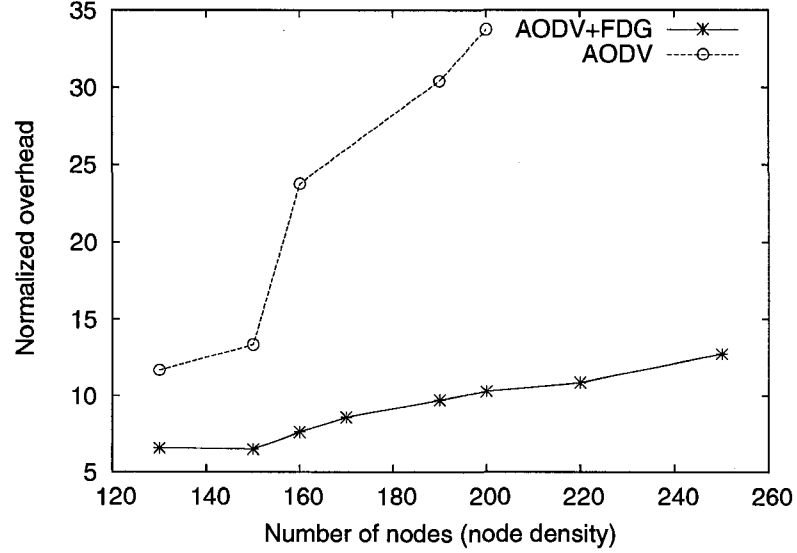


Figure 6.10: Normalized overhead versus number of nodes

network with two competing protocols. As shown in the figure, delivery ratio of modified routing protocol outperforms the AODV alone. The difference was significant (3 to 5 times higher) especially at higher node densities, the modified protocol performed and delivered close to 95% packets, whereas the non-modified protocol did not work at all. Reduction in routing overhead also helped reduce delays in transferring data packets. Figure 6.12 compares the average end-to-end delay in using AODV with FDG, versus using AODV alone in the same network. The network with FDG was not sensitive to the increasing node densities, whereas the network with AODV showed a sharp increase in packet delay with increasing node densities.

6.7 Summary

This chapter introduced a game theoretic approach, called forwarding dilemma game (FDG), for forwarding the flooding packets in wireless ad hoc networks. The FDG nodes the use of a strategy set $S = \{Forward, Not\ Forward\}$. Then the probability to select the strategy is calculated based on the mixed strategy Nash equilibrium of the game. This limits

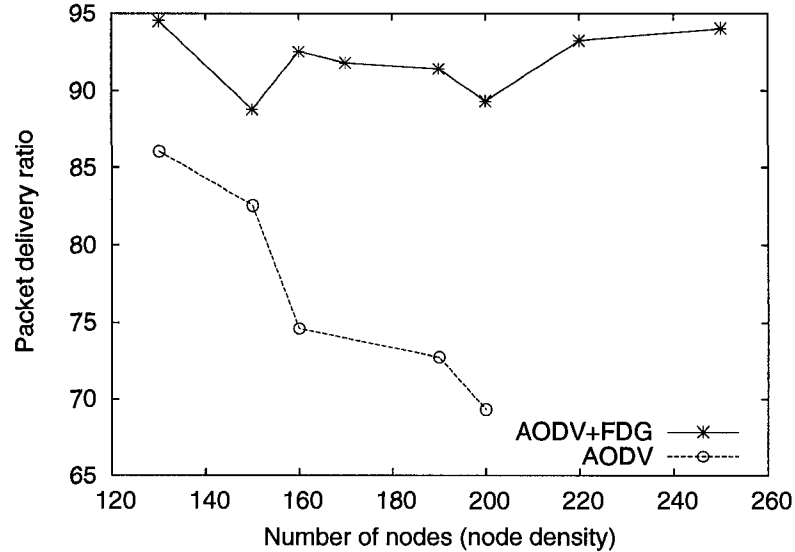


Figure 6.11: Packet delivery ratio versus number of nodes

the number of redundant broadcasts in dense networks, while still allowing connectivity. This approach has two advantages over other previously proposed methods used to control flooding. Firstly, nodes employ FDG to calculate the probability of forwarding adaptively. Secondly, unlike hierarchical or clustering methods, the proposed modification does not cause extra routing overhead. Simulation results show that AODV with FDG outperforms the AODV routing protocol especially in dense network scenarios where routing overhead is a dominant factor degrading the network performance. This game can be applied to a large class of routing protocols that have flooding as a preliminary method of route discovery. In addition to the FDG, a neighbor discovery algorithm that enables nodes to discover the number of their neighbors was integrated in AODV to allow FDG to work properly.

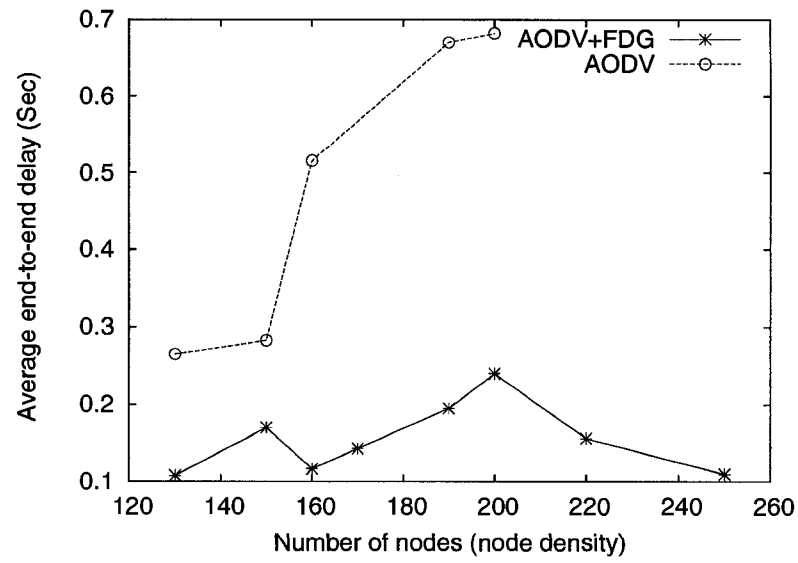


Figure 6.12: Average end-to-end delay versus number of nodes

Chapter 7

Game Theoretic Dynamic Probabilistic Forwarding in Wireless Ad Hoc Networks

This chapter introduces a game theoretic approach to induce dynamic probabilistic forwarding in ad hoc wireless networks. Forwarding Game Routing Protocol (FGRP) can be applied to any routing protocol in wireless ad hoc network that utilizes flooding. A node enters the forwarding game upon receiving a flooding packet that is required to be forwarded to other nodes. The strategy of the players of the game is the forwarding probability of the flooding packet. Every player has a utility that is a function of its availability, selected strategy and forwarding probability of other nodes. Nodes select a strategy that maximizes the utility function. Parameters such as residual energy level, congestion, number of packets in the queue and the distance from the source of the flooding packet can be included in the availability parameter that makes FGRP a flexible protocol using cross layer information. Since the forwarding decision is made locally by every node, unlike other clustering or hierarchical algorithms, there is no extra overhead involved. FGRP was integrated with AODV in network simulator NS-2. Simulation results showed that FGRP consumed less energy compared to AODV, while average end-to-end delay per packet, network throughput and packet delivery ratio improved tremendously.

7.1 Introduction

This chapter provides a dynamic probabilistic flooding method for reactive routing protocols in wireless ad hoc network. The simplest probabilistic flooding is when nodes that receive a broadcast packet retransmit that packet with some probability p or discard (drop) this packet with probability $(1 - p)$ [39] and [36]. Through extensive simulations, it was shown in [36] that a simple probabilistic forwarding used up to 35% fewer overhead packets than flooding and could improve performance of AODV even in small networks of 150 nodes. A critical value for forwarding probability exists that depends on the number of neighbors of a node. As the number of neighbors of each node increases the critical value of p should decrease [37]. The major problem of probabilistic schemes is that the probability at which a node should rebroadcast is not universal, but specific to network topology and there is no analytical formula to obtain that probability, p . In some studies, node density or the number has been used in a function to calculate forwarding probability [41, 42, 43] and [44]. Zhang and Dharma [45] introduced dynamic probabilistic scheme where every node calculates p based on the node density and the number of broadcasts of the same flooding packet. Forwarding is performed after a random delay which increases latency. Local topology information is used to avoid unnecessary rebroadcasts in location-based schemes.

In the proposed Forwarding Game Routing Protocol (FGRP), a node enters the forwarding game to make a forwarding decision when it receives a flooding packet that needs to be forwarded for other nodes. The players of the game are the wireless nodes that are receiving the same flooding packet in the same time slot. In other words, neighbors of the source of the flooding packet are the players of the forwarding game. The strategy of the players is the forwarding probability that each node forwards the flooding packet. Every player has a utility that is the function of its forwarding probability and availability and also forwarding probability of other nodes. Availability of a node is a normalized factor based on parameters like distance from the source of the flooding packet, residual battery, congestion or any other cross layer information that are valuable in routing. Utilizing this model in any routing protocol that uses (control message or data) flooding improves the performance of the routing protocol. We integrated FGRP with AODV and simulated different scenarios

in NS-2 [71]. Simulation results confirmed network performance improvement with FGRP. FGRP limits the number of nodes that participate in the route discovery of the protocol, which in turn reduces overhead and delay. In dense networks, because number of nodes that involve in the route discovery is smaller, routes are found faster with FGRP. In our proposal, unlike clustering or hierarchical protocols, wireless nodes do not exchange extra control messages and forwarding decisions are made locally at each node. Such reductions could significantly save bandwidth of the network, hence improve total throughput of the network. If residual battery level of nodes is used in availability parameter α_i , FGRP also distributes energy consumption among the nodes of the network. Wireless nodes with low energy resources last longer in the network.

7.2 Forwarding Game

In wireless ad hoc networks, when a source node S wishes to send some data packets to a destination node D , located outside of wireless transmission range of S , it relies on its neighbors (nodes that are in its range) and other intermediate to relay packet to D . Data is either broadcasted directly by the source (data flooding) or a routing protocol is used to seek a route to the destination which also implements flooding of control packets. In a reactive routing protocol such as AODV, node S broadcasts a route request (RREQ) packet that is re-broadcasted by all of its neighbors. Either way, nodes that are in the wireless transmission range of S (neighbors of S) have to be involved and broadcast messages (data or control packets) to establish the communication session for S . When a flooding packet is received by a node that is not the destination of that packet, the flooding packet is re-broadcasted by that node. In a dense network, many redundant broadcasts of a single message are generated. Destination node may be multiple hops away, therefore, broadcasts may reach entire network. In the shared wireless medium, where only one node can broadcast in a time slot, unnecessary broadcasts degrade the performance of the network enormously. This phenomenon is referred as broadcast storm [39]. In our approach, neighbors of S will enter a forwarding game upon receiving the flooding packet, where they choose forwarding probability as their strategy. The outcome of the game is the probability that each node

forwards the flooding packet for S . Please note that here node S is not necessarily the originator of the data packet and could be an intermediate node itself. *Forwarding Game* G is defined as

$$G = \{N, (S_i)_{i \in N}, (u_i)_{i \in N}\}, \quad (7.1)$$

where N is the number of players of the game, and S_i and u_i are strategy and utility function of an arbitrary node i respectively [77] and [78]. A node enters the forwarding game when it receives a flooding packet that needs to be forwarded to establish a communication link for other nodes of the network. Strategy S_i is defined as the probability that node i forwards the received flooding packet and $S_i \in (0, 1]$. If $S_i = 1$ is selected, node i will forward the flooding packet. For $S_i < 1$ the forwarding is based on probability.

7.3 Utility Function of the Forwarding Game

In this section, the utility function of the forwarding game will be defined. A player of the forwarding game always selects a strategy that maximizes its utility function. The strategy of other players (neighbors of the source of the flooding packet other than node i is denoted as S_{-i} . A node can have an estimate of its neighbors participation simply by listening to the channel. $Q_i \in (0, 1]$ is defined as the neighbor action reflection and is written as

$$Q_i = 1 - S_{-i}. \quad (7.2)$$

We would like to include availability of nodes into the forwarding game as well. Availability of an arbitrary node i , denoted as α_i , reflects the amount of resources that it has available to forward packet for others. Parameters like residual battery level, congestion, number of packets in the MAC layer queue and distance from the source of the flooding packet can be included in node availability, which is between 0 and 1. The availability parameter could be a normalized average of one or all of the parameters that are important to the network designer. A node with zero availability is not a player of the forwarding game. Our goal is to reduce the routing overhead and improve the overall performance of the network by eliminating redundant broadcasts. To achieve this goal, the utility function of the players should have the following characteristics:

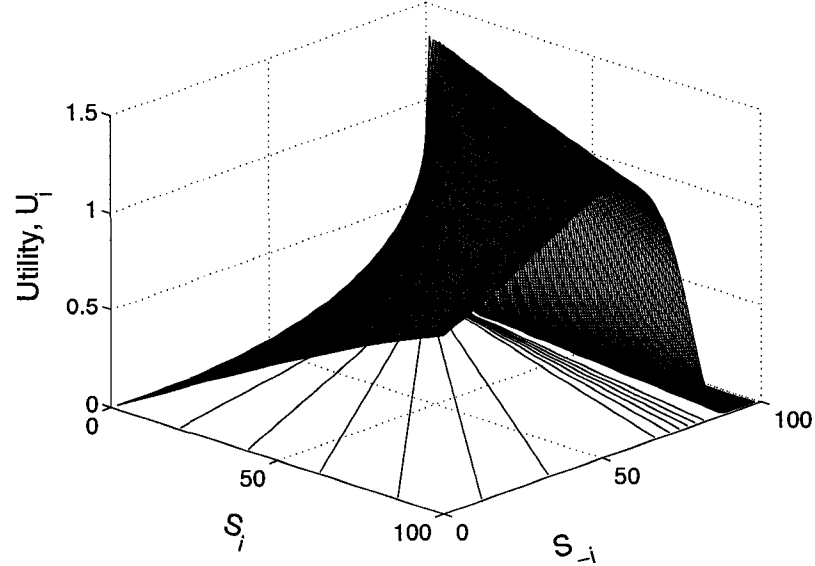
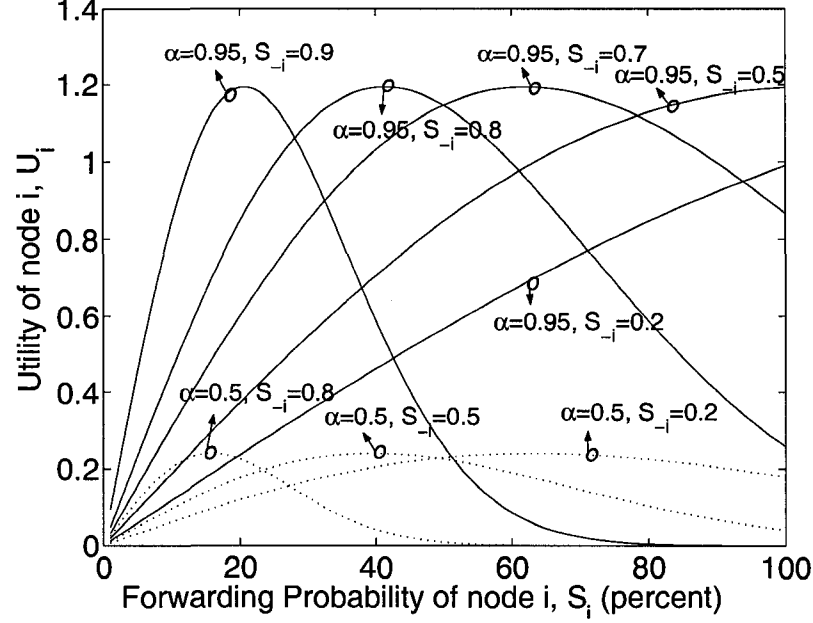


Figure 7.1: Utility of node i versus S_i and S_{-i}

1. Differentiable function of S_i .
2. Increasing function of S_i , when $\alpha_i \rightarrow 1$.
3. Decreasing function of S_i , when $\alpha_i \rightarrow 0$.
4. Increasing function of S_i , when $S_{-i} \rightarrow 0$.
5. Decreasing function of S_i , when $S_{-i} \rightarrow 1$.

The second and third properties include availability in the utility function. Nodes with lower α_i would gain lower utility when the forwarding probability is increased more than a certain value. On the other hand, a node with higher availability will receive a lower utility if it decreases its forwarding probability more than a certain value. For example, a node that has higher energy resources is encouraged to increase its forwarding probability. The fourth property ensures that when a node finds out that other neighbors may not forward the flooding packet with high probability, it should increase its forwarding probability to help the network in establishing communication. The last property implies that when node i has

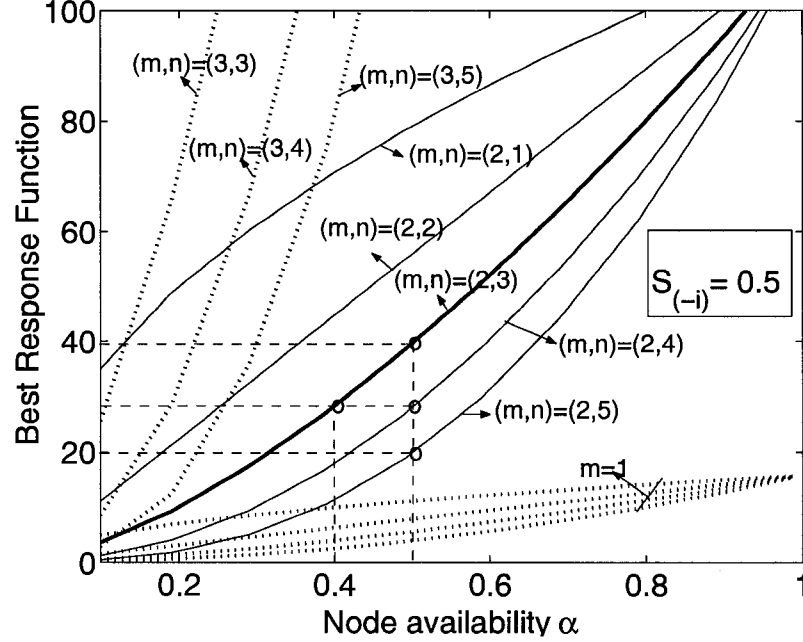

 Figure 7.2: Utility of node i versus S_{-i} , $K=4$, $m=2$ and $n=3$

the knowledge that some of its neighboring nodes are forwarding the same flooding packet that it has under process with high probability, it selects a lower forwarding probability to save its resources. The utility function of the forwarding game for an arbitrary node i that meets all of the above properties is defined as

$$u_i(S_i, \alpha_i, S_{-i}) = \frac{\alpha_i S_i}{Q_i} \exp\left(\frac{-S_i^2}{2K\alpha_i^n Q_i^m}\right), \quad (7.3)$$

where K , m and n are constants values.

Figure 7.1 depicts a plot of the utility function when different strategies are selected by an arbitrary player i . Every player tries to maximize its utility and improve the overall performance of the network. Figure 7.2 depicts the utility of an arbitrary node i , u_i , versus its forwarding probability (strategy) with different α_i and S_{-i} . In that figure, high and moderate values of node availability ($\alpha_i = 0.95$ and $\alpha_i = 0.5$) are plotted. Utility has only one maximum point that is dependent on i 's selected forwarding probability. When i has lower availability, the maximum of utility function occurs in lower S_i . This encourages the node to select a lower forwarding probability. If other neighbors have shown high partic-


 Figure 7.3: Equation coefficients α

ipation level in forwarding packets for others, node i decreases its forwarding probability and relies on its neighbors and the maximum of u_i occurs at lower values of S_i . In other words, node i would not gain higher utility if it increases its forwarding probability more than a certain value. On the contrary, if other neighbors, due to any reason, have shown low participation level, node i gains higher utility if it increases its forwarding probability. In this case, the maximum utility is reached at higher values of S_i . Neighbor action reflection factor Q_i generates a balance between i and other neighbors for forwarding flooding packets. This controls overhead and reduces total energy consumption by eliminating redundant broadcasts. In order to estimate constants K , m and n in the utility function of Equation (7.3) we look into the best response function of players that can be achieved by setting the partial derivative of the utility function to zero as

$$\frac{\partial u_i}{\partial S_i} = \left(\frac{\alpha_i^2}{Q_i} - \frac{S_i^2}{K \alpha_i^{n-1} Q_i^{m+1}} \right) \exp \left(\frac{-S_i^2}{2K \alpha_i^n Q_i^m} \right) = 0. \quad (7.4)$$

Solving for S_i , the best response for node i can be written in terms of α_i and Q_i :

$$S_i^* = \sqrt{K\alpha_i^n Q_i^m}, \quad i = 1, 2, \dots, N. \quad (7.5)$$

Selecting S_i^* yields maximum utility for node i based on its availability as well as other neighbors' strategy. In order to find values for parameters m and n , we consider the best response function of Equation (7.5) with different m and n values. Figure 7.3 depicts the best response function of a node when the participation of other neighbors is $S_{-i} = 0.5$. When $m = 1$, node availability does not have the appropriate effect on the node's forwarding probability. For instance, with $\alpha_i = 1$, the forwarding probability (S_i) selected by the node as the best response is very low (around 20 percent). That is not a desired outcome when $S_{-i} = 0.5$. Therefore, $m = 1$ is not an appropriate parameter for the forwarding game. With $m = 3$ a very high forwarding probability is selected by the nodes regardless of their availability. For instance, a node with low availability ($\alpha_i = 0.3$) may have a forwarding probability equal to 1. When $m = 2$, the best response function of nodes would be reasonably related to the availability. Therefore, $m = 2$ is selected in the utility function given in Equation (7.3). Parameter n can be any value from 2 to 5, while our simulation results showed that $n = 3$ or $n = 2$ would provide optimum results. Best response function for a node is depicted versus its availability with $n = 3$ and $n = 2$ in Figure 7.4. This figure shows that the best response of node i can be located in a wide range based on α_i and S_{-i} . For example, if $\alpha_i = 0.8$, the best response that provides the highest utility will be in the range of 20 to 100 percent depending on the response of other nodes.

7.4 Equilibrium Point

In the forwarding game with N players, if every player looks at the average forwarding probability of other nodes, i.e. $S_{-i} = \sum_{j=1, j \neq i}^N \frac{S_j}{N-1}$, with $m = 2$, Equation (7.5) can be written as

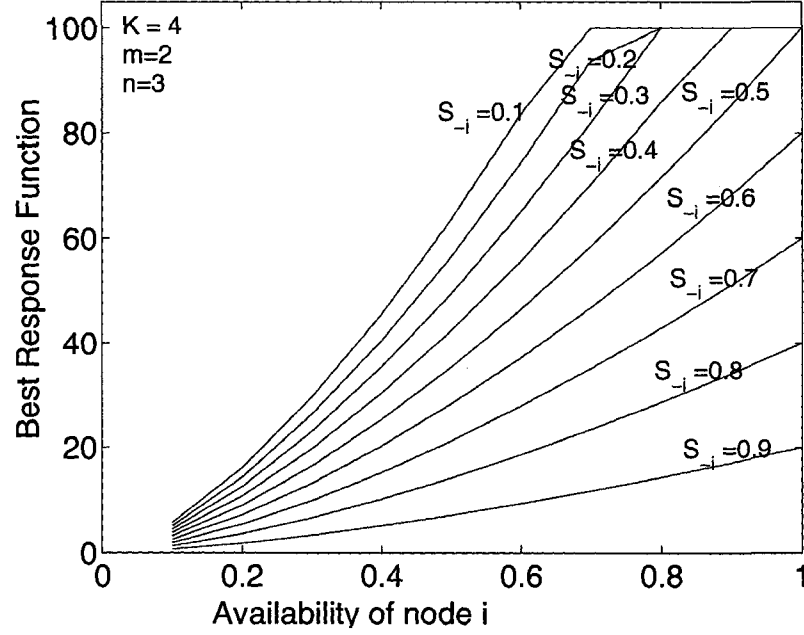


Figure 7.4: EQ vs. alpha

$$S_i^* = \beta_i \left(1 - \sum_{j=1, j \neq i}^N \frac{S_j}{N-1} \right), \quad i = 1, 2, \dots, N, \quad (7.6)$$

where $\beta_i = \sqrt{K\alpha_i^n}$. The above equation set consists of N equations that can be written in a matrix form, and after rearranging as:

$$\begin{pmatrix} N-1 & \beta_1 & \beta_1 & \cdots & \beta_1 \\ \beta_2 & N-1 & \beta_2 & \cdots & \beta_2 \\ \vdots & \vdots & \ddots & \vdots & \vdots \\ \beta_{N-1} & \beta_{N-1} & \cdots & N-1 & \beta_{N-1} \\ \beta_N & \beta_N & \cdots & \beta_N & N-1 \end{pmatrix} \begin{pmatrix} S_1^* \\ S_2^* \\ \vdots \\ S_{N-1}^* \\ S_N^* \end{pmatrix} = (N-1) \begin{pmatrix} \beta_1 \\ \beta_2 \\ \vdots \\ \beta_{N-1} \\ \beta_N \end{pmatrix}, \quad (7.7)$$

where $(S_1^*, S_2^*, \dots, S_N^*)$ is the equilibrium point of the forwarding game. By solving the set of Equations (7.7), every node can find its best strategy to play the game. The number of

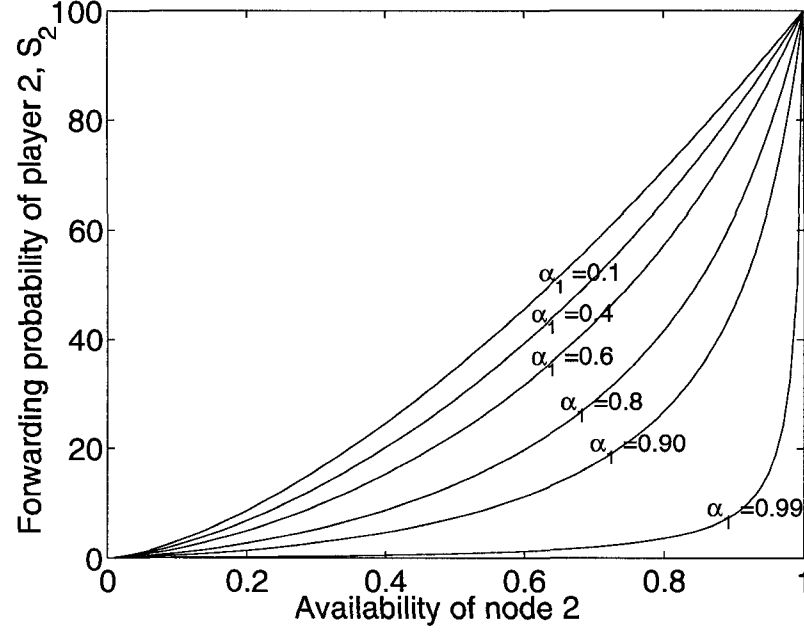


Figure 7.5: Strategies of the players in a two-player game

players and the availability of each player is known. For example, node 1 can calculate its forwarding probability using Cramer's

$$S_1^* = \frac{\det \begin{pmatrix} (N-1)\beta_1 & \beta_1 & \beta_1 & \cdots & \beta_1 \\ (N-1)\beta_2 & N-1 & \beta_2 & \cdots & \beta_2 \\ \vdots & \vdots & \ddots & \vdots & \vdots \\ (N-1)\beta_{N-1} & \beta_{N-1} & \cdots & N-1 & \beta_{N-1} \\ (N-1)\beta_N & \beta_N & \cdots & \beta_N & N-1 \end{pmatrix}}{\det \begin{pmatrix} N-1 & \beta_1 & \beta_1 & \cdots & \beta_1 \\ \beta_2 & N-1 & \beta_2 & \cdots & \beta_2 \\ \vdots & \vdots & \ddots & \vdots & \vdots \\ \beta_{N-1} & \beta_{N-1} & \cdots & N-1 & \beta_{N-1} \\ \beta_N & \beta_N & \cdots & \beta_N & N-1 \end{pmatrix}}. \quad (7.8)$$

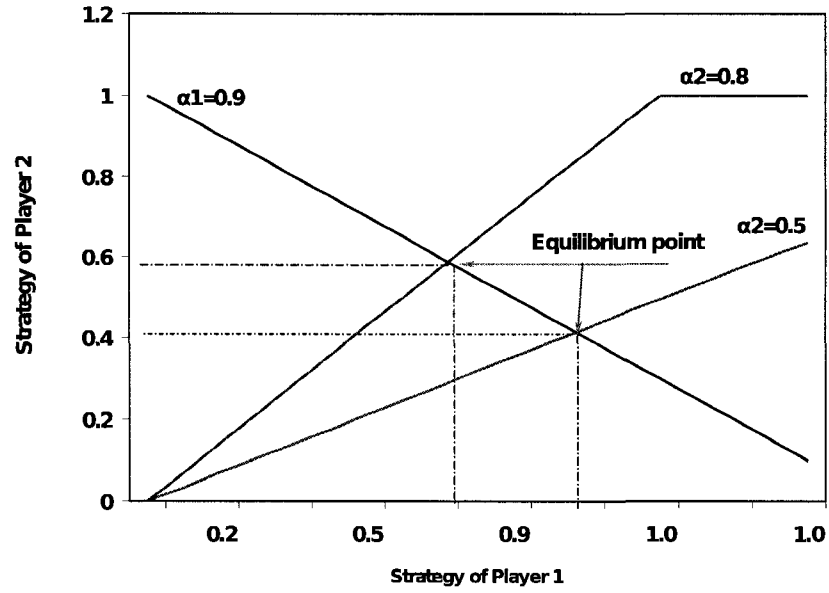


Figure 7.6: NASH Equilibrium

In a two-player game, the best response functions for the two players can be written as

$$S_i^* = \beta_i Q_i, \quad i = 1, 2. \quad (7.9)$$

Since $S_{-1} = S_2$ and $S_{-2} = S_1$, we can write $Q_1 = 1 - S_2$ and $Q_2 = 1 - S_1$. Solving the above equations for S_1^* and S_2^* , the equilibrium point of the two-player game is:

$$S_1^* = \frac{\beta_1 (1 - \beta_2)}{1 - \beta_1 \beta_2}, \quad (7.10)$$

and

$$S_1^* = \frac{\beta_2 (1 - \beta_1)}{1 - \beta_1 \beta_2}. \quad (7.11)$$

Figure 7.5 shows the forwarding probability selection of a player in a two-player game in terms of players availability. In order to decide on the forwarding probability, a node only needs to know the availability of the other player. Equilibrium point of the two-player game is shown in Figure 7.6 with two different values of availability for the second player. Equilibrium point of the game moves to a new point when the availability of the players is changed. For instance, when availability of the second player changes from $\alpha_2 = 0.5$ to $\alpha_2 = 0.8$, the second player increases its forwarding probability. This forces the other player to drop its forwarding probability that shifts the equilibrium point of the game.

7.5 Integration of FGRP with AODV

In this section, the implementation of the Forwarding Game Routing Protocol (FGRP) into AODV routing protocol is explained. In the structure of AODV protocol, HELLO messages are periodically broadcasted by nodes and are used for link monitoring. When node *A* receives a HELLO message from node *B*, it discovers that node *B* is in its wireless transmission range and therefore its neighbor. On the other hand, not receiving a HELLO message from a node is interpreted as a broken link. We added a field to the AODV HELLO messages to contain nodes availability. Then HELLO messages are utilized to obtain neighbor information for FGRP. A neighbor discovery protocol (NDP) is introduced in Figure 7.7. In NDP, it is assumed that the links are symmetric. The source ID of the sender is deciphered from the header of the HELLO messages. Every node generates a time-stamped list of its neighbors (i.e., the source ID of the HELLO message that it has received) and their availability. The neighbor list is updated periodically and outdated entries are removed. The number of neighbors of a node is the number of entries in the updated neighbor list.

In order to implement the FGRP, the route discovery process and the structure of RREQ packet in AODV protocol are modified. Extra fields are added to the RREQ to carry the

```
1 ReceiveHelloMessage(*Packet Hello){
2   // Extracting the source of the packet and its Availability
3   SourceID=Hello → src;
4   SourceID → alpha=Hello → alpha;
5   Call CreateNeighborList(SourceId);
6 }
7 CreateNeighborList(ThisNeighborId) {
8   //search the list and add if it is not in the list.
9   if (SearchNeighborList(ThisNeighborId)=0) {
10    for i = 1 to ListSize
11    {
12    //Find the end of the list and add it there
13    if (NeighborList[i] → NeighborId = empty)
14    {
15    MyNeighborList[i] → NeighborId=SourceId
16    MyNeighborList[i] → SourceIDalpha=SourceIDalpha
17    MyNeighborList[i] → Time=CurrentTime
18    break;
19    }
20    }
21 }
22 }
23
24 Bool SearchNeighborList(ThisNeighborId) {
25   for i = 1 to ListSize
26   {
27     if (NeighborList[i] → NeighborId ≠ ThisNeighborId)
28     {
29       //This was already in the list
30       MyNeighborList[i] → Time=CurrentTime
31       return 1;
32       break;
33     }
34     else {
35       return 0;
36     }
37   }
38 }
39 UpdateNeighborList(NodeId) {
40   //Entries older than ExpPeriod seconds are expired
41   Expired =CurrentTime -ExpPeriod
42   for i = 1 to ListSize
43   {
44     if (NodeId → MyNeighborList[i] → Time < ExpiredTime)
45     {
46       //remove this neighbor from the list
47     }
48   }
49 }
50 //This function is called when a node needs neighbors count
51 CountMyNeighbors(MyNodeId){
52   Call UpdateNeighborList(MyNodeId)
53   for i = 1 to ListSize {
54     if (MyNodeId → MyNeighborList[i] → NeighborId ≠ Empty)
55     NeighborCount ++;
56   }
57   return NeighborCount;
58 }
59
60
```

Figure 7.7: Integrating NDP with AODV

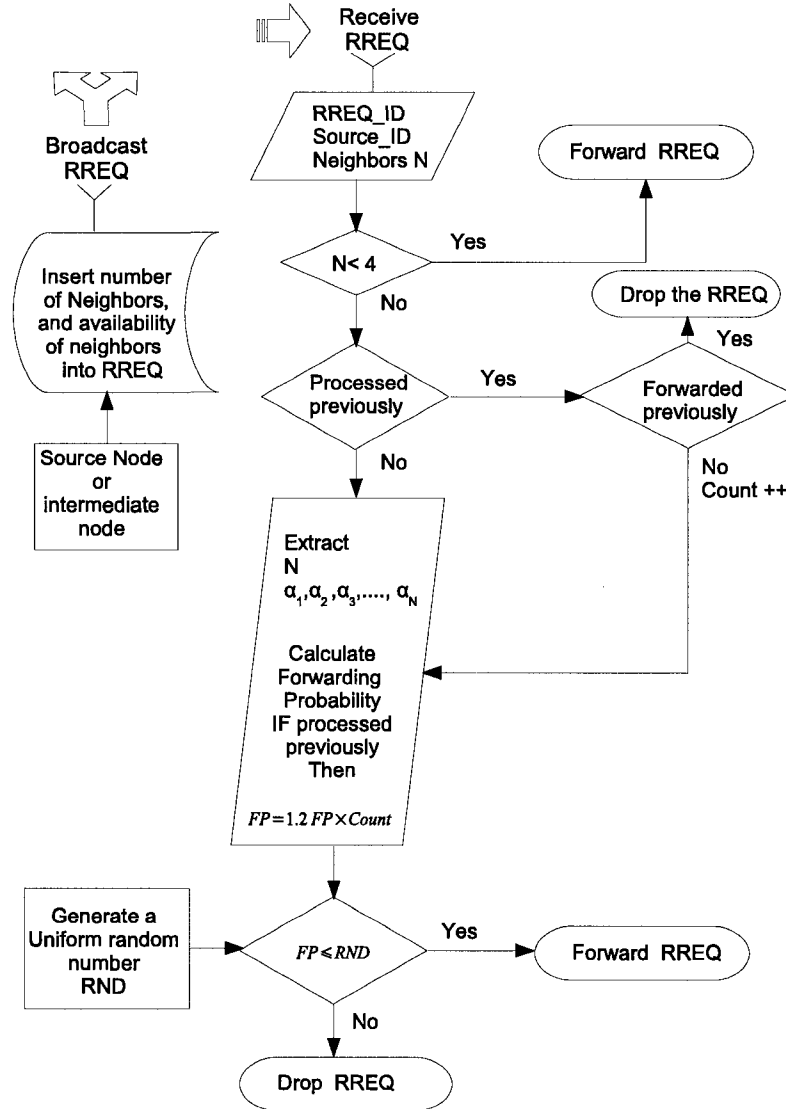


Figure 7.8: Forwarding Game Routing Protocol flowchart

neighbor information of the originator of the RREQ packet. Number of neighbors and their availability values are added to these fields. Figure 7.8 shows the modification in the route discovery process of AODV. When a source node generates a RREQ packet, in addition to its ID, it also inserts the number of its neighbors, N , and availability values of its neighbors into the RREQ packet. This is also done at intermediate nodes. When the RREQ packet is forwarded by an intermediate node, the number of neighbors of the intermediate node and its neighbors availability are inserted into the related fields of the RREQ packet. When the RREQ packet is received by other nodes, neighbor information of the originator can be discovered. If the receiver node detects that the originator had less than four neighbors, it does not enter the forwarding game and forwards the RREQ packet immediately. We required a minimum of four neighbors, based on the results of [93] and [94]. When $N \geq 4$, the receiver node enters the forwarding game and the forwarding probability of the RREQ packet is calculated according to Equation (7.8). To make the forwarding decision, the calculated forwarding probability is compared to a generated uniform random number. In AODV protocol, if the source node does not receive a RREP from the destination for any reason (e.g. link quality), it initiates another RREQ. In FGRP, nodes that did not forward the RREQ in the previous round increase their forwarding probabilities by 20 percent each time they hear that the RREQ is re-broadcasted by the source. This is similar to the ring search technique in AODV and guarantees arrival of the RREQ at the destination.

7.6 Simulation Results

Simulation results are reported in two sections. First, we investigate the connectivity and show that connectivity is not compromised in FGRP by utilizing probability in forwarding of flooding packets. Then the performance evaluation results of AODV and AODV with FGRP is presented in three parts: traffic test, scalability test, and mobility test. In our simulations, the average of normalized distance from the originator of the RREQ packet and the residual battery power was considered as the availability parameter α_i by each node. It was assumed that the transmitted signal power was the same for all nodes. Distance from the originator was calculated from the received power of the RREQ message based

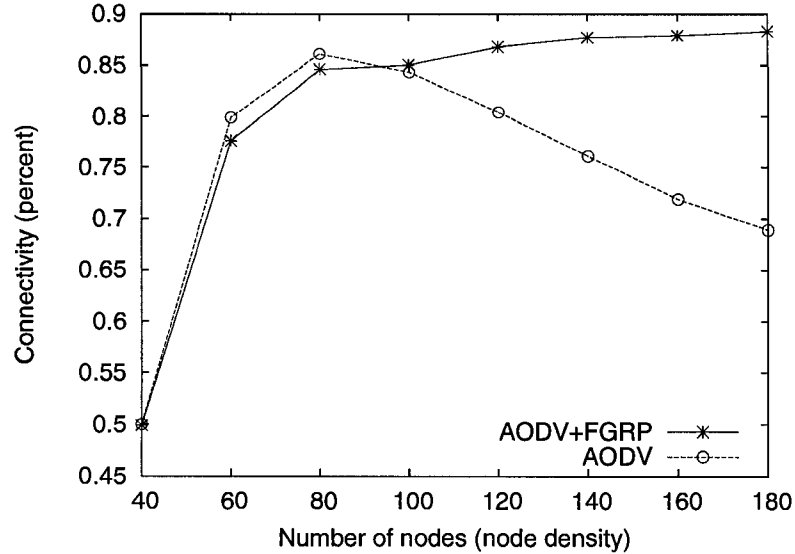


Figure 7.9: Connectivity versus number of nodes

on the free space propagation model. Then, the distance was normalized with the wireless transmission range of the nodes. This way, a further away node enters the game with higher availability value since it provides extra coverage [39].

7.6.1 Connectivity

Connectivity is a major concern in any routing protocol for ad hoc networks. Because FGRP functionality is based on probability, one concern is that flooding messages may not be forwarded by some of the nodes. In FGRP, if the source node does not receive a reply from the destination, the flooding packet is rebroadcasted by the source. Neighbors that have not forwarded the flooding packet in the previous rounds, increase their forwarding probability by 20 percent in each subsequent round. This is similar to the previous chapter and to the ring search technique in AODV. This increase in forwarding probability in the subsequent rounds guarantees arrival of the RREQ at the destination. A test was conducted to verify connectivity in FGRP and compared it with AODV results. In this test, source and destination nodes are positioned at two diagonal corners in a 1000 by 1000 meters field, while other nodes are uniformly distributed in the area and do not generate data packets.

Nodes are static and there is no mobility. At the beginning of the simulation the source node generates only one data packet for the destination node. To discover the route, a RREQ packet is broadcasted by the source. If source does not receive a RREP from the destination within a certain time (30 msec in this setup), it broadcasts another RREQ up to a predefined number of times (4 times in our setup) [7]. If the data packet is not received by the destination within 4 seconds, this event is declared as disconnectivity, otherwise it is counted as connectivity. The number of nodes in the network were varied from 40 to 180 nodes, and simulations were repeated 1000 times for every scenario with different random seeds. The average of those simulations is shown in Figure 7.9. Disconnectivity is expected in low node density regardless of the routing protocol (e.g. 40 nodes). When the number of neighbors $N < 4$ nodes does not enter the forwarding game and forward the flooding packet directly. Therefore, FGRP will be like AODV for these cases. That is why connectivity in network with FGRP was close to the one with AODV in moderate node densities (40 to 100 nodes). Surprisingly, connectivity in the network with AODV dropped when the number of nodes in the network increased to more than 80 nodes. This is related to the broadcast storm problem discussed previously. Our investigation showed that AODV with FGRP not only matches the connectivity achieved by AODV but also improved connectivity in moderate to high node densities.

7.6.2 Performance Evaluation

Our hypothesis was that implementing FGRP in a routing protocol would improve the performance of the routing protocol. To verify that, we designed different scenarios to perform traffic, scalability and mobility test on FGRP and results were compared with those of AODV. In our simulations, nodes were randomly distributed in an area of 1000 by 1000 meter with no mobility except for the mobility test. The initial battery power of nodes were considered different. In each scenario, battery power of 100%, 80%, 60% and 40% were assigned equally to the nodes. For instance, 25 percent of the wireless nodes had full battery power. Traffic sources were CBR with packet size of 512 Bytes. Source nodes were selected randomly at the beginning of the every simulation and started to send data

packets at a random time to a random destination. Simulations were repeated 5 times and the reported results are the average of those 5 simulation runs.

Traffic Test

This was performed to test the protocol sensitivity to increasing traffic in the network. A network with 50 wireless nodes (moderate node density) with 40 randomly selected communication links was considered. Packet generation rate of the source nodes were varied from 1 to 5 packets per second to simulate the effect of increasing traffic.

Figure 7.10, 7.11, 7.12, and 7.13 show respectively normalized routing overhead, packet delivery ratio, average end-to-end delay and throughput of the network for FGRP and AODV. When the data packet rate is increased, there are more route discovery initiations in a certain time and higher chances of collisions of data or control packets. That is why packet delivery ratio have a sharper drop in AODV. Routing overhead in AODV was around two times higher than FGRP. Increasing the data packet rate from 2 to 4 packet per second generated around 35% extra routing overhead in AODV, whereas FGRP did not show such a jump in routing overhead packets. The packet delivery ratio (PDR) of AODV protocol and FGRP protocol are compared in Figure 7.11. PDR is defined as the ratio between number of packet delivered to the destination and the number of packet sent by the sources. In AODV protocol, the delivery ratio dropped from 80% to 46% when data packet rate increases from 2 to 5 packet per second. In FGRP protocol, the delivery ratios dropped from 85% to 67% only. Hence it can be concluded that FGRP protocol showed better performance in terms of delivery ratio compared to AODV protocol. That means FGRP protocol has less number of packet loss compared to AODV protocol. Average end-to-end delay per data packet was two times lower in the network with FGRP (Figure 7.13). The simulation results presented in this section show that FGRP reduces overhead, improves delay and delivery ratio. Our simulations also confirmed that FGRP was not as sensitive as AODV to increasing network traffic load.

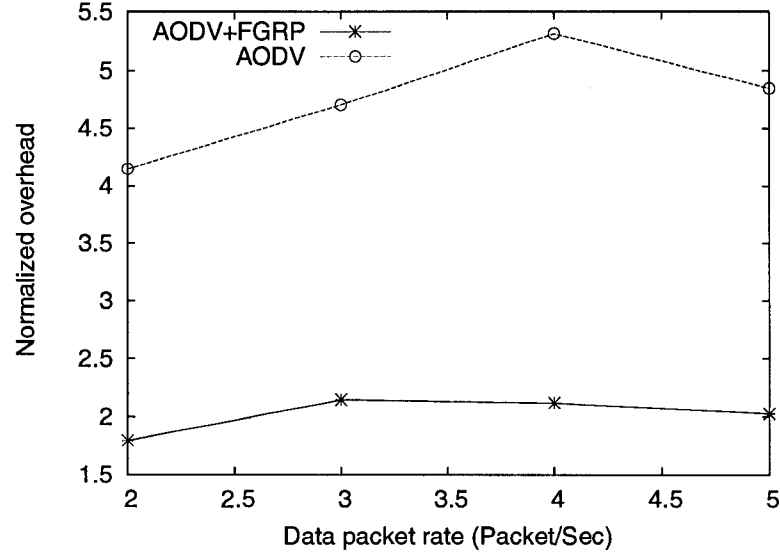


Figure 7.10: Normalized overhead versus CBR packet generation rate

Scalability Test

The number of participating nodes (node density) in the network affects the performance metrics of flooding-based routing protocols. In order to verify that FGRP improves the sensitivity of the routing protocol to node density, the size of the network was kept constant (1000 by 1000 meters) while the number of nodes were varied from 50 to 150 nodes. At higher node densities, the number of redundant re-broadcasts for every flooding packet increases. That is why routing overhead grows with node density in flooding-based protocols such as AODV and DSR. Because of the shared nature of the wireless medium, nodes can not transmit at the same time and packet delay is expected to increase with node density. In FGRP, neighbor nodes that are in close proximity to the source would have a smaller forwarding probability and therefore there is a smaller chance to be selected as a forwarding node. Figures 7.15, 7.14, 7.17 and 7.16 compare packet delivery ratio, normalized overhead, average end-to-end delay and throughput of a network utilizing AODV and FGRP. The overhead generated by AODV and FGRP protocol are shown in Figure 7.14. The overhead packets shown in that figure consist of routing and MAC packets per data packet. AODV

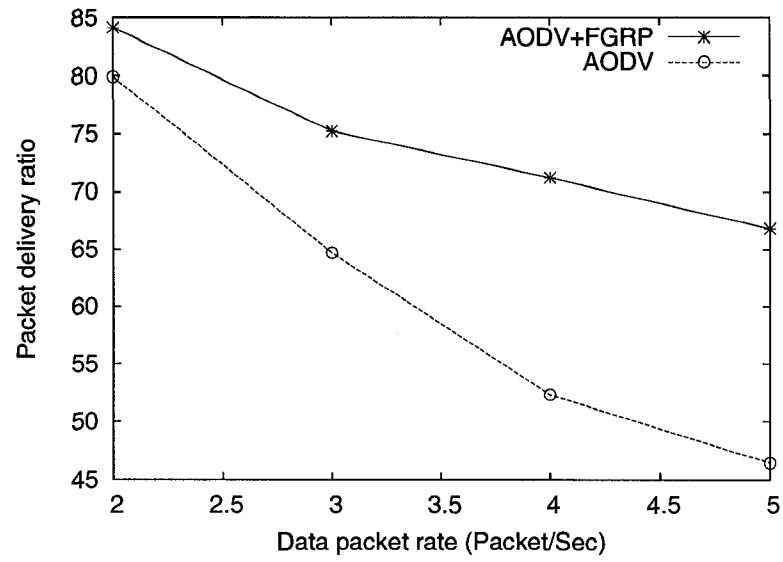


Figure 7.11: Packet delivery ratio versus CBR packet generation rate

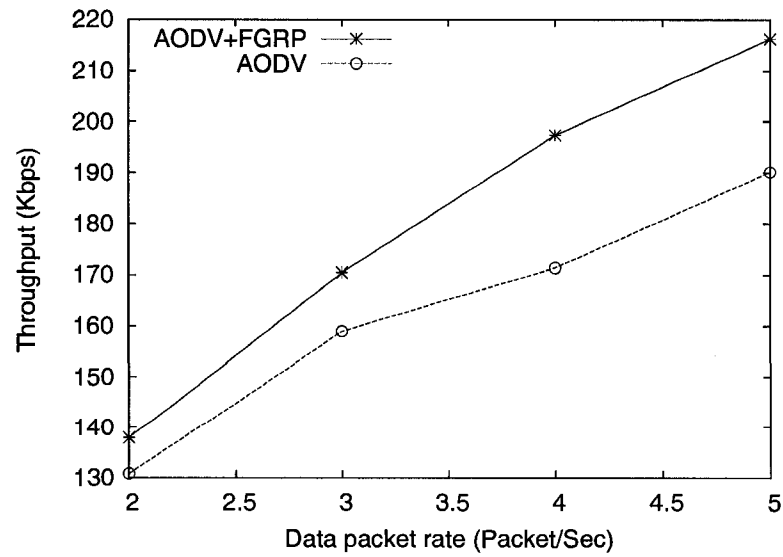


Figure 7.12: Throughput versus CBR packet generation rate

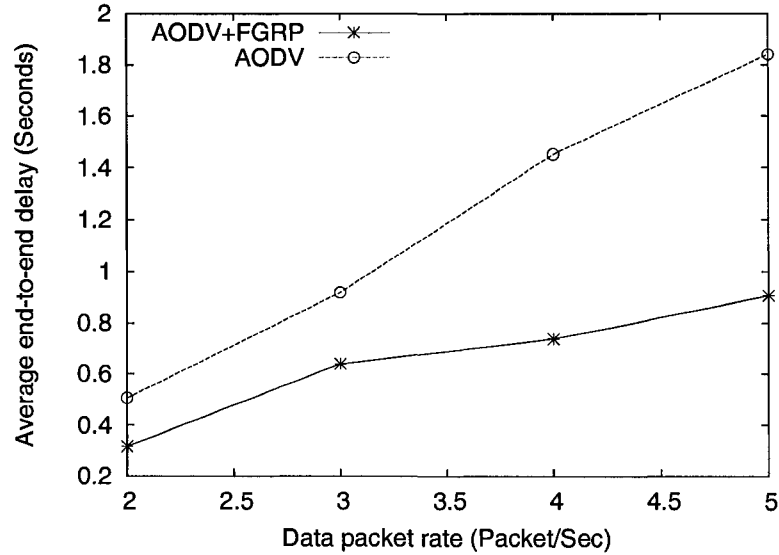


Figure 7.13: Average end-to-end delay versus CBR packet generation rate

showed an exponential increase in the routing overhead packets with increasing the node density. Increasing the node density by three times (50 to 150) increased the routing overhead of AODV by six times, whereas FGRP had significantly lower overhead at high node density compared to AODV. Routing overhead in FGRP was four times lower in high node densities than AODV. That significant overhead reduction helps improving the other performance metrics of FGRP. AODV showed a sharp drop in packet delivery ratio in high node densities. Packet delivery ratio in AODV dropped to 36% (half of its maximum) in the network of 150 nodes, where FGRP delivered more than 55%. Average end-to-end delay in FGRP was two times shorter than AODV. Our simulation results verified that the severe performance degradation that existed in a network with AODV with increasing node density can not be observed in a network with FGRP.

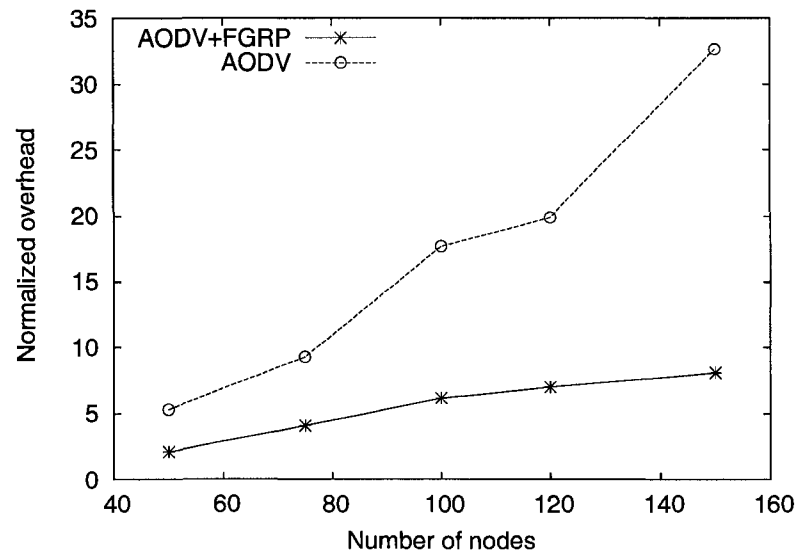


Figure 7.14: Normalized overhead versus node density

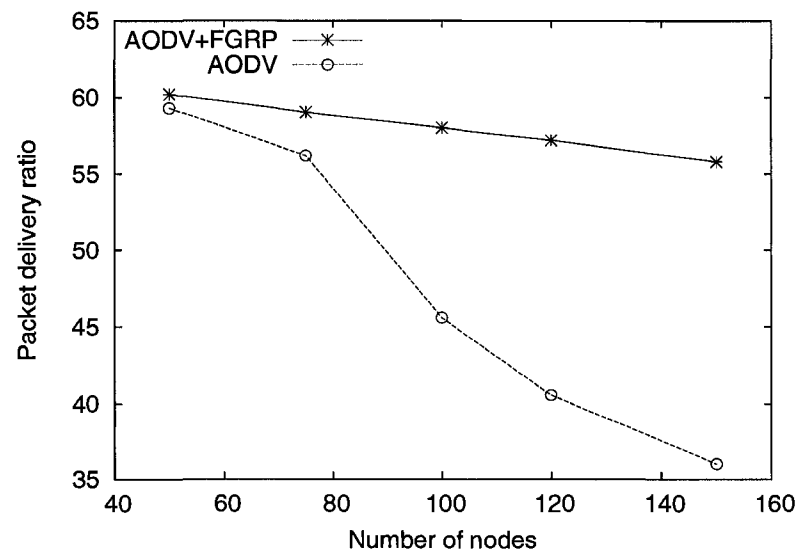


Figure 7.15: Packet delivery ratio versus node density

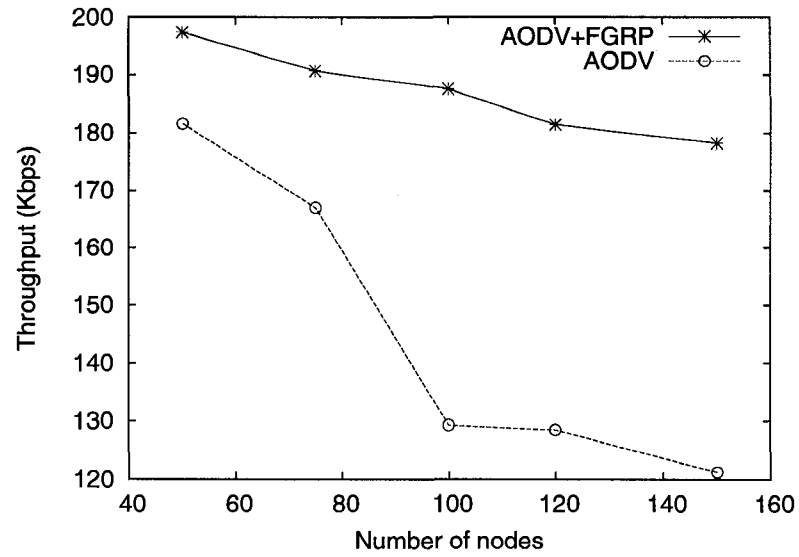


Figure 7.16: Throughput versus node density

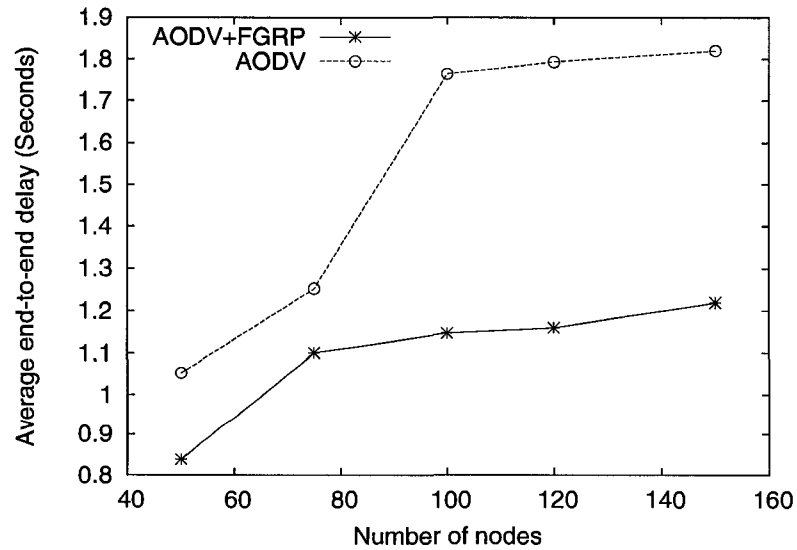


Figure 7.17: Average end-to-end delay versus node density

Mobility Test

Our goal in conducting the mobility test was to verify that FGRP performs at least as well as the unmodified protocol. In order to evaluate the performance of FGRP in mobility situations, we considered scenarios with wireless mobile nodes. The Random Waypoint Model (RWM) was utilized to model the mobility of wireless nodes. In RWM model a mobile node chooses a random point in the network and moves toward that point with a speed randomly chosen up to a maximum speed. Once the mobile node reaches that destination, it stays at that destination for a certain pause time. Once the pause time expires, the node chooses another random destination and speed, and moves toward this destination. In our simulations, we considered the pause time of all nodes to be zero. We set up NS-2 simulation with 100 mobile nodes uniformly distributed in an area of 400 by 1600 meters. In each simulation, there were 100 CBR sources transmitting 50 data packets. Simulations were repeated for different maximum speed of mobile nodes in the RWM. The results are reported in Figures 7.18, 7.19, 7.20 and 7.21. Similar to static node scenarios, FGRP protocol had 80 to 100 percent lower routing overhead compared with the AODV protocol (Figure 7.18). Packet delivery ratio of the network with FGRP was slightly improved (around 5%) compared to the network with AODV protocol (Figure 7.19). Results of our mobile node simulations confirmed that increasing mobility does not have a negative impact on the performance of FGRP. In fact, average end-to-end delay showed slight improvement with increasing the speed of mobile nodes in FGRP (Figure 7.21). FGRP outperformed AODV at different speeds of the mobile nodes.

FGRP increases the life time of the network. Since nodes broadcast less number of overhead packet, network with FGRP can function longer compared to the same network with AODV. On the other hand, if residual battery power is used in the availability parameter of the FGRP, nodes with lower battery power would have lower availability and therefore smaller forwarding probability. FGRP synchronizes the power usage among nodes of the network. Figure 7.22 depicts the percentage of the initial energy of nodes that were categorized as low battery (i.e, average of battery level of nodes with 40 percent initial battery level) in the above mobile scenario. The average of energy level of these nodes has

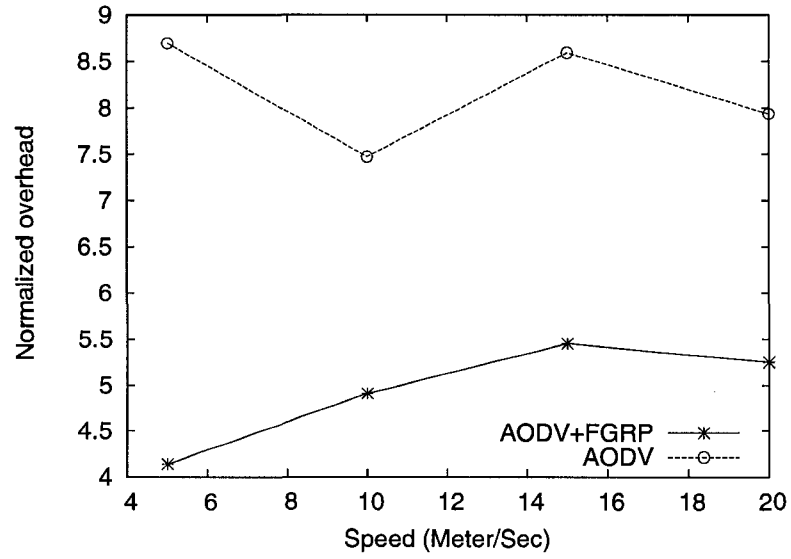


Figure 7.18: Normalized routing overhead versus maximum speed of mobile nodes

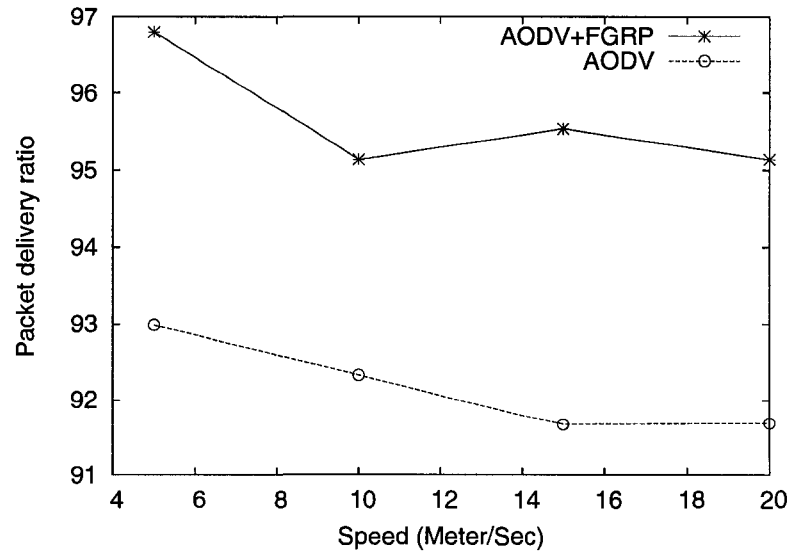


Figure 7.19: Packet delivery ratio versus maximum speed of mobile nodes

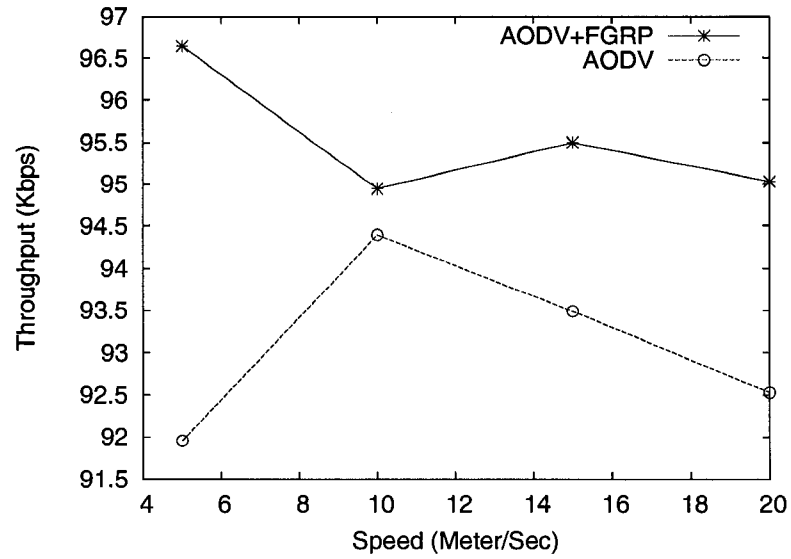


Figure 7.20: Throughput versus maximum speed of mobile nodes

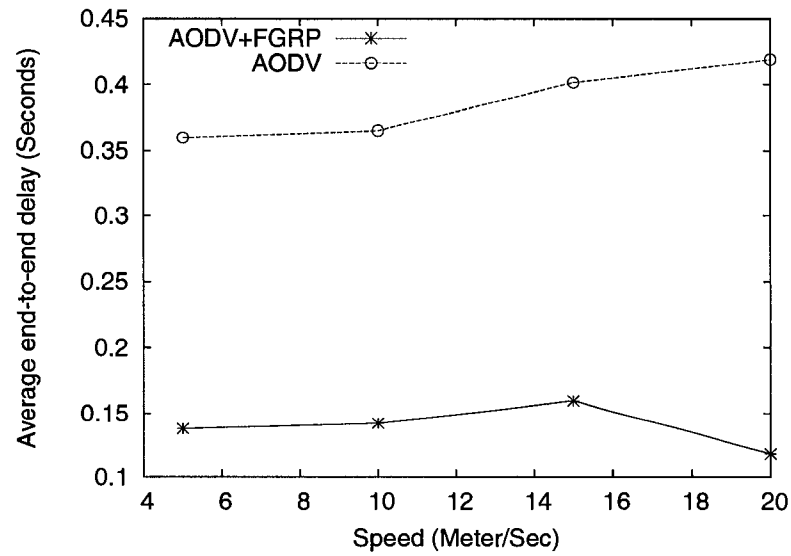


Figure 7.21: Average end-to-end delay versus maximum speed of mobile nodes

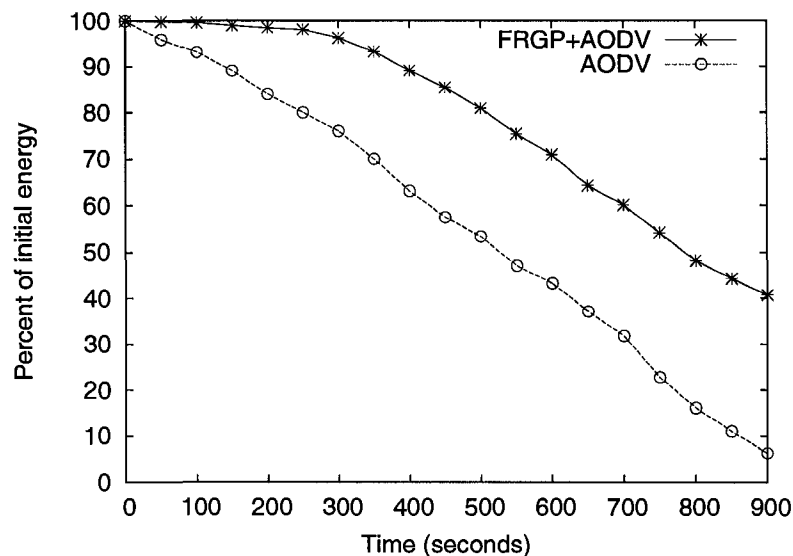


Figure 7.22: Network life time

a sharp drop at the beginning in the AODV network. These nodes are utilized equally for packet forwarding for other nodes. In FGRP, that residual energy is included in node availability parameter, it is less likely that a node with lower battery level compared to its neighbors would be selected as a forwarding node. Therefore, higher energy level nodes act as intermediate nodes at the beginning, to a point that the battery level of the nodes are close to each other. Thus in many instances the length of time that the first node runs out of battery (dies) increases extensively.

7.7 Summary

A dynamic probabilistic forwarding protocol for wireless ad hoc network was introduced based on game theory. In Forwarding Game Routing Protocol (FGRP), wireless nodes of the ad hoc network are the players of the game and the forwarding probability of the nodes is the strategy of the players. Each node has a utility that is a function of its strategy and its availability to forward packet for other nodes. Parameters such as energy, congestion and the distance from the source of the received packet can be included in node availability parameter. A node enters the forwarding game upon receiving a flooding packet. Every node tries to maximize its utility and the selected forwarding probability (strategy) by each node is the equilibrium point of the game. The utility function is designed to improve the network performance. Therefore, every node of the network is contributing to enhance the performance by maximizing their utility function. The proposed algorithm can be applied to a large class of flooding-based routing protocols. Since the forwarding decision is made locally at every node, unlike hierarchical or clustering methods FGRP does not generate overhead or delay. In order to evaluate the performance of FGRP, extensive NS-2 simulations were performed. It was verified that FGRP does not create disconnectivity in the network by forwarding the flooding packets based on probability. Our simulation results included traffic, scalability and mobility tests and showed that FGRP outperformed AODV in all the test scenarios in throughput, average end-to-end delay and packet delivery ratio. FGRP also helps to save energy and increases the network life by regulating the energy consumption of the nodes.

Chapter 8

Concluding Remarks

8.1 Summary of Contributions

The main objective of this dissertation was to resolve the 'flooding' problem in existing routing protocols in ad hoc networks. In Chapter 4, it was shown through mathematical model [102] and simulations that reactive routing protocols like DSR and AODV are not scalable. In Chapter 5 we focused on DSR and showed that it utilizes blind 'flooding' mechanism to discover paths to destination. Each node in the network is obliged to forward route discovery control messages upon receiving from other nodes. It has also been shown that blind 'flooding' affects the performance of the network specially when network size is large. The main problems of blind 'flooding' are (1) redundant control message generation, (2) high contention level, and (3) packet collisions. Redundant control messages consume network resources like bandwidth and energy. High contention increases packet end-to-end delay. Packet collision increases packet loss. To reduce 'flooding' problem, many routing protocols have been proposed. Those protocols need special arrangements such as GPS system or additional control messaging. GPS adds to the cost and size of the wireless nodes, which is not desirable in most applications. Additional control messaging that is introduced by clustering methods can cause extra overhead and has its own problems. A new routing

protocol called 'Hierarchical Dynamic Source Routing (HDSR) protocol [75] and [104], was introduced in Chapter 5. The HDSR protocol does not need any special arrangement like GPS system or "Hello" messaging. A hierarchy among network nodes is created in HDSR and network nodes are classified into Mobile Node (MN) and Forwarding Node(FN). MNs host the application and FNs forward the route discovery control messages. Since only FNs participate in the route discovery process, overhead control messages generated in the network are reduced significantly. Two game theoretic methods were proposed to make forwarding decisions by wireless nodes. Both methods limit the flooding phenomena in reactive routing protocols and improve the performance of the protocol. A Neighbor Discovery Protocol was developed and implemented in AODV. NS-2 C++ code was modified to contain this protocol. FDG [100] offers a node to use a strategy set $S = \{Forward, Not Forward\}$. Then the probability of selected strategy is calculated based on mixed strategy Nash equilibrium of the game. This limits the number of redundant broadcasts in dense networks, while still allowing connectivity. NS-2 simulations verified that FDG addition to AODV improves the AODV scalability and performance tremendously.

FGRP [101] is a dynamic probabilistic forwarding protocol that was designed based on game theory. Wireless nodes of the ad hoc network are the players of the forwarding game, and the forwarding probability is their strategy. Each node has a utility that is a function of its strategy and its availability to forward packets for other nodes. Parameters such as energy, congestion and the distance from the source of the received packet can be included in node availability parameter. A node enters the forwarding game upon receiving a flooding packet. Every node tries to maximize its utility and the selected forwarding probability (strategy) by each node is the equilibrium point of the game. The utility function is designed to improve the network performance. Therefore, every node of the network is contributing to enhance the performance by maximizing their utility function. The proposed algorithm can be applied to a large class of flooding-based routing protocols.

8.2 Future Works

In two proposed game theoretic methods, the outcome of the forwarding game was the forwarding probability that a wireless node utilize to forward the flooding packet. For instance, in FGRP, forwarding probability is the strategy selected by the wireless nodes participating in the forwarding game. We feel that there is more room for performance improvement. As a future work, we suggest recognizing different strategies for the forwarding game other than forwarding probability. At this point, we think that waiting time to forward a flooding packet can be selected as a continuous strategy set of the players of the forwarding game. Nodes will select a time from their strategy set, based on the utility function and wait for that time before forwarding the flooding packet. For this purpose, a new utility function should be designed.

While designing a routing protocol, we assumed that the underlying MAC protocol was IEEE 802.11. It has been suggested that IEEE 802.11 is not an appropriate medium access control mechanism for ad hoc network [105, 106, 107, 108] and [109]. These MAC protocols proposed in [105, 106, 107, 108] and [109] could be used as the underlying MAC protocol, along with the routing protocols proposed in this dissertation.

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Appendix A

List of Publications

1. Mohammad Naserian and Kemal E. Tepe, “ Game Theoretic Approach in Routing Protocol for Wireless Ad Hoc Networks”, Accepted for publication in Elsevier Journal of Ad Hoc Networks.
2. Mohammad Naserian and Kemal E. Tepe, “Game Theoretic Dynamic Probabilistic Forwarding in Wireless Ad Hoc Networks”, Submitted to Elsevier Journal of Ad Hoc Networks.
3. Mohammed Tarique, Kemal E. Tepe and Mohammad Naserian, “A Cross layer Design for Forwarding Node Selection in Wireless Ad Hoc Network”, In the Proceedings of International Conference on Wireless Networks, Communications and Mobile Computing (IEEE WirelessCom), Hawaii, USA, pp. 802-807, June 2005.

4. Mohammad Naserian, Kemal E. Tepe and Mohammed Tarique, "Routing Overhead Analysis for Reactive Routing Protocols in Wireless Ad Hoc Network", In the Proceedings of IEEE International Conference on Wireless and Mobile Computing, Networking and Communication (WIMOB), Montreal, Quebec, Canada, pp. 87-92, August 2005.
 5. Mohammad Naserian, Kemal E. Tepe and Mohammed Tarique, "On the connectivity of nodes in wireless ad hoc and sensor networks", In the Proceedings of IEEE Canadian Conference on Electrical and Computer Engineering, Saskatoon, Canada, pp. 2073-2075, May 2005.
 6. Mohammed Tarique, Kemal E. Tepe and Mohammad Naserian, "Hierarchical dynamic source routing : passive forwarding node selection for Wireless Ad Hoc Network", In the Proceedings of IEEE International Conference on Wireless and Mobile Computing, Networking and Communication (WIMOB), Montreal, Quebec, Canada, pp. 73-78, August 2005.
 7. Mohammed Tarique, Kemal E. Tepe and Mohammad Naserian, "Energy Saving Dynamic Source Routing for Wireless Ad Hoc Network", In the Proceedings of the third International Symposium on Modeling and Optimization in Mobile, Ad Hoc and Wireless Networks, Trenito, Italy, pp. 305-310, April 2005.
 8. Kemal E. Tepe, Mohammad Naserian and Mohammed Tarique, "A New Hierarchical Architecture for Wireless Ad Hoc Network", In the Proceedings of Wireless 2004, Calgary, Alberta, pp. 246-254, July 2004.
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9. Mohammad Naserian, Kemal E. Tepe and Mohammed Tarique, "HDSR: Hierarchical Dynamic Source routing for Heterogeneous Wireless Mobile Ad Hoc Networks", In the Proceedings of the 10th IFIP International Conference on Personal Wireless Communications (PWC), Colmar, France, pp. 125-132, August 2005.
10. Sasan Adibi, Mohammad Naserian and Shervin Erfani, "A fast handover M-MANET with QoS support", Canadian Conference on Electrical and Computer Engineering, pp. 1090-1092, May 2005.
11. Sasan Adibi, Mohammad Naserian and Shervin Erfani, "Mobile-IP MPLS-based networks", Canadian Conference on Electrical and Computer Engineering, pp. 168-171, May 2005.

Appendix B

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From: j.hansson@ieee.org

Sent: Monday, May 12, 2008 1:34 PM To: Naserian, Mo

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Good morning Mr. Hagen,

I have published the following 2 paper in IEEE and I would like to use the material as part of my dissertation. I appreciate if you could reply to me by May 26, 2008.

Mohammad Naserian, Kemal Tepe, Tarique Mohammed, "On the connectivity of nodes in wireless ad hoc and sensor networks", In the Proceedings of IEEE Canadian Conference on Electrical and Computer Engineering, Saskatoon, Canada, pp. 2073-2075.

Mohammad Naserian, Kemal Tepe, Tarique Mohammed, "Routing Overhead Analysis for Reactive Routing Protocols in Wireless Ad Hoc Network", In the Proceedings of IEEE International Conference on Wireless and Mobile Computing, Networking and Communication (WIMOB), Montreal, Quebec, Canada, pp. 87-92, August 2005.

Regards,

Mohammad Naserian

VITA AUCTORIS

Mohammad Naserian, P.Eng. received B.A.Sc. from University of Tehran and M.A.Sc. degree from Iran University of Science and Technology (IUST) both in Electrical Engineering in 1996 and 1999 respectively. He joined the Department of Electrical and Computer Engineering at University of Windsor, where he started his Ph.D. research in January 2003. During his studies at university of Windsor, he won many scholarships such as Ontario Graduate Scholarship (OGS) and Ontario Graduate Scholarship in Science and Technology (OGSST). He joined university of Detroit Mercy as an adjunct professor in May 2007. His research interest is in wireless communication systems, wireless mobile ad hoc networks (MANETs), wireless sensor networks, game theory applications in communications, network security and distributed networking.