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A cross-layer implementation of Ad hoc On-demand Distance Vector routing (AODV) protocol

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A Cross-Layer Implementation of Ad Hoc On-Demand Distance Vector Routing (AODV) Protocol

By

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Abstract

Mobile Ad hoc Networks (MANETs) are networks which will form the basis for the ubiquitous data access because of their ease of deployment. Due to the dynamic nature of a MANET, routing is one of the most critical elements of MANET. Routing protocols for MANET can be broadly classified as a proactive routing protocol or a reactive routing protocol. In the proactive routing protocols, 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 work on-demand. Thereby generating less 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. 'Flooding' generates a huge number of overhead messages in the network. Those overhead messages affect the performance of reactive routing protocols in term of network throughput. That kind of performance problem is called 'scaling' problem. Ad hoc On-demand Distance Vector Routing with Cross-Layer Design (AODV-CL) protocol has been proposed to solve this scaling problem. The AODV routing protocol has been modified to implement AODV-CL protocol. AODV-CL protocol reduces 'flooding' problem of reactive routing protocols by limiting the number of nodes that should participate in route discovery process based on their status in the network and also avoiding congested area of the network. It is shown that AODV-CL protocol reduces overhead messages by 73% and reduces end-to-end delay per packet by 32% compared to regular AODV protocol.

To our Lord Jesus Christ and Blessed Mother Mary

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Abbreviations

ACK	Acknowledge
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
DSR	Dynamic Source Routing
DSDV	Destination Sequence Distance Vector
DARPA	Defense Advance Research Project Agency
DHCP	Dynamic Host Configuration Protocol
DCF	Distributed Coordination Function
DIFS	DCF Inter Frame Space

DCA	Distributed Clustering Algorithm
FN	Forwarding Node
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
IP	Internet Protocol
LCC	Least Cluster Change
LAN	Local Area Network
LCA	Linked Cluster Architecture
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
RTS	Request To Send
RR	Route Request
SIFS	Short Inter Frame Space
TCP	Transport Control Protocol
UDP	Unigram Data Protocol
VINT	Virtual InterNetwork Testbed

Chapter 1

Introduction

1.1 Motivation

Wireless networking over the past years is becoming more popular in the field of telecommunications. This increasing popularity can be traced back to the early days of packet radio network introduced by Defense Advanced Research Project Agency (DARPA) [33] and the popularity that it has attracted in the research and academic environment. The current breakthroughs in the development of portable mobile devices such as personal digital assistance (PDAs), mobile phones and laptops have increased the drive towards ubiquitous computing. Information can be accessed anytime and anywhere. The era of ubiquitous computing can only be achieved by a mobile network which extends to large areas. Such mobile network can not be realized by infrastructure networks only because there are places and situations where it will be difficult to build a new infrastructure. An example is a battle field, where it is impossible and infeasible to have a fixed infrastructure because soldiers, war plane and war ships need to communicate and they are constantly on the move. Another example is the case of natural disasters where existing networks could have been destroyed by cyclone, tsunami and tornado. In such a case, a temporary network needs to be set up to carry out rescue missions. The above examples show the need for a temporary network in order to have a true ubiquitous communication. The temporary network can be provided by Mobile Ad hoc Networks

(MANETs). MANETs consist of mobile devices with limited power and processing capabilities who comes together to form a temporary network without a central administrator. They are self-organizing and self-configuring. A MANET can find an application in military, distributed and collaborative computing and wireless sensor networks [39]. A typical MANET network is shown in Figure 1.1.

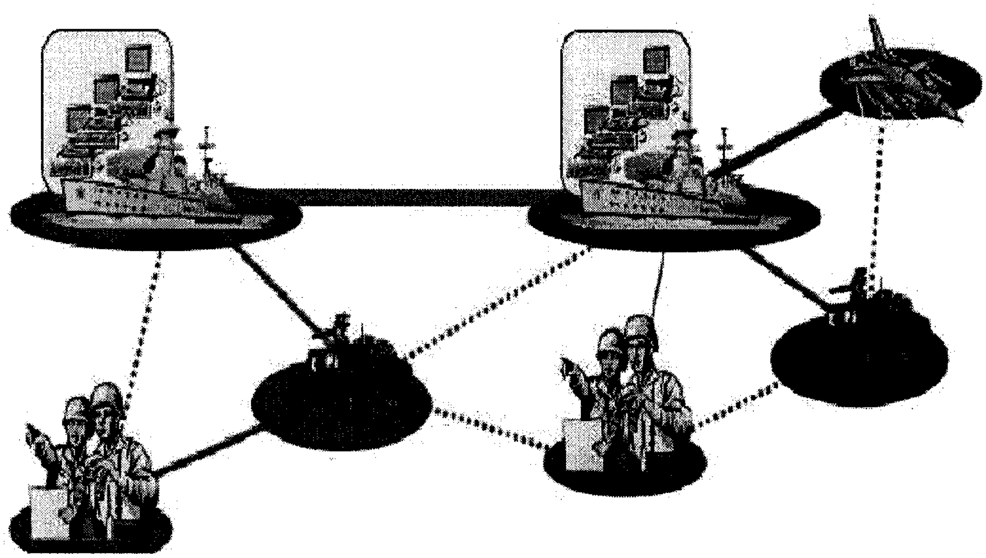

Figure 1.1: A mobile ad hoc network

MANETs have some characteristics which are not present in wired networks. It has a dynamic topology. Mobile nodes are free to move randomly which leads to frequent path breaks. Because the transmission medium used is wireless, MANETs also inherit some of the features of wireless communications such as higher error rate than the wired medium, lower and limited bandwidth, and security treats.

There are various challenges still facing the MANETs such as routing, multicasting, energy management and scalability [39]. Routing is the most important issue in the MANET. Routing in MANETs can be categorized into two major categories; proactive and reactive. In proactive routing protocols such as Destination Sequence Distance Vector (DSDV) [21] and Wireless Routing Protocol (WRP) [25], every node maintains a global view of the topology through periodical routing table exchanges flooded throughout the network. The periodical exchanges generate large number of overhead packets in the network which makes proactive routing protocol unsuitable for MANET's. Reactive routing protocols such as Ad hoc On-demand Distance Vector (AODV) [4] and Dynamic Source Routing (DSR) work on-demand [7], they do not maintain a global view of the network topology. These protocols obtain paths when they are needed. This approach has far less overhead than proactive approach. But reactive protocols use a global search procedure called "flooding" during a route search. In the route search a mobile node generates a special packet called Route Request (RR) packet which is broadcasted to all its neighbors. When a neighbor receives RR packet, it replies if it is the destination or if it has a route to the destination in its routing table, else it re-broadcasts the RR packet to its neighbors. This procedure continues until the destination node receives the RR packet. Thus the whole network is flooded with RR packets. The flooding significantly affects the performance of a large network. Some of the problems associated with "flooding" are (1) collision, (2) contention, and (3) redundancy [23]. A simultaneous retransmission of RR packets by two neighboring nodes causes a collision. There is a high probability that a node will receive multiple copies of the same RR packet which are redundant. Researchers have proposed various schemes to reduce "flooding" problem in the MANETs. The schemes are broadly classified into three major categories (1) location based schemes [3, 10] and [12], (2) clustering schemes [26] and [27] and (3) probability based schemes [12] and [13]. There are also other schemes which do not directly fall into any of the above schemes such as node caching [14] and [15]. In the location based schemes, routing is performed based on the location of a node in the network. For example location based routing schemes can select routing nodes based on their proximity to the destination node. In clustering schemes, the network consists of various clusters with one "cluster head" and a group of "ordinary nodes". The "cluster head" forwards RR packets on behalf of the "ordinary nodes" through a node, called "gateway nodes" which connects two clusters. In probabilistic schemes, nodes broadcast a packet with a probability which is less than 1.0. The probability of each node is calculated using various parameters. One of the important requirements for an efficient operation of the schemes mentioned above is that the network topology must be known by each node. In the location schemes the global view is achieved by the use of Global Positioning System (GPS) by each node in the network. This introduces additional cost in terms of hardware and software requirements. In cluster based schemes, nodes are required to transmit "HELLO" messages among themselves in order to get a global view of the network and, in some cases, to determine or to elect a "cluster head". This definitely generates extra overheard in the network.

Another problem that occurs in the MANETs is congestion. Congestion in MANET leads to longer delay, higher overhead and high packet loss [30]. Reactive routing protocols such as AODV and DSR use the shortest path during routing, which is the path with the minimum number of hops out of all the paths discovered during the route discovery. According to [28], the shortest path routing might not be the best for the MANETs. Analysis in [28] showed that the center of a network using the shortest path routing decisions tends to be more congested than the other parts of the network. That is the nodes at the center of the network carry more traffic than the nodes at the edges. This is also collaborated by [29]. Protocols such as [29] and [30] have been proposed to mitigate the effect of congestion in the MANETs. These protocols obtain congestion information of a node through the interface queue and this information is used in routing.

The goal of a routing protocol is to find route to a destination efficiently. This requires the protocol to be able to mitigate the effects of "flooding" and congestion. But most times routing protocols hardly meet these requirements. There are usually trade offs in meeting these objectives. Different applications have their own unique requirements. For example, security plays an important role in military applications. In sensor networks, energy conservation is important. Reliability takes priority in collaborative and distributed systems. These applications also require different information to achieve their own unique requirements. For example information about node mobility is useful for routing and network management. Energy statuses of nodes are needed in the routing decision of energy sensitive applications. The need for MANET to meet diverse application requirements has led researchers to suggest that the present Open System Interconnect (OSI) fixed protocol stack is not suitable for MANET [30]. The OSI model was designed primarily for wired networks and therefore cannot meet the requirements of a dynamic network like MANET. They have proposed interactions among protocol stack which is called "Cross Layer" design [38]. Some examples of cross layer design are [2, 29, 31] and [32]. A design that uses MAC layer feedback to notify TCP about congestion was proposed in [31]. Using congestion information obtained from the MAC layer for routing decisions has been investigated in [2, 29] and [32]. In [32] the ratio of packet being currently buffered to the link layer buffer size is used to categorize a node as "green", "yellow" and "red". Routes are chosen to forward packets based on the above indicators. In [2], contention window size from the MAC layer is used in routing decision.

1.2 Contribution and applicability

This thesis addresses the problem of efficient reactive routing protocol for MANET that reduced the problem of "flooding" and congestion effect by having only few nodes involved in route selection and also avoiding congested area of the network. The proposed routing protocol is called Ad hoc On-demand Distance Vector routing protocol with Cross layer design (AODV-CL). The popular Ad Hoc On-demand Distance Vector routing

(AODV) protocol has been modified and optimized to implement AODV-CL. In the AODV-CL, nodes are classified either as Mobile Nodes (MN) or Forwarding Nodes (FN). The MNs are source and destination nodes while FNs act as packet forwarding nodes and are selected based on some criteria. Since only FNs participate in route discovery process, less overhead packet are generated in the network. Reduction in overhead lowers collisions and contentions in the network usually caused by overhead packets. Since less number of nodes are contending for the medium in a given area of the network, network resources such as bandwidth are used more efficiently in AODV-CL than AODV. This implies that there will be more bandwidth in transmitting actual data packets instead of overhead packets. In AODV-CL, nodes after receiving route request packet, only a few number of them, re-broadcast this packet to their neighbors. This effectively reduces the collision probability in the medium. When nodes receive route request packet, they execute an algorithm similar to that used in HDSR [2] to determine if they'll become an FN. This FN selection algorithm can be used by any on-demand routing protocol [2]. In AODV-CL this FN selection algorithm is further modified by using a cross-layer design to select FN in less congested area of the network in order to improve delay performance. MAC layer congestion information is used in FN selection. It is shown in this thesis that using congestion information in FN selection algorithm further improves network performance in terms of delay, throughput and overhead reduction. In the modified FN selection algorithm, MNs located in less congested area of the network have higher probability of becoming FN than nodes located in the congested area. Hence the FN selection algorithm can be implemented on any MAC layer where congestion information is available such as the IEEE 802.11 protocol [33].

Energy efficiency is a major concern in MANET which is usually achieved by controlling the transmit power levels of nodes. Though energy efficiency is not address in this thesis, the goal of AODC-CL is to reduce flooding. That reduction in packet overhead is useful in energy saving of the nodes.

The AODV-CL has the following advantages:

- No additional hardware (i.e., GPS) is required.
- No additional control message like 'Hello' message is needed. Existing control messages such as RR packets has been used. Hence AODV-CL protocol is a passive routing protocol
- It works on-demand. That means nodes exercise FN algorithm when there is need to discover a route
- The global information about network is not required. FN selection algorithm uses only information that is already available at the node locally at different layers of protocol stacks.
- Cross layer interactions are used to implement AODV-CL protocol

The AODV-CL protocol uses node energy efficiently. Hence network life is maximized

1.3 Thesis Organization

This thesis consists of 4 chapters. Each chapter will contain an introductory section to give an overview of the chapter and a conclusion section to summarize the chapter. In this chapter motivation for this thesis was presented.

A brief overview of Mobile Ad hoc Network (MANET) is provided in Chapter 2. The operations of proactive and reactive routing protocols are explained. A detailed operation of Ad hoc on-demand distance vector (AODV) routing protocol and the effects of 'flooding' in MANET is explained in details. A brief review of related studies on solving "flooding" is presented. Cross-layer design for MANET is introduced in Chapter 2 with examples. Network Simulator (NS-2) has been used in this thesis to simulate the protocols and to measure performances of these protocols. Chapter 2 also contains background of NS-2.

In Chapter 3, Ad hoc On-demand Distance Vector Routing with Cross-layer design (AODV-CL) is introduced. FN selection algorithm is introduced in this chapter. A comparative performance analysis of AODV protocol and AODV-CL protocol is presented in this chapter.

The summary of this work and future research will be presented in Chapter 4.

Chapter 2

Background

2.1 Introduction to Mobile Ad Hoc Network

Mobile ad hoc network (MANET) is a distributed system comprising of mobile nodes to form a temporary network. MANET is dynamic, self-organizing and has no central administration. These attributes make MANET a viable candidate for the ubiquitous computing age. The drive for the ubiquitous computing has been on the rise due to proliferation of mobile computing and communication devices. Wireless network is certainly the easiest solution to provide connectivity to ubiquitous computing services. MANET comes as an option for a flexible and low cost deployment of a network where wireless devices need to interconnect with each other in the absence of a fixed infrastructure. A MANET is highly dynamic and therefore its topology is highly unpredictable. This constantly changing topology makes link breakages a regular occurrence and routing in such dynamic networks is very difficult. Previously MANET was developed to provide communication network for the military communication systems especially in the battle field. Some of the other applications of MANET are in crisis management, telemedicine, tele-geoprocessing, process control, personal communication, virtual navigation, education and security.

- Crisis Management: The frequent occurrence of natural disasters such as tsunami, cyclone and tornado makes us have an infrastructure-less communication network which can be deployed quickly. With such networks rescue workers can communicate with each other despite the destruction of the fixed communication infrastructure. Also these infrastructureless networks can serve to temporarily restore the communication facilities in the disaster area.

- Telemedicine: In the event of a traffic accident in a location without fixed communication access, MANET can be used by the paramedic to obtain medical records of the victim such as X-ray and blood type. The paramedic can relay back vital information about the victim to the hospital. Assistance may also be received from experts in case of emergency intervention.
- Tele-geoprocessing: The combination of MANET, geographical information system (GIS) and Global Position Systems (GPS) can be used in the areas of sensor networks to monitor the environment.
- Process Control: MANET such as sensor networks can be used in industrial and manufacturing processes to remotely monitor temperature, pressure and humidity.
- Personal Communication: The world is moving towards an era of personal communication where devices such as laptop, personal digital assistance (PDA), mobile phones and household appliances (Television, gas cooker, microwave oven) will be able to from a network and communicate with each other.
- Virtual navigation: Vehicles can receive information from a remote database containing graphical representation of streets, buildings and layout of metropolis in order for the occupants of the vehicle to navigate the city. Also this information may assist in an emergency rescue plan.
- Education via the Internet: In remote places around the world, educational opportunities can be made available to the students who do not have access to a nearby school.
- Security: Safety plays an important role in our world today. Sensors can be placed

around facilities such as airports and restricted areas in order to monitor and detect intrusion.

2.2 Routing protocols of MANET

Routing is the most active research area within MANET. The complexities and challenges in designing an efficient routing protocol for MANET are large. That is why many routing protocols have been proposed and their performance evaluated by the Internet Engineering Task Force (IETF)'s MANET working group [31]. A routing protocol must find feasible paths to a destination, minimize consumption of node's energy, maintain the discovered routes, and utilize bandwidth efficiently. Challenges in designing a protocol for MANET are mobility, resource constraint, error prone channel, bandwidth constraint and contention.

- Mobility: MANET topology is highly dynamic due to movements of nodes. The node movement leads to frequent link breakages, routing loops, stale routing information and difficulty in resource reservation. These disruptions do not occur in wired networks. Therefore routing protocols used for wired network can hardly be used in MANET. That is why efficient routing protocols for MANET should be designed to address mobility related challenges.
- Bandwidth constraint: In contrast with wired networks, wireless networks have limited bandwidth. This limited bandwidth needs to be used effectively. So a routing protocol for MANET needs to make use of the limited bandwidth efficiently by reducing overhead in the network.
- Error prone channel: Wireless communication channel has high bit error rate (BER). That is why the routing protocol needs to consider channel properties while making routing decisions.
- Resource constraint: In MANET, resources such as battery life, storage and

processing are usually limited. Therefore, the routing protocol should be able to manage these limited resources efficiently.

Because of difficulties mentioned above, MANET requires specialized type of routing protocols. A routing protocol in MANET should have the following characteristics: distributed, minimum route acquisition, loop-free route discovery, quick route maintenance, minimum control overhead and scalability.

- Distributed: Routing in MANET must be distributed because centralized routing is prone to single point of failure.
- Minimum route acquisition: the time needed for route acquisition by a source to a destination depends on some factors such as the size of the network, collision probability and congestion in the network. A good routing protocol should have minimum delay in acquiring route.
- Loop-free route discovery: For a dynamic environment like MANET, transient route is usually common. A routing protocol for this type of network should be able to eliminate, detect and recover from routing loop as soon as possible.
- Quick route maintenance: Constant route breakage is a frequent occurrence in any dynamic network. A good routing protocol should be able to detect link failures as quickly as possible. It should also find alternate routes to the destination in a short time.
- Minimum control overhead: A lot of overhead packets are usually generated when finding a route. These overhead lead to collision in the network and inefficient use of scare bandwidth. The routing protocol must ensure that limited overhead packets are used during route discovery.
- Scalability: The ability of a routing protocol to work with network of any size without incurring excessive overhead is desirable. This can be achieved by

designing a protocol that minimizes the number of overhead packets used during route acquisition.

2.3 Review of routing protocol for MANET

Large number of protocols has been designed for MANET. Routing protocols in MANET can be broadly classified into three major categories: proactive, reactive and hybrid. In proactive routing protocols [21] and [25], each node maintains the network topology information in their routing tables. This is done by periodical exchange of routing information through flooding. Therefore each node can find current route to other nodes in the network. Constant flooding of routing information generates large overhead in the network. This large overhead makes it very difficult to use proactive routing protocols in MANET. Reactive routing protocols [4] and [7] find route to destination only when needed this is why they are also called on-demand. Reactive routing protocols do not maintain a global view of the network. When a route is needed a global search called “flooding” is initiated. The “flooding” generates a large overhead during route request. Also there is a delay in finding routes to a destination in reactive protocols because the route to a destination might not be readily available all the time like proactive protocols. The third type of routing protocols is the hybrid routing protocol which combines the best features of both proactive and reactive protocols [24].

2.4 Proactive routing protocols

Proactive routing protocols maintain consistent and current routing information of the network in the form of routing tables. That is why they are also called table-driven routing protocols. In order to maintain an accurate view of the network and also respond to changes in the network topology, each node is required to propagate updates throughout the network. Examples of proactive routing protocol are Destination Sequenced Distance vector Routing (DSDV) [21] and Clusterhead Gateway Switch Routing (CGSR) [42]. The DSDV protocol is one of the first protocols proposed for ad hoc networks [39] and is based on the Bellman-Ford algorithm [40] with some improvements such as faster convergence and avoidance of routing loops. Just like any other table-driven protocols, every mobile node in the network maintains a routing table containing route to all destination and also the number of hops to each destination. The nodes exchange this routing table frequently in order to maintain a consistent view of the network. The periodic exchange of routing information leads to increased traffic in the network. In order to reduce the volume of traffic in the network, two types of update packets are used: Full dump and incremental. "Full dump" packets carry all available routing information and can may need multiple network protocol data units (NPDUS).They are used when there is a significant change in the network topology. On the other hand, "incremental" packets contain information about changes which occurred after the last "full dump". They usually fit into one NPDU. Each route entry on the routing table is marked by a sequence number. Routes with the most recent sequence number are always used. In the event that two updates have the same sequence number, the route with lower hop distance is chosen.

The CGRS routing protocol is another proactive routing protocol but differ from DSDV in the type of addressing and network organization scheme used [34]. It uses hierarchical network topology instead of a flat one. In the CGRS, nodes are grouped into clusters with each cluster having a cluster head (CH) which controls the nodes in the cluster. A distributed algorithm is used to elect the CH within the cluster. The dynamic nature of the topology can lead to frequent CH changes which can adversely affect routing protocol performance. A clustering algorithm called Least Cluster Change (LCC) is employed to mitigate this problem. Every node within a cluster is within one hop of its CH and DSDV is the underlying protocol used within the cluster. Other nodes defined by CGRS are "cluster members" and "gateway nodes". Gateway nodes are nodes that are in the communication range of two CHs. When a node wants to send a packet to another node, not in its cluster, it sends the packet to its CH and the packet is routed through a gateway node to another CH and so on until the packet gets to the CH of the destination node. Figure 2.1 illustrates routing in the CGRS. Each node maintains two tables; cluster member table and routing table. The cluster member table contains destination CH for each node in the network and is propagated periodically. Routing table is used to determine the next hop to reach a destination.

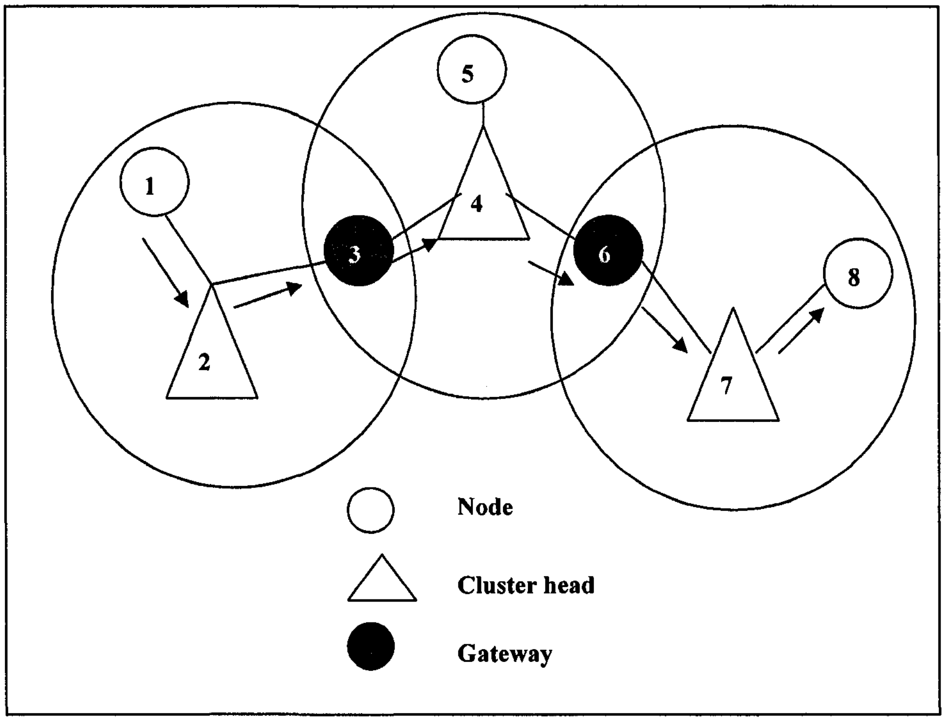

Fig 2.1: CGSR: routing from node 1 to 8

2.5 Reactive routing protocols

Reactive routing protocols are also known as source-initiated on demand routing. Unlike the proactive routing protocol they do not maintain the network topology information. Routes are generated on-demand. If a source has a packet to be delivered to a particular destination, it checks its routing table if it has a current route to the destination, if not, it initiates a route discovery process, which ends when a route to the destination is found. Since frequent route breaks do occur in dynamic topology, reactive protocol performs route maintenance procedure to maintain the routes. Some reactive routing protocols are Ad Hoc On-demand Distance Vector routing (AODV) [4] and Dynamic Source Routing (DSR) [7]. DSR is an on-demand protocol designed to reduce the bandwidth taken by control packets in MANET [39]. It differs from other proactive protocols by not requiring a periodical beacon transmission in its operations. DSR like most reactive protocols have two major phases: route discovery and route maintenance. When a mobile node has a packet to send, it checks its route cache to see if it has a route to the destination. If it has, it uses that route else it initiates a route discovery by broadcasting a route request packet. This route request packet contains (1) the address of the destination (2) source node address and (3) a unique identification number. Each node in the network receiving this route request packet checks whether it has a route to the destination. If it does not, it appends its address to the packet and forwards it. This is illustrated in Figure 2.2 until the route request packet reaches the destination or an intermediate node having a route to the destination. To limit the amount of packet flooded in the network a node only forwards the route request packet if it has not received the packet initially or if its address is not in the packet already. When the destination node receive the route request packet, it generates a route reply packet back to the source node by either using the reverse route from the route request packet or if symmetric links are not allowed, it initiates a route request back to the source by piggybacking the response on it. If an intermediate node with a current route to the destination receives the route request packet, it appends the route in its cache to the ones already in the route request packet and generates a route reply.

Route maintenance is accomplished in DSR with route error packet and acknowledgments. When a link to a destination is broken, the node close to that point generates a route error packet which is sent to all nodes in the network. When a node receives a route error packet, the erroneous route is removed from the node's route cache. Acknowledgment such as that from the MAC layer can be used to verify the correct operation of a link.

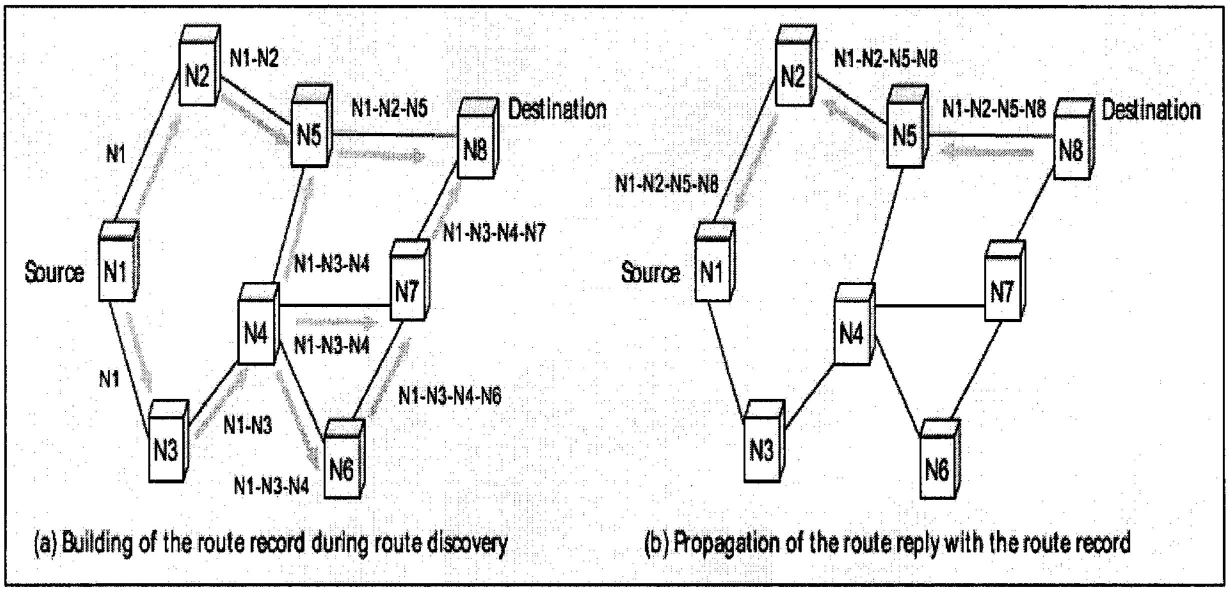

Figure 2.2: Route discovery in DSR

2.6 Ad Hoc On-Demand Distance Vector (AODV) Routing Protocol

Ad hoc on-demand distance vector is another reactive protocol which is based on DSDV. AODV is an improvement over DSDV because it minimizes broadcast and transmission latency. The authors classified the AODV as a pure on-demand route acquisition system because nodes that do not lie on active path do not maintain routing information or participate in periodic routing table exchanges [4]. It differs from DSR in that it dynamically establishes routing table entries at intermediate nodes as opposed to the source routing used in the DSR. Another difference is that the AODV uses only symmetric links. The protocol proposed in this thesis is based on AODV. This is the reason why the AODV is investigated and analyzed in detail in this section. The author in [4] stated the primary objective of the protocol to be the following;

- To broadcast discovery packets only when necessary,
- To distinguish between local connectivity management neighborhood detection and general topology maintenance,
- To disseminate information about changes in local connectivity such as hello messages, to those neighboring mobile nodes that are likely to need the information.

AODV uses two major mechanisms in its operations (1) route discovery (2) route maintenance. Route discovery allows a source to discover route to a destination. Route maintenance allows source to discover broken links and to recover from it.

2.6.1 Route Discovery

Route discovery mechanism is used to find a route to a destination. A source node having a packet to send to a destination node and not having a route to that destination in its route cache initiates a route discovery process. This is done by broadcasting a route request (RREQ) packet to its neighbors which then forward the request to their neighbors as shown in Figure 2.3, by increasing the hop count field of the packet. The process continues until the request reaches to the destination or to an intermediate node with a current route to the destination.

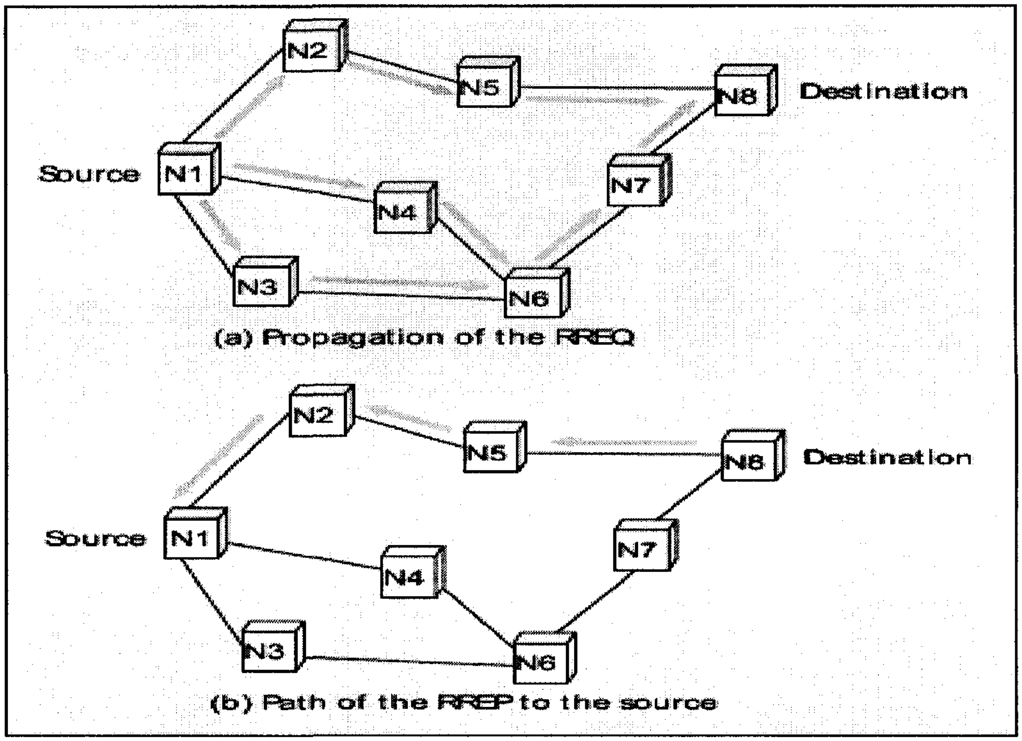

Figure 2.3: AODV route discovery

The RREQ packet contains the following fields; source address, source sequence number, broadcast ID, destination address and hop count. The RREQ is uniquely identified by the sequence number and broadcast ID. Each node maintains its own sequence number and broadcast ID. The sequence number is utilized by AODV to ensure that there are no routing loops. The broadcast ID is incremented each time a node initiate a route request process. As the RREQ is forwarded in the network, intermediate nodes record the neighbor through which the packet is received. This process is used to form a reversed path as shown in Figure 2.4. If a node receives additional copies of the same RREQ, these packets are discarded. As soon as the RREQ reaches the destination or an intermediate node with a fresh route to the destination, the destination/intermediate node unicasts a route reply (RREP) packet back to the source along the reverse path already formed. As the RREP is routed along the reverse path, nodes also form forward path just the same way the reverse path were formed. Figure 2.5 shows the formation of forward paths. An intermediate node receiving a RREP packet propagates it towards the source. If the node receive further RREP packet towards the same source, it updates its routing information, and only propagates the RREP only if the sequence number is greater than the previous RREP or if the RREP and the previous RREP have the same sequence number with a smaller hop count.

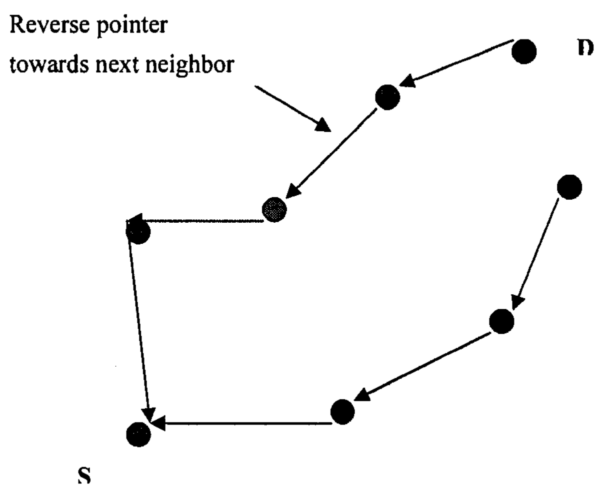

Figure 2.4: Reverse path formation

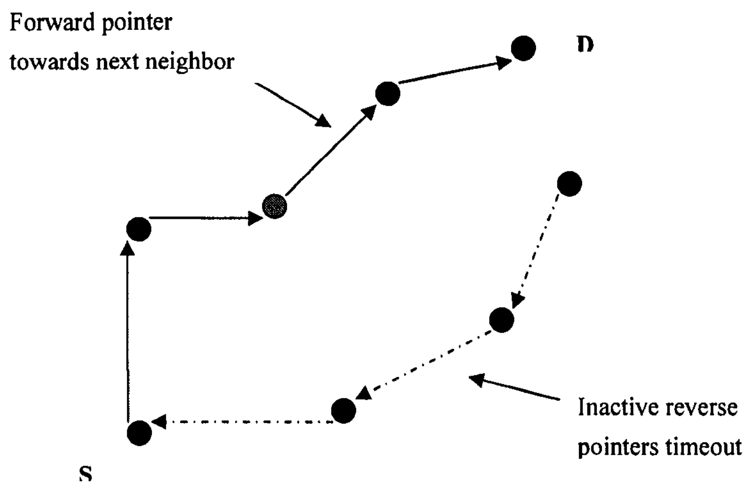

Figure 2.5: Forward path formation

2.6.2 Route Maintenance

Route maintenance is a mechanism used in the network topology changes such as link breakages. The acknowledgment packet sent by the underlying MAC protocol such as IEEE 802.11 Wireless LAN can be used to detect link failures when nodes move. If a source node moves, it's able to re-initiate a route discovery mechanism to find a new path to the destination. When an intermediate node moves, its upstream neighbors inform the end node about the breakage by propagating an unsolicited route reply packet with hop count set to infinity. This unsolicited route reply is also called route error (RERR) packet. The upstream neighbors also subsequently relay the message to their own neighbors. This relaying continues until all active nodes are notified. The source node can then re-initiate a new route discovery if it still needs to send packets to the destination node.

2.7 Flooding problems in AODV

The AODV, like any other on-demand routing protocol, finds route to a destination only when needed. This route finding entails a global search of the network by broadcasting route request packet to neighbors. If the neighbors themselves are not the destination or do not have a valid route to the destination in their route cache, they in turn rebroadcast the route request to their neighbors. This rebroadcast goes on until route request packet gets to the destination or an intermediate node with a valid route. This re-broadcasting of route request leads to "flooding" or "storming" of overhead packets in the network. Some measures, such as limiting the rate of route discovery and imposing shorter hop count in finding route (route search are restricted to a ring), have been proposed to reduce flooding in AODV. Even with these measures, flooding problem still persist in AODV and is still a major issue. The effects of flooding are contention, collision and redundant broadcast.

- Contention: when nodes within the same coverage area receive a packet, they all try to re-broadcast at the same time. This ultimately leads to contention for the medium among the nodes. More the number of nodes are, more the severity of the contention is.
- Collision: if several nodes try to broadcast packets at the same time, there is a high probability that the packets will collide.
- Redundant broadcast: nodes in the neighborhood of each other will receive duplicated copy of a packet that have once been sent by a node in that neighborhood when the packet is rebroadcasted by another node in the neighborhood.

2.7.1 Analysis of Contention

To really understand contention problem, consider a scenario when a host A having n host as neighbors, transmit a broadcast message. If all the neighbors try to rebroadcast the message, contention will occur between two or more neighbor nodes around A.

Researchers in [23] showed that contention will increase as the number of nodes around A increases. It was also shown in [23] that for just two nodes around A, the probability of having contention in the medium is 59%.

2.7.2 Analysis of Collision

The IEEE 802.11 MAC layer has been used to minimize collision in MANET because of its medium access control mechanism called carrier sensed multiple access with collision avoidance (CSMA/CA). The CSMA/CA requires a node to start a back-off procedure when it senses that another node is transmitting a message, or when the medium is busy and the previous back-off has expired. This back-off procedure limits the amount of collision in MANET. But there are situations such as when the medium have been idle for a long period and all the nodes have completed their back-off procedures. In such situations, if two or more nodes have packet to broadcast, they'll all try to transmit at the same time thereby causing collision.

In [22], the collision probability for IEEE 802.11 MAC layer is given by

$$\gamma = 1 - e^{-(n-1)\beta} \quad , \qquad (2.1)$$

where n is the number of neighbors in a given area, and β is the parameter of the exponential back-off period. It can be concluded from (2.1) that as the number of nodes in a given region increases, the probability of collision increases.

2.7.3 Analysis of Redundant Broadcast

Redundant broadcast in MANET is illustrated in Figure 2.6, where node A is the source node while node D is the destination node. Node A initiates a route discovery process by sending a route request packet. Other nodes in the network also rebroadcast that request. Therefore, there are six transmissions before node D gets the request if no attempt is made to reduce redundancy.

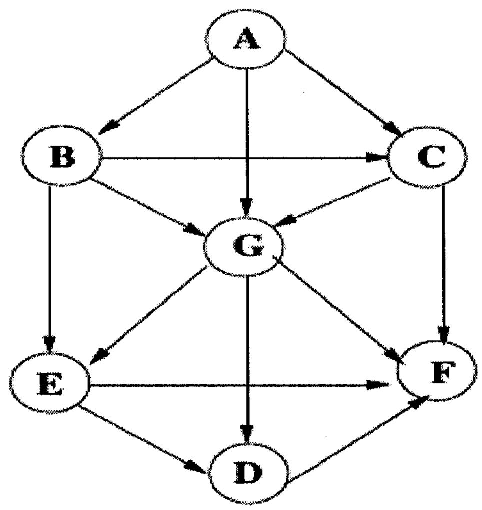

Figure 2.6: Redundant broadcast scenario 1

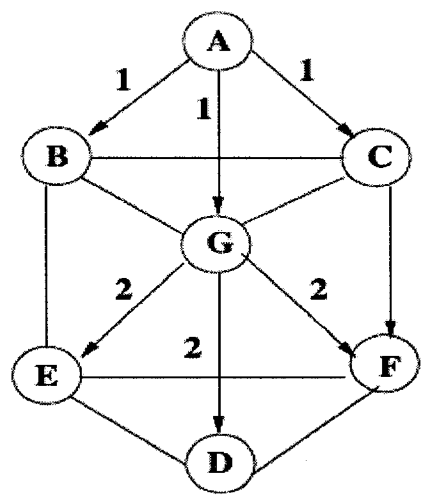

Figure 2.7: Redundant broadcast scenario 2

On the other hand if some of the nodes are selected to participate in forwarding of the route request, the number of route request packets will be reduced. For example, if node G is selected to be the only node to forward route request and node B, C, E and F are restricted from forwarding. The number of transmissions required to get the request to node D is just two. This gives a reduction of four transmissions from six. The new scenario is illustrated in Figure 2.7. It can be seen that only one route to the destination is obtained by reducing the number of transmissions. There is generally a trade off between the number of route discovered and the overhead in the network.

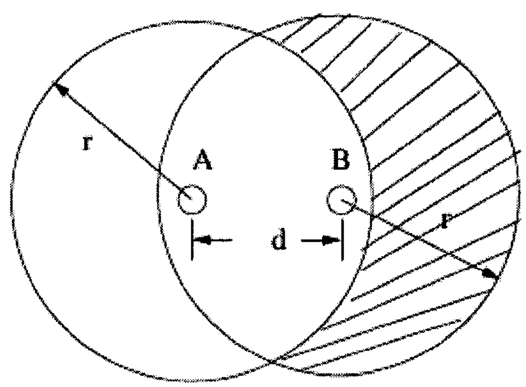

Figure 2.8: Additional area covered by a rebroadcast

To further illustrate the problem of redundant broadcast. We look at the additional area covered by a new broadcast. The additional area covered by a new broadcast depends on the location of the nodes. Consider the scenario in Figure 2.8, node A sends a broadcast massage and node B decides to rebroadcast the message. Let r be the radius of the transmission range of A and B, and d is the distance between them. The additional area covered by B's rebroadcast is formulated in [23] as

$$INC(d) = 4\int_{d/2}^{r}\sqrt{r^2 - x^2}\,dx \qquad (2.2)$$

The coverage area is the largest when d = r, and is given by $\pi r^2 - INC(r) = 0.61\pi r^2$. This shows that a rebroadcast can provide 61% additional coverage over that already covered by the previous transmission. It is also shown in [23] that on average, a rebroadcast covers only additional 41% area. The additional area covered by a rebroadcast depends on the distance between the nodes.

Flooding problem is generally not prevalent in small networks because there are always a small number of nodes present in any given area. Therefore the performance of a small network is unaffected by flooding. But as the network gets larger, flooding problem becomes more prevalent and performance is greatly affected because of collisions, contentions and redundant broadcast. The aim of this thesis is to mitigate the effect of flooding in MANET by introducing an algorithm that reduces the number of nodes that can participate in the route request process. Detailed description of this algorithm is given in Chapter 3 of this thesis. Simulation and performance analysis of this algorithm where carried out using a powerful simulator called NS-2. The NS-2 simulator is described in the next section.

2.8 Network simulator

The network simulator (NS-2) is a discrete event simulator used mainly in the networking research. It was developed by the University of California, Berkeley. It initially started in 1989 as a variant of the REAL network simulator at Cornell University, Ithica, New York [35]. The development of NS-2 throughout the years have been supported by the Defense Advance Research Project Agency (DARPA) through the Virtual Inter-network Testbed (VINT) project at Lawrence Berkeley Laboratory (LBL), Xerox Palo Altto Research

Center (PARC), University of California at Berkeley (UCB), Information Science Institute (ISI) of the University of Southern California (USC) and Collaborative Simulation for Education and Research (CONSER) by The National Science Foundation (NSF). There are many other contributions to NS-2 from other researchers especially the wireless code which was contributed by researchers working at UCB at Daedelus and Carnegie Mellon University (CMU) Monarch projects and Sun Microsystems. NS-2 can simulate Transport Control Protocol (TCP) and Unigram Data 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), Ad hoc On-demand Distance Vector (AODV), Destination Sequence Distance Vector (DSDV) and MAC protocol like IEEE 802.11. NS-2 is an open source simulator and it is evolving continuously through research and development.

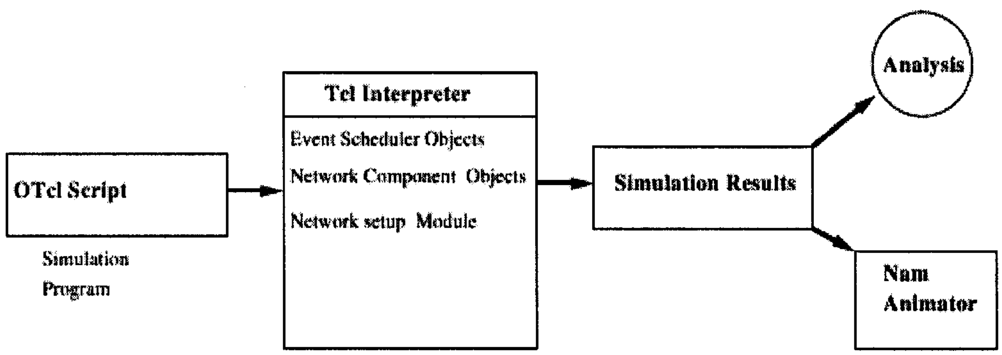

Figure 2.9: NS-2 model

Currently, NS-2 is based on two languages; an object oriented simulator written in C++ and Object Tool Command Language (Otcl): Tcl script language with Object oriented extensions developed at Massachusetts Institute of Technology (MIT). It has a rich set of library for network and protocol objects. NS-2 consists of two class hierarchies: the complied hierarchy written in C++ and the interpreted one written in Otcl. Figure 2.9

shows a simplified model for NS-2. It has an Object oriented Tcl (OTcl) script which consists of a simulation event scheduler and network component object libraries, and network setup libraries. Users of NS-2 program in OTcl script language setup and run a simulation network. The packet generated by the NS-2 has unique identification and the record of each packet is stored in the trace file. Trace file stores all the events related to a packet such as when it was generated, its size, what was the source node of that packet and when it reached the destination. Network Animator (NAM) can show graphically the network activities in terms of packet drop, mobile node movement, and other network parameters.

2.9 Wireless Network Model

The wireless network extension to NS-2 was implemented by the Monarch project of Carnegie Mellon University. New elements were added to NS-2 at the physical, MAC and routing layers. These elements make it possible to construct detailed and accurate simulations of wireless subnets, LANs, and multi-hop ad hoc networks [36]. The logical view of node connections using the CMU Monarch extensions to NS-2 is shown in Figure 2.10.

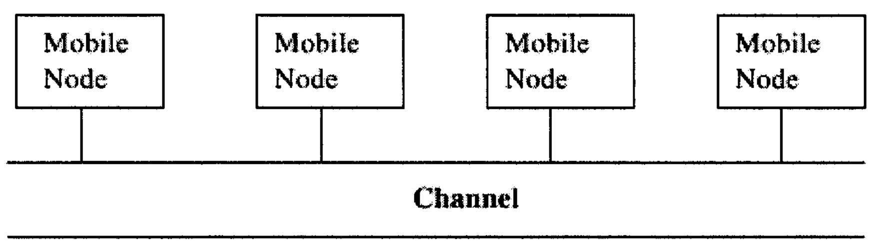

Figure 2.10: Logical view of mobile node connection

Each mobile node acts as an independent entity which might have one or more network interfaces attached to a channel. The channel acts as the link that carries packet between mobile nodes. Every packet transmitted to the channel has a copy distributed to all the network interfaces on the channel. Each interface then uses a radio propagation model to determine if it can receive the packet. Mobile nodes are responsible for computing their position and velocity as a function of time.

The mobile node architecture of NS is shown in Figure 2.11. Each arriving packet from the channel is stamped by the network interface with the receiving properties and then invokes the propagation model. Based on the propagation model and the receiving properties the network interface determines if the node can receive the packet or not. If it can receive the packet, the packet is handed to the MAC layer where it determines if the packet has an error or arrives collision free. If it has no error and arrives collision free, the MAC layer hands the packet to the mobile's node entry point. At this point if the node is the final destination of the packet, the address demux will hand the packet to the port demux, and then to the proper sink agent. If the node is not the packet's final destination, it will be handed to the default target of the address demux, and the routing agent will assign the packet a next hop address and pass the packet back to the link layer. If the next hop address is an IP address, the Link Layer (LL) object queries the ARP object to translate the IP address to a hardware address. On getting the hardware address, the packet is inserted into the interface queue (IFq). The MAC layer takes packets from the head of the interface queue and sends them to the networking interface (NetIF) at the right time.

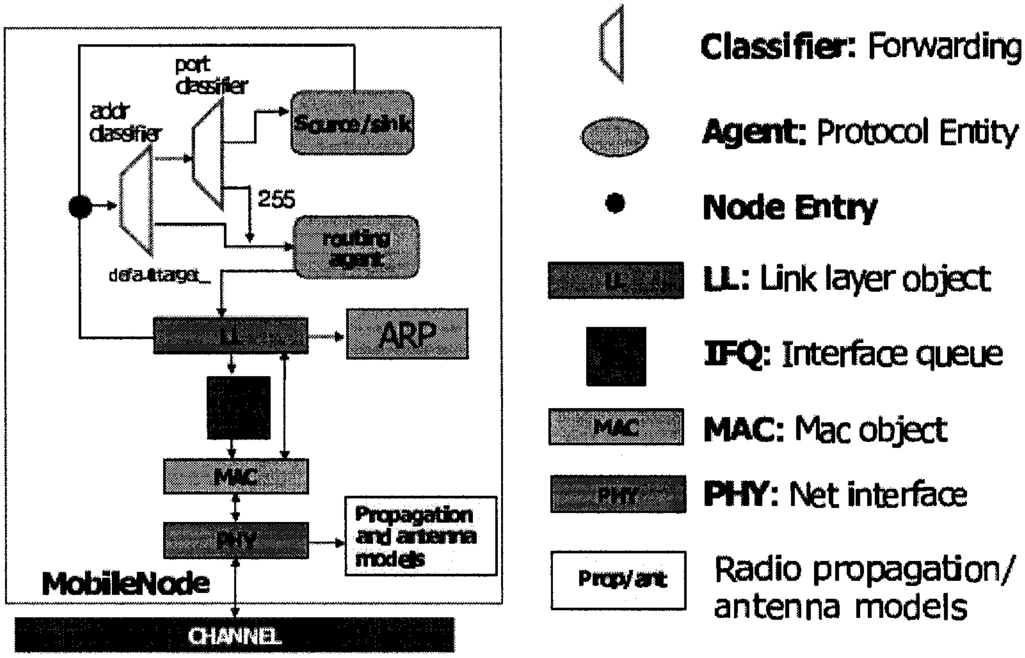

Figure 2.11: Portrait of mobile node

2.10 Cross Layer Design for MANET

Recently, there has been an increase in the design of routing protocols for MANET which are based on cross-layer design. MANET needs to meet different type of Quality of Service (QoS) for the different applications. Some of the applications of MANET are sensor networks, personal networks, home networks. These applications are different from one another and thus require unique service level requirements. A sensor network consist of various sensor nodes which work together to gather specific information such as temperature, pressure, humidity. The sensors used in this network usually have limited power and processing capabilities. Thus reliability of data is crucial in sensor networks. Personal networks consist of cell phone, laptop, and personal digital assistance (PDA). The mode of connection of these devices is usually peer-to-peer. Such networks do need to support different requirements such as reliability, data rate, and delay. Home networks are made of house hold appliances, entertainment centers, home phones, computers, security devices. Rate of connectivity between devices in home networks are diverse; they connect with each other using different rates.

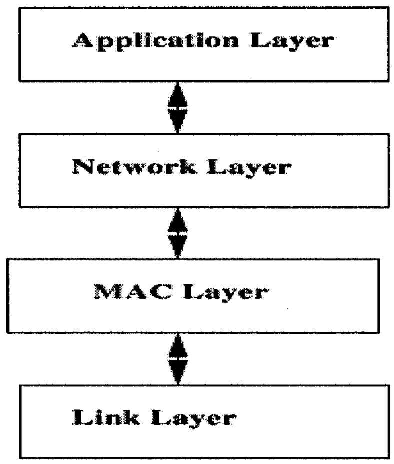

Figure 2.12: OSI model for protocol stack

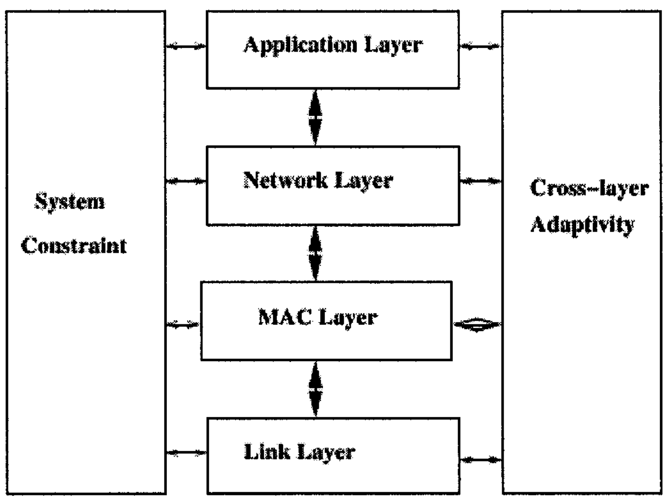

Figure 2.13: Cross-layer architecture

Future applications will also need diversified requirements. Researchers have also argue that the fixed layered architecture shown in Figure 2.12, which has worked well for wired networks, is not suitable for wireless networks.

In fixed protocol stack, the overall networking tasks are divided into layers which act independently to provide services. These layers cannot communicate directly with nonadjacent layers and only communicate with adjacent layers through defined procedure calls and responses. This type of system prevents a layer from adapting its performance in response to performance from other layers. Researchers have stated that the best way to meet the performance requirement of the various applications of MANET is to allow for interactions among layers because changes in some layers might affect performance in other layers. A cross-layer architecture shown in Figure 2.13 was proposed in [38]. The figure indicates that information needs to be exchange by all layers of the protocol stack so that protocols in each layer will be able to adapt universally to network conditions and application requirements. There are also some system level constraints which need to be met by joint optimization by the layers.

Numerous literatures have been published on cross-layer design. A survey and summary of those publications can be found in [37]. Challenges and new modalities for design protocols were pointed out in the publication. Some cross-layer designs such as those presented in [2, 29, 32], and [37] are related to this thesis and will be briefly explained.

A cross-layer design called Hierarchical Dynamic Source Routing (DSR) is presented in [2]. This protocol's objective was to reduce the effect of flooding in MANET by using a novel node selection algorithm called FN selection algorithm and further improve the selection algorithm by combining with a cross-layer design. The FN selection algorithm classifies nodes as either mobile nodes (MN) or forwarding nodes (FN). The cross-layer design works by using congestion information (contention window) obtained from the MAC layer in node selection. This MAC layer information helps in selecting nodes in less congested areas of the network. Results obtained show a significant improvement over DSR protocol in terms of overhead reduction, delays and throughput.

Cross-Layer Ad hoc On-demand Distance Vector (CLAODV) was proposed in [37].This protocol which is based on Ad hoc On-demand Distance Vector (AODV), make use of information interaction between MAC sub-layer and routing sub-layer to reduce the size of the HELLO message in the network and thereby reducing overhead. Each node saves its current sequence number in the header field of the data frame in the MAC layer. When the MAC layer of a node receive a data frame from a neighbor it passes the new sequence number to its routing layer where it is saved in its routing table together with MAC address of the neighbor. This form of exchange of sequence number information between neighbors helps to reduce the frequency of sending HELLO messages. Also the size of the HELLO messages are reduce because the sequence numbers are saved in the headers of the data frames instead of the body.

In [29] the authors stated that nodes can measure the degree of congestion around themselves by monitoring the instantaneous transmission queue length and the average MAC layer utilization at the node. The average MAC layer utilization is defined as the fraction of time that node either (1) has one or more packets to transmit in its network interface queue, or (2) has attempted to transmit a packet but failed. Since the instantaneous utilization at a node is either "0" or "1", these values were average over a period of 10 seconds. The authors in [29] suggested that the congestion level measurement can be used by routing protocols in various ways such as: (1) not attempting local route repairs in congested areas in protocols such as AODV, (2) reduction of periodic advertisement when the medium is busy and (3) chosen route in less congested areas during route discovery. Simulation results presented in [29] showed an improvement in packet delivery and overhead reduction when routes are selected in less congested areas. The congestion level measurement can be used in other layers such as the transport layer where the information can be used to set the Explicit Congestion Notification (ECN) bit in a packet IP header. It can also be used in the presentation layer to compress data before transmission if the medium around the node is very busy.

Congestion-adaptive Routing Protocol (CRP) was proposed in [32]. The authors argue that most existing routing protocols such as AODV are congestion-unadaptive protocols. The congestion unawareness in these protocols causes long delay, high overhead and high packet losses. In reactive protocols, such as AODV, there is a delay between the time congestion is detected and the time it takes to search for a new route. A lot of overhead is generated in discovering a new route to a destination. Also before congestion is detected, a lot of packets could have been lost already. The CRP has been proposed to mitigate the above mentioned problems by avoiding congested route. In the CRP, each node gets congestion information from its next node along a route to a destination. Depending on the severity of the congestion, a node uses a "bypass" route to avoid the potentially congested area. The authors suggested various parameters for monitoring congestion by a node such as average packet delay, number of packets discarded due to a filled buffer, average queue length, number of packets timed out and standard deviation of packet delay. The authors made use of the ratio between the numbers of packets waiting for transmission in the buffer to the buffer size. This ratio is used to classify a node as "green" (i.e., far from congested), "red" (i.e., congested), or "yellow" (i.e., getting congested). When the next node on a route becomes "yellow" or "red", the previous node looks for a bypass route to avoid the congested area. Simulation results showed that the CRP performed better than AODV and DSR in terms of packet delivery and end-to-end delay.

The various cross-layer design approaches presented here show that cross-layer design can improve the performance of a network. This is a great advantage for MANET. But cross-layer design also comes with some adverse effects. These adverse effects have been investigated by [43]. Some of them are:

- It can lead to disorderly design which will make further innovation difficult.
- Proliferation might be hampered because updates might require a total redesign.

2.11 Conclusions

In this chapter, MANET was introduced. The unique characteristic of MANET that makes it different from wired network, the importance of an efficient routing protocol in MANET and also the features of such routing protocols were discussed. Proactive and reactive routing protocols were explained. "Flooding" problem in reactive routing protocols was explained and the effect of "flooding" was analyzed. Cross-layer design was introduced in this chapter. The importance of cross-layer design in helping to meet the performance requirement of MANET was shown and its advantages and disadvantages were stated.

Chapter 3

Ad Hoc On-Demand Distance Vector Routing Protocol with Cross-Layer Design (AODV-CL)

3.1 Introduction

Finding routes in less congested areas of the network and reducing flooding in MANET leads to reduction in the amount of overhead packet generated in the network and hence improves bandwidth utilization and scalability. A lot of protocols have been proposed to reduce the amount of overheads generated in MANET. These protocols are classified as (i) location based schemes such as [3, 8, 9, 10] and [23], (ii) probability schemes such as [12, 13] and [23] and (iii) clustering schemes such as [1] and [27].

In [3] a location based scheme using Mobile Backbone Network (MBN) was proposed. Three types of nodes exist in this type of network, that are backbone nodes (BN), backbone capable nodes (BCN) and regular nodes (RN). It is assumed that each node is equipped with a Global Positioning System (GPS). The RN acquires the location of other RNs through the BNs. Thereby eliminating the need for a central location server and reducing the overhead incurred in updating the location server. The RN performs route discovery by propagating route request message toward the location of the destination using the AODV protocol. This limits the search area thereby reducing overhead. This scheme does not find route to destination using least number of hops rather determines a route to destination with the lowest delay. Providing GPS for every node adds extra cost. The greedy perimeter stateless routing (GPSR) proposed in [8] broadcasts route request packet to the closest node to the destination node. The location of each node is assumed to be known by other nodes through a location server. Updating and retrieving location from the server adds extra overhead. The Location-aided routing protocol proposed in [9] reduces overhead in MANET by forwarding route request towards destination and not the entire network. It assumes the availability of GPS and finding the location of nodes is quite challenging.

A probability scheme was proposed in [23] where each node broadcasts a packet with probability *P*, which is lesser than 1. Route request packets are also forwarded with this probability during route discovery. A gossip-based scheme was proposed in [12] where nodes propagate routing messages with some probability. It was stated that gossip exhibit bimodal behavior whereby the gossip dies out before all nodes in the network hear the gossip. Some improvements were made to the plain gossip scheme such as letting the first *K* nodes propagate the message with a probability of 1 and the other nodes with a probability *P* less than 1. It was shown that the gossip reduces overhead by 35%. The effect of phase transition phenomenon in MANET was investigated in [13] to determine the optimal probability threshold, *P*, for probability schemes. The major problem of probabilistic schemes is the determination of the optimal probability value *P* at which a node will rebroadcast a route request. *P* is determined from a number of parameters, one of which is the density of the network.

Clusterhead gateway switch routing (CGSR) protocol was presented in [27] where nodes are grouped into clusters with each cluster having a cluster head. A cluster head controls the regular nodes in the cluster, called member nodes. Communication between two clusters is through other nodes, called gateway nodes. Routing performance is achieved by routing packets through the cluster heads and the gateways nodes instead of broadcasting throughout the network. The routing performance achieved also leads to a drawback because some overhead are generated when electing new cluster head. The least cluster-head change (LCC) algorithm has been introduced to reduce this drawback. A hierarchical protocol called heterogeneous routing protocol was proposed in [1]. It uses clustering by classifying nodes as backbone and ordinary nodes. The backbone nodes operate with a different radio frequency from the ordinary nodes and control the ordinary nodes. A proactive routing protocol is used within the clusters while an on-demand protocol is used among the backbone nodes. A routing scheme called hierarchical AODV (H-AODV) was proposed in [1] which uses the AODV algorithm within the clusters and between the backbones nodes. Acquiring additional radio frequency adds additional cost.

Apart from the three categories of reducing overhead packets stated above, there are other schemes for reducing overhead in MANET. A dynamic route catching scheme for AODV protocol was proposed in [15] which works by increasing the active route timeout (ART) of each nodes. This increase in ART reduces the number of route discoveries carried out and thereby reducing the overhead. Due to increase in the ART, the scheme could result in the storing of staled routes which might result in higher overhead. Another protocol is the hierarchical dynamic source routing (HDSR) proposed in [2]. HDSR uses passive hierarchy by classifying nodes as having two states, either mobile nodes (MN) or forwarding nodes (FN). In the MN state nodes acts as either source node or destination nodes while the FN state they act as packet forwarder. Due to the fact that only FNs forward packets, there is a considerable reduction in overhead in the network. The protocol proposed in this chapter will use the node selection algorithm of the HDSR protocol.

Cross-layer designs are continuously been investigated in order to improve the efficiency of MANET. Some of the cross-layer design approaches have been proposed in [2, 29, 32] and [37]. The protocol proposed in this thesis uses a cross-layer scheme in selecting FN. The cross-layer element that will be used in the selection decision is the medium access congestion information. Some researchers, such as [2], have also used medium access congestion information in their design.

Just like in [2] the protocol proposed in this thesis uses the congestion information to select route in less congested areas of the network. The route selection algorithm proposed in [2] and the cross-layer design has been combined with AODV protocol for a cross-layer implementation of the AODV routing protocol (AODV-CL). AODVCL has been implemented and tested using a network simulator tool called Network Simulator (NS-2).

Obtained results showed that there was a significant reduction in packet overhead and an improvement in delay over AODV.

3.2 AODV-CL Protocol

The AODV-CL protocol, like the HDSR protocol, classifies network nodes into Mobile Nodes (MNs) and Forwarding Nodes (FNs). The MNs initiate route discovery and the FNs are responsible for forwarding data packets to the destination. The destination also sends route reply packets to the source through the FNs. The MNs sends data packet to the destination through the FNs. Nodes can switch from MN to an FN and also from an FN to an MN. Objectives of the AODV-CL aims are (I) selecting FNs in such a way that there is always a route to a destination (ii) reducing the number of nodes participating in the data forwarding process and (iii) selecting FNs based on a distributed algorithm.

AODVCL consist of two main selection process; FN selection and FN de-selection.

3.2.1 FN selection algorithm

When MN receives a request packet from a source node or from another FN, it determines through an FN eligibility rule if it should become an FN or not. As stated in [2]:

"MN should wait for a random back-off period after receiving a request message from the source and it does not hear any node re-broadcasting that request message during that back-off period".

The pseudo code of the selection algorithm is shown in Figures 3.2. When a source node has a packet to send, it initiates a route discovery process and sends route request packets to its neighbors. On receiving the request packets, the neighboring nodes check if the packet has been processed initially if yes they discard the packet. If no, they check to see if there is a saved unused back-off time in the memory.

```
Received request packet
if (request already processed) then
    /* nothing to do with that request */
    return;
else
    /* check timer whether it is running */
     if (timer is running) then
          set timer to delay;
     else  {
          select random back–off time;
          start timer;
          }
      endif
endif
/* listen to ongoing traffic*/
if (hear rebroadcast of the request) then
{
   set delay to remaining time;
   flag the request;
   return;
}
else
   /* check whether timer expires */
    if (timer expires) then
      {
         switch to forwarding node;
         return ;
    }
        return;
    endif
endif
```

Figure 3.1: The pseudo code of FN selection algorithm

If there is, nodes set their timers to the unused back-off time and start counting down. If not, nodes generate a random back-off time and start their timers. During the period of counting down, each nodes listen to hear if the same request is re-broadcasted by another node. If a re-broadcast is heard before the timer expires, the node stops the timer and saves the remaining unused time which will be used during another FN selection process. If the countdown is completed and no re-broadcast is heard, then the node becomes an FN and re-broadcasts the packet and marks this request as processed. The random back-off time is expressed in [2] by

$$T_{delay}=R*K, \tag{3.1}$$

where R is a uniformly distributed random variable between [0, 1] and K is a delay multiplying factor. K is important for the stability and efficiency of the protocol. The effects of varying values of K are shown in Figure 3.5. Larger values of K give lesser overhead.

An illustration of how the FN selection algorithm works is given in Figure 3.2. Source node S and destination node D are out of radio range of each other. S initiates a route discovery process by sending route request packet to all its neighbors', labeled MN_1, MN_2, MN_3..........MN_n. Upon receiving the route request packet, each neighboring node executes the FN selection algorithm by randomly selecting a back-off time labeled T1, T2, T3,...........,T*n*, respectively. In that example the delay time of MN_3 is the smallest. So MN_3's timer expires before the other MNs' timers and therefore MN_3 turns to an FN then re-broadcasts the packet. Upon hearing the re-broadcast from MN_3, other nodes stop their timers and save the remaining backoff time to use next time when the FN selection algorithm is executed. After receiving the request, the destination node D replies back to the source through MN_3, which becomes FN_3. The source node will then start sending packet through the route S-FN_3-D. There might be some nodes not in the vicinity of MN_3

and consequently not hear the re-broadcast of MN3. These nodes too will re-broadcast the request and node D will also send a reply through them to S.

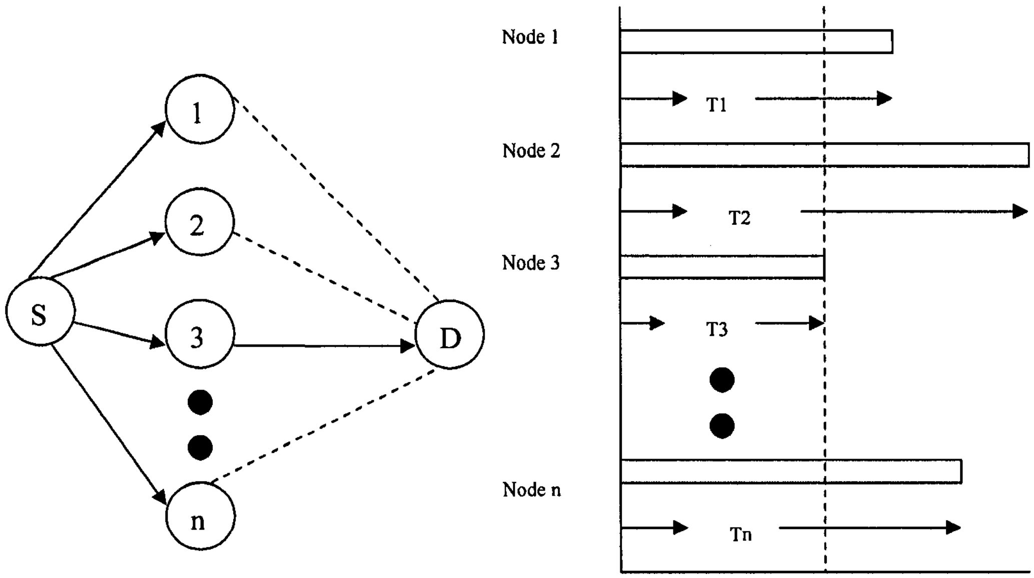

Figure 3.2: Transition from MN to FN

3.2.2 FN de-selection

The essence of FN de-selection algorithm is to make sure that there are not more than the required FNs in the network. The FN de-selection rules are stated in [2] as; "*FN should become MN if it is the source or destination or it discovers that its role as an FN is redundant.*" A node needs to operate its network interface in promiscuous mode in order to hear and detect if it is no longer needed as an FN.

To illustrate a typical scenario of FN de-selection process, let's take the scenario depicted in Figure 3.3. There are two source nodes labeled S1 and S2 and two destination nodes labeled D1 and D2. Let's assume there is an ongoing communication along S1-FN1-D1. When source S2 initiate a route discovery process to destination D2, it finds two routes: S2-FN1-FN4-D2 and S2-FN3-D2. Since route S2-FN3-D2 is the shortest, this route will be used. When FN4 overhears D2 receiving packets from FN3, it switches back to MN. FN1 does not switch back to MN because it is used by another source node S1.

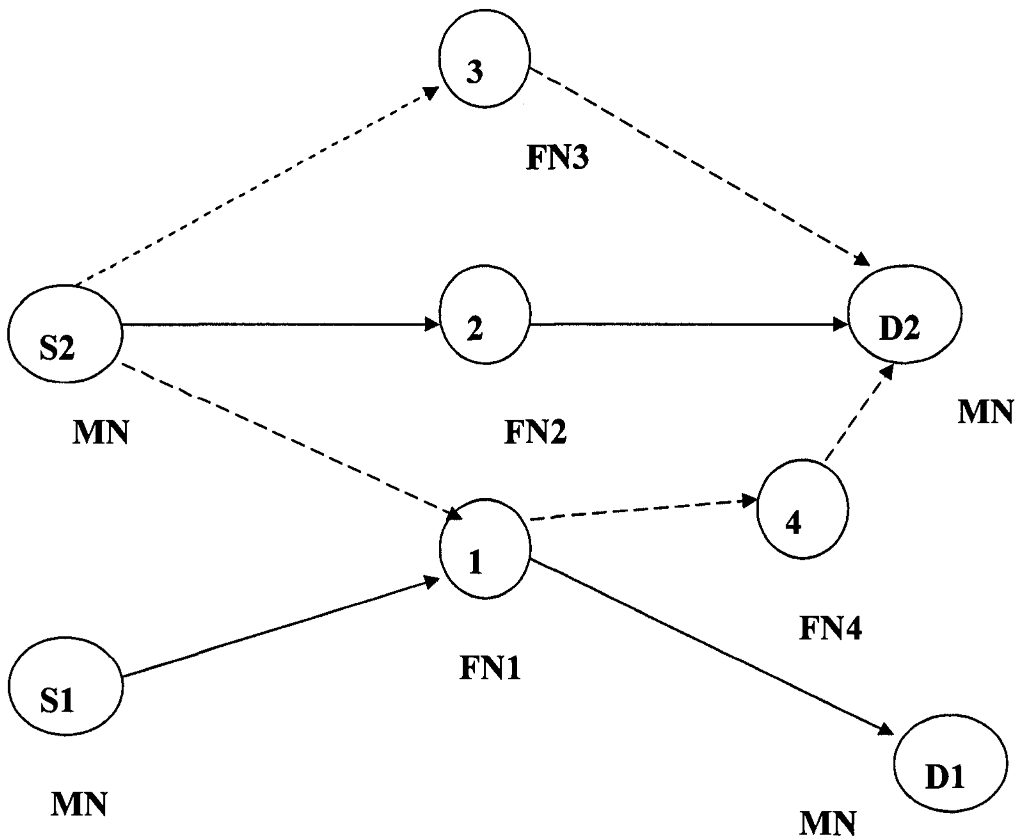

Figure 3.3: Transition from FN to MN

3.3 Overhead and delay analysis

The FN selection algorithm was tested in a random network where 50 nodes were distributed over an area of 500 x 800 m^2. In the following simulations, the network size was increased by keeping the node densities constant. That is, 100 nodes occupied an area of

1000 x 800 m^2, 150 nodes occupied an area of 1500 x 800 m^2 and so on. Twenty pairs of connections were set up in the simulation. Figure 3.4 shows the reduction in overhead for varying values of *K*. This figure shows that overhead increases as the number of nodes increases in the network. But the number of overhead is always lower in the FN selection algorithm than in the AODV. Also it can be seen from the figure that the value of *K* determines the amount of overhead generated in the network. The higher the value of *K* is, lower the overhead generated. Increasing the value of *K* also increases the delay in finding routes because the nodes wait longer before re-broadcasting. For the future experiments carried out in this thesis *K* was set to 10. This value was arrived at after experimenting with other values of *K* and found to be the best in terms of overhead performance. Like the above simulation, the parameter for the other simulation results reported in this thesis except stated otherwise were carried out with the network nodes static and nodes are uniformly distributed on a flat area. Nodes densities were kept constant as the number of nodes increased in the network. Traffic sources are constant bit rate (CBR) with packet size of 512 bytes and data rate of 1.5 packets per second. There are 20 pairs of connections in each simulation with source-destination pairs placed randomly over the network. The simulations were done using NS-2 simulator. The radio model used was the Lucent's WaveLAN radio whose nominal bit rate was 2 megabit per second (mbps) and radio range of 250 m. For statistical reliability of the results, each scenario was simulated 10 times with different random topology. Each simulation lasted 200 seconds. Reported results in this thesis are average of 10 simulation runs.

Figure 3.5 shows the overhead comparison between AODV and modified AODV with FN selection algorithm. The figure reveals that there is a significant overhead reduction with the FN selection algorithm. For example the number of overhead per packet at 50, 100, 150 and 200 nodes for AODV are 0.14, 0.36, 0.4 and 0.7, respectively while that of the AODV with FN selection algorithm for the same scenarios are 0.04, 0.12, 0.16 and 0.26, respectively.

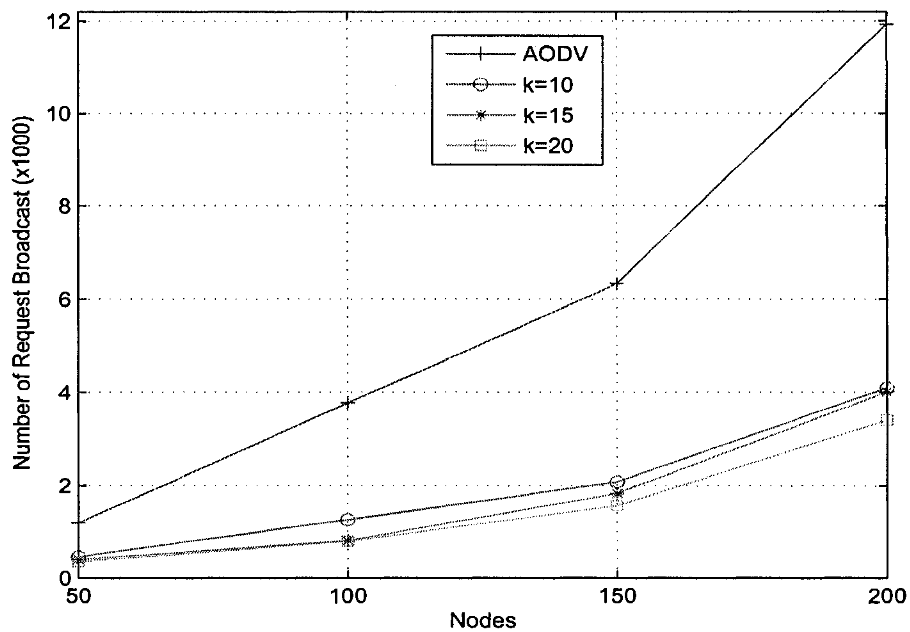

Figure 3.4: Broadcast reduction with varying values of k

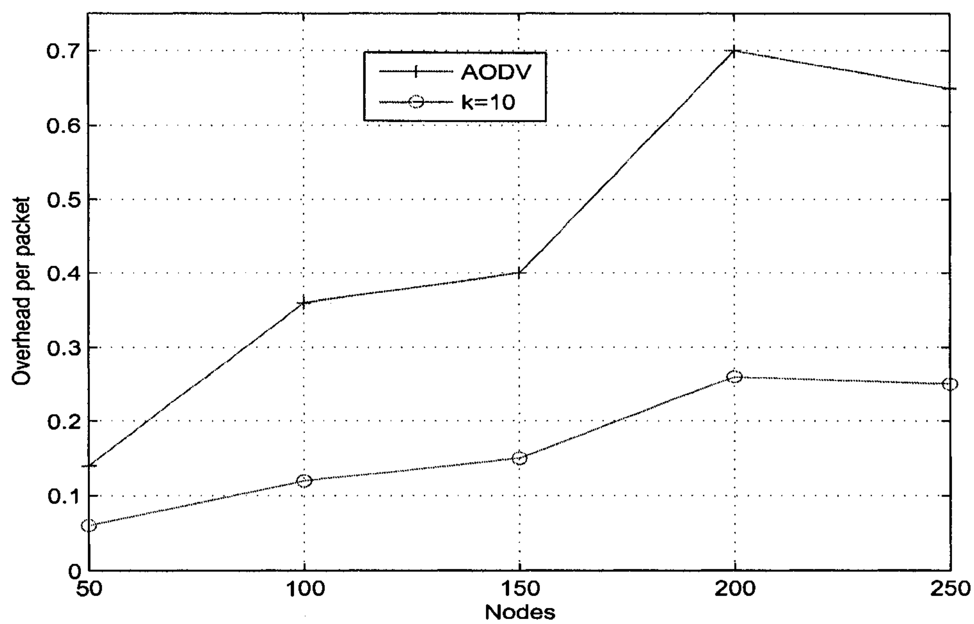

Figure 3.5: Broadcast reduction with 20 connections

These amount to 71.4%, 66.7%, 62.5% and 62.8% reduction in overhead per packet respectively. The average delays per packet performances of AODV and AODV with FN selection algorithm are compared in Figure 3.6. The average delay per packet is 0.059 second, 0.056 second and 0.066 second for 100, 150 and 200 nodes scenarios respectively in AODV. In AODV with FN Selection algorithm, these are 0.037 second, 0.049 second and 0.067 second respectively for the same scenario. It can be seen from the figure that in large network such as at 250 nodes the delay performance of AODV is slightly better than the AODV with FN selection algorithm. This is due to the fact that the algorithm introduces some delay during the route selection process. At networks with 100 nodes and 150 nodes, there is a delay improvement of 37.2% and 12.5% respectively. It can be shown from the results simulated so far that FN selection algorithm in AODV reduces overhead and improves delay. In order to improve upon these performances it is necessary to chose nodes that are located in less congested areas of the network and also to make use of nodes with low delay access to the medium. MAC layer congestion information was used in determining the level of congestion around a node and the value of the MAC layer random backoff timer was used in selecting nodes with less delay access to the medium.

3.4 Cross-layer design in FN selection

Recently, cross-layer design in MANET has been gaining popularity. The congestion status of nodes is one of the parameters that can be used in cross-layer designs. Various ways of measuring the congestion status of nodes have been suggested by different literature. The authors in [29] used the average MAC layer utilization at each node and the instantaneous transmission queue length to measure the level of congestion at a node. In [32] the authors suggested various ways for measuring congestion at a node. These are: average packet delay, number of discarded packets due to a filled buffer, average queue length, number of packet timed out and standard deviation of packet delay.

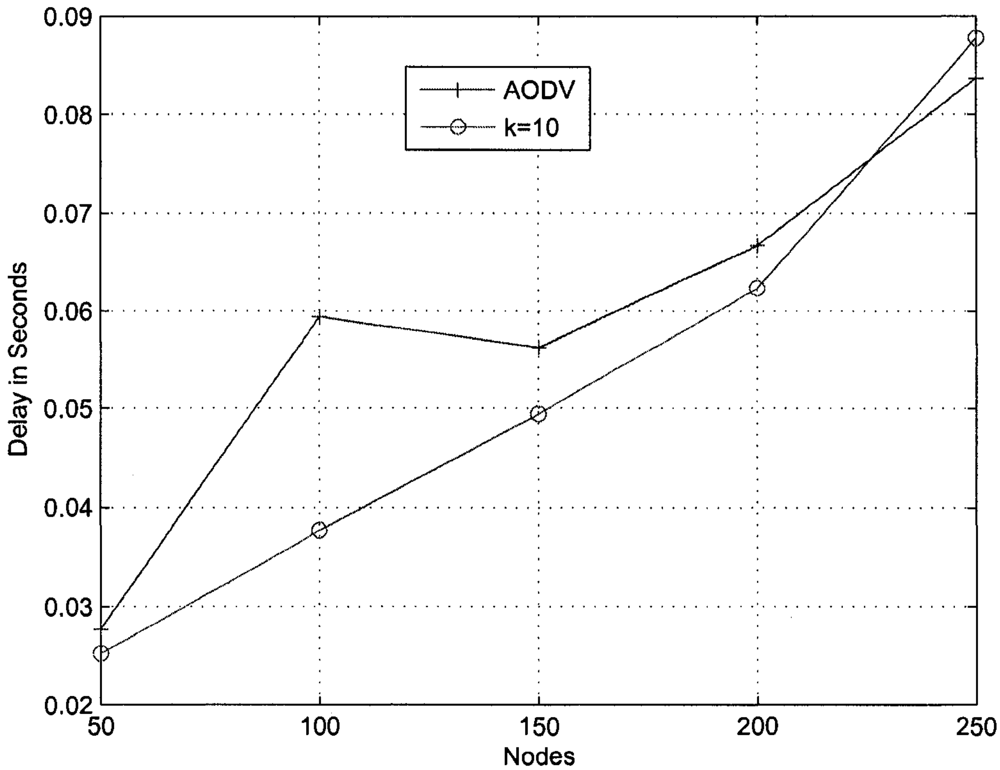

Figure 3.6: Delay reduction in FN selection algorithm

The cross-layer design proposed for improving the FN selection algorithm called AODV with cross-layer design (AODV-CL) uses the MAC layer congestion window information as an indication of the level of congestion around a node. The MAC layer protocol used in this thesis is the IEEE 802.11 protocol.

The IEEE 802.11 is the *defacto* standard for wireless local area networks (WLAN). It operates in two modes: distributed coordination function (DFC) and point coordination function (PCF). The DCF is the primary access method of IEEE 802.11. It is based on carrier sense with multiple access and collision avoidance (CSMA/CA). The PCF is used to provide real time services with an access point (AP) controlling the access to the medium. The IEEE 802.11 defines various priority levels for access to the medium called inter-frame spacing (IFS). IFS is the time interval between the transmissions of two successive frames by a station. The common IFS are; short inter-frame spacing (SIFS), PCF inter-frame spacing (PIFS) and DCF inter-frame spacing (DIFS). The SIFS indicates the highest priority and is used for short control messages such acknowledgment packets. The PIFS is used when operating in the PCF mode. The DIFS is used when operating in the DFC mode and has lower priority than the other two priorities. The DFC is used in the simulations since it allows ad hoc operation of the network.

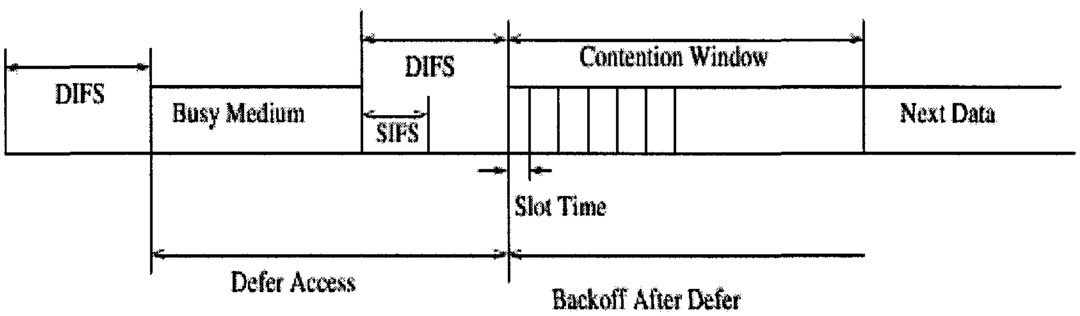

Figure 3.7: Basic access mechanism in IEEE 802.11

When a node has a packet to send it senses the medium, if the medium is idle for a period of DIFS, the node sends its packet. During the DIFS period if the medium is sensed to be busy due to another node transmitting a frame, the node defers transmission until the end of the current frame transmission. After the transmission, the node again waits for another DIFS after which it picks a random back-off time and start counting down. If the medium remains idle after counting down the back-off time then the node transmit its packet. If the medium becomes busy during the random back-off time, the back-off time is halted and resumed after the medium becomes idle for a period of DIFS. The mechanism just described is shown in Figure 3.7

The back-off time in the cross-layer implementation is randomly chosen in the interval [0, CW] called the contention window. The back-off time is an integral multiple of slot times. This is given by

$$T_{back\text{-}off} = [R*CW]*T_{slot} \quad , \qquad (3.2)$$

where R is a uniformly random distributed variable between [0, 1], CW is the contention window and T_{slot} is the slot time.

The contention window indicates the level of congestion in the vicinity of a node. The initial contention window size is set to CW_{min} ($CW=CW_{min}$). This value doubles after a collision occurs, but CW cannot exceed the maximum of CW_{max}. The contention window size is therefore an indicator for the amount of collision occurring in the area surrounding a node. For a direct sequence spread spectrum technology, CW_{min}=32 and CW_{max} =1024. The SIFS= $10\mu sec$, T_{slot}=$20\mu sec$ *and* DIFS= SIFS + ($2xT_{slot}$) = $50\mu sec$

The back-off time in the MAC layer varies in the range of micro seconds while the network layer parameters such as interval between requests are in seconds. In order to use the back-off time in the network layer for routing decisions, there is a need to re-scale the MAC layer back-off time. The rescaling can be done by eliminating the T_{slot} term from Equation (3.2). Therefore, Equation (3.2) can be re-written by

$$T_{back\text{-}off} = (R*CW). \qquad (3.3)$$

Equation (3.3) indicates that nodes that have high contention window will have longer delays and those with lower contention windows will have shorter delays. The value of $T_{back\text{-}off}$ and CW were transferred to the network layer to be used for routing decisions. Both MAC layer parameters were transferred to the network layer by inserting the information in packet headers. This information were used by the network layer in routing decision by making the FN selection algorithm to select nodes located in less congested to

```
Received request packet
if (request already processed) then
     /* nothing to do with that request */
     return;
else
     /* check timer whether it is running */
    if (timer is running) then
        set timer to delay;
    else {
      if (T_back-off <= 16 and Contention window <= 64) then
            T_delay = random back-off time;
      else{ T_delay =10; }
      start timer;}
    endif
endif
/* listen to ongoing traffic*/
if (hear rebroadcast of the request) then
  {
    set delay to remaining time;
    flag the request;
    return;
}
else
    /* check whether timer expires */
    if (timer expires) then
    {
       switch to forwarding node;
       return ;}
    return;
    endif
endif
```

Figure 3.8: New pseudo-codes for FN selection algorithm

areas to become forwarding nodes (FNs). The new algorithm works by imposing some threshold conditions on the information received from the MAC layer. A random delay T_{delay} as in (3.1) is chosen by nodes whose $T_{back\text{-}off}$ is less than a threshold of 16 and whose *CW* is not more than 64. The threshold of 64 placed on the contention window is to choose nodes that have experience not more than two collisions in their vicinity. If the $T_{back\text{-}off}$ parameter is used alone, there is a probability that nodes having high congestion window might be selected. Nodes not meeting these requirements are assigned a fixed T_{delay} of 10. Thereby having to wait more than nodes located in less congested areas. The pseudo-code for the AODV-CL algorithm is shown in Figure 3.8

3.5 Simulation results: delays and overhead analysis

The protocol was simulated and tested in similar scenarios used while testing AODV with the FN algorithm. Figure 3.9 shows the overhead performance of the protocol as compared with AODV and AODV with FN selection algorithm. The figure shows that AODV-CL has a better overhead performance than AODV and AODV with FN selection scheme. At 200 and 250 nodes, AODV-CL achieved an overhead reduction of 72.9% and 70.8% respectively as compared with AODV. This is better than the 62.8% and 61.5% overhead reduction achieved by the random FN selection algorithm for the same number of nodes. The delay performance is presented in Figure 3.10. The figure shows an improvement in average delay per packet over AODV especially at large networks where the AODV with FN selection algorithm failed to outperform AODV. The average delay per packet for AODV with 100 nodes and 250 nodes are 0.056 second and 0.084 second respectively. While for AODV-CL the delays are 0.04 second and 0.070 second respectively for the same numbers of nodes. This amounts to a delay improvement of 32.2% and 16.67% respectively.

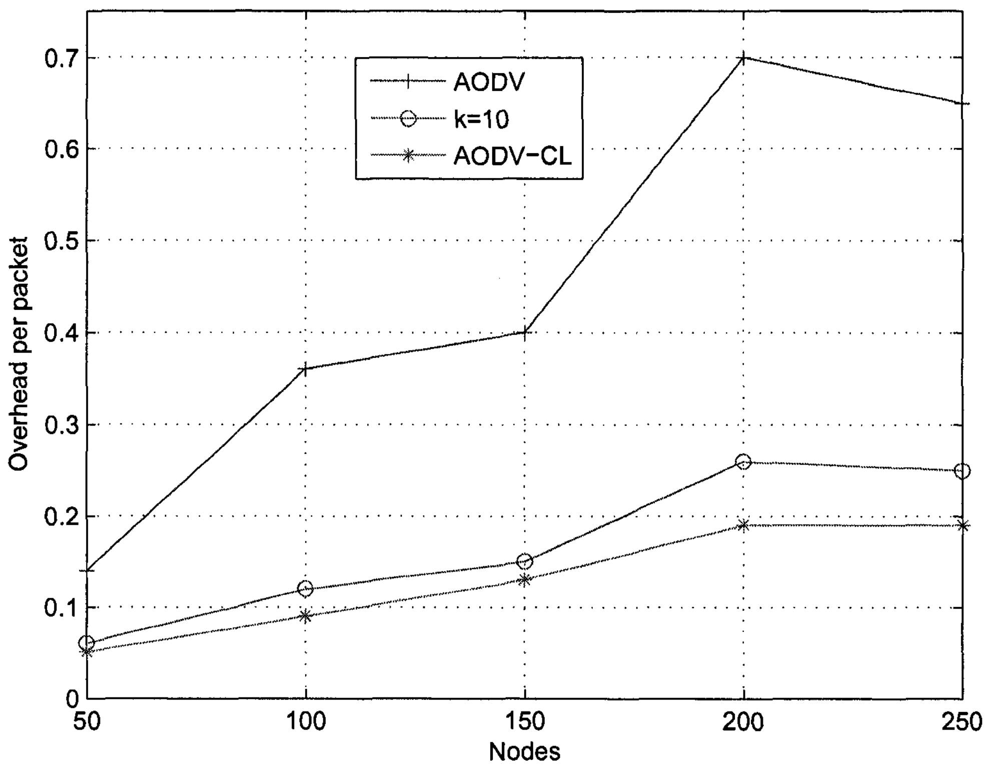

Figure 3.9: Overhead reduction with AODV-CL

3.6 Performance analysis with varying rates

In order to measure how the cross-layer design handles varying loads, a simulation of 100 nodes in a flat area of 1000 x 800 m^2 was carried out. The nodes were randomly distributed on this area. Traffic rate was varied between 1 packet per second to 8 packets per second.

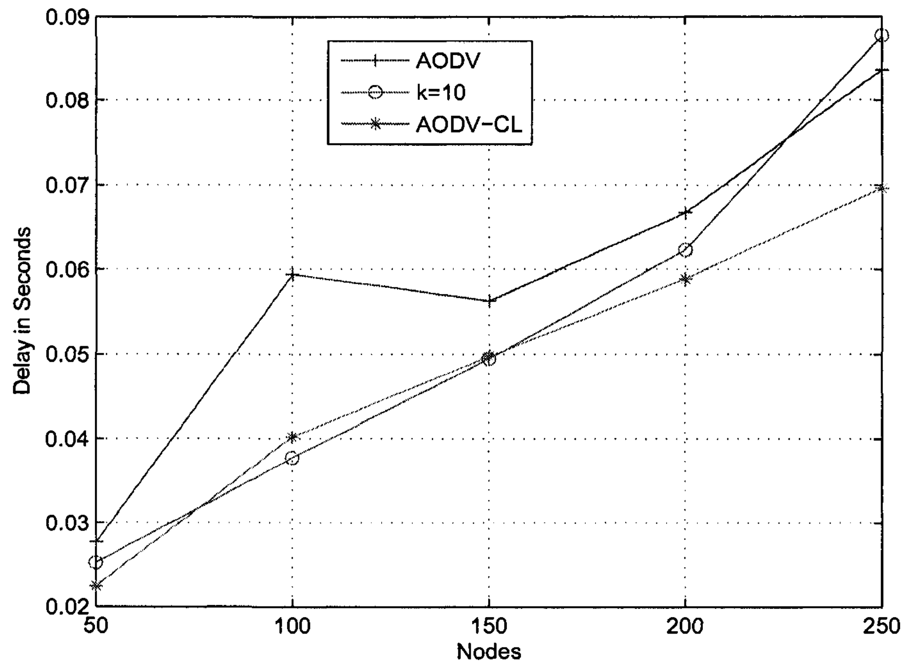

Figure 3.10: Delay improvement with AODV-CL

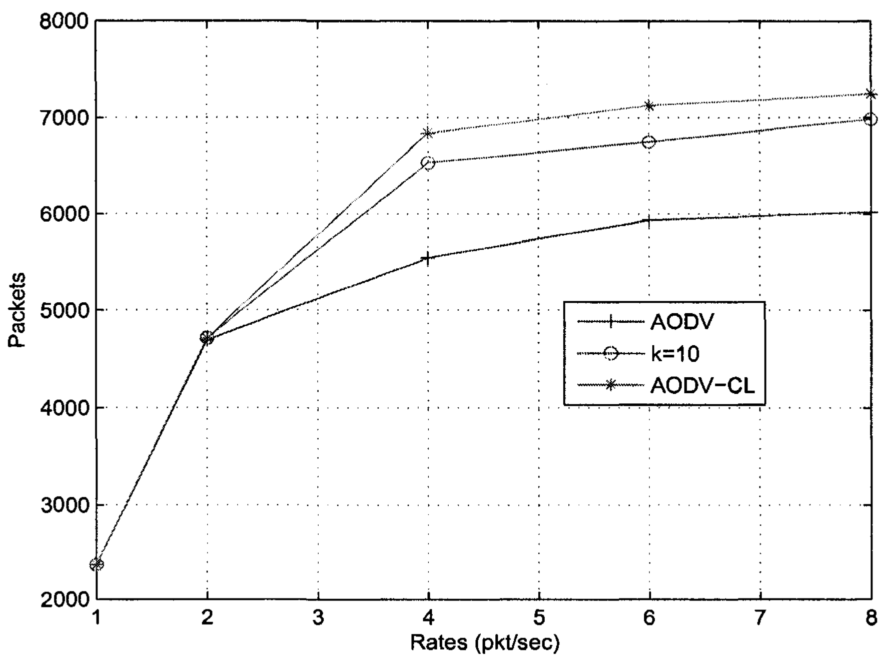

Figure 3.11: Data packet delivered with varying loads

The performance of the network in terms of data packet that successfully reached the destination is depicted in Figure 3.11. It shows that more packets are delivered by AODV-CL than AODV except in low traffic rates where they have equal performance. At high traffic rates AODV-CL outperforms AODV. When the traffic rate is 8 packets per second, AODV-CL delivered 7246 packets while AODV delivered 6021 packets. The percentage increase is 20% in packet delivery. The delay comparison for the same scenario is shown in Figure 3.12., which indicates an improvement in delay.

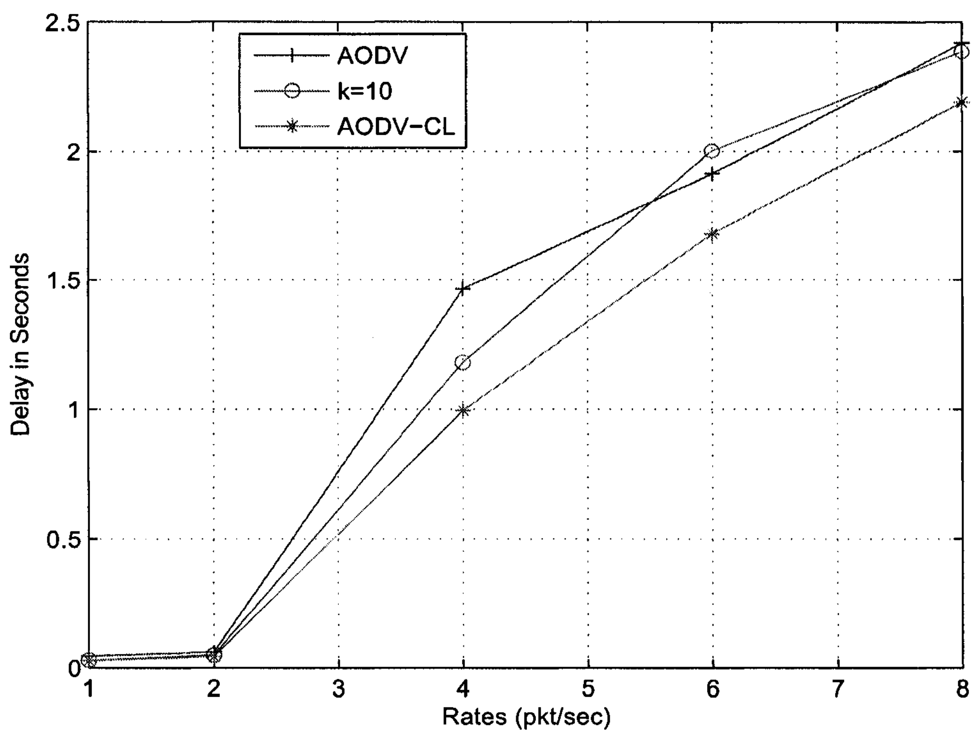

Figure 3.12: Delay comparison with varying loads

For example at traffic rate of 4 packets per second, the delay for AODV was 1.46 seconds and that of AODV-CL was 0.99. This represents a 32% improvement in delay. This is achieved because nodes select routes in less congested areas of the network. Figure 3.13 shows the throughput comparison for the network. It shows that AODV-CL achieved better throughput than AODV under the same scenario. Throughput at traffic rate of 8 packets per second is 30 packets per seconds for AODV while it is 36 packets per second for AODV-CL. This is a 20% increase in throughput over AODV.

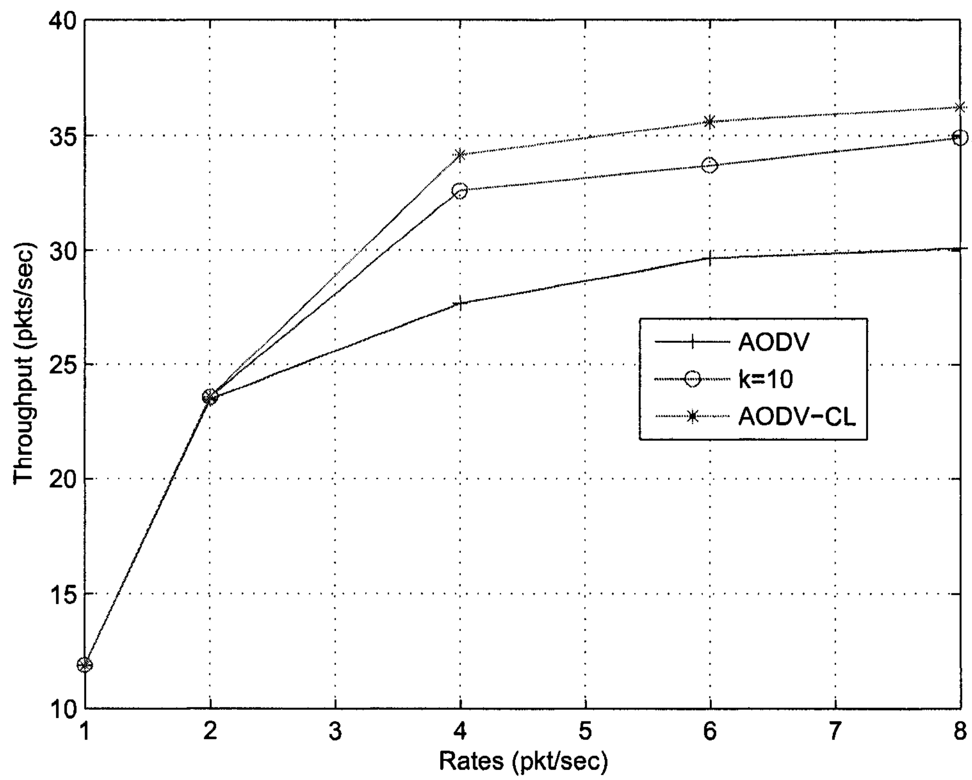

Figure 3.13 Throughput comparison with varying loads

3.7 Verification of Cross-layer design

In order to verify that AODV-CL works as it designed, this is selecting routes in less congested areas of the network. The average contention window sizes along the route taken by each packet were recorded. The simulation consists of 100 nodes randomly distributed on a flat area of 1000 x 800 m^2. The rate used is 4 packets per second and packet size is 512 bytes. The average contention window size is shown in Figure 3.14. It verifies that more packets travel through nodes with less contention window size in AODV-CL than in

AODV. This is an indication that AODV-CL selects routes in less congested areas of the network.

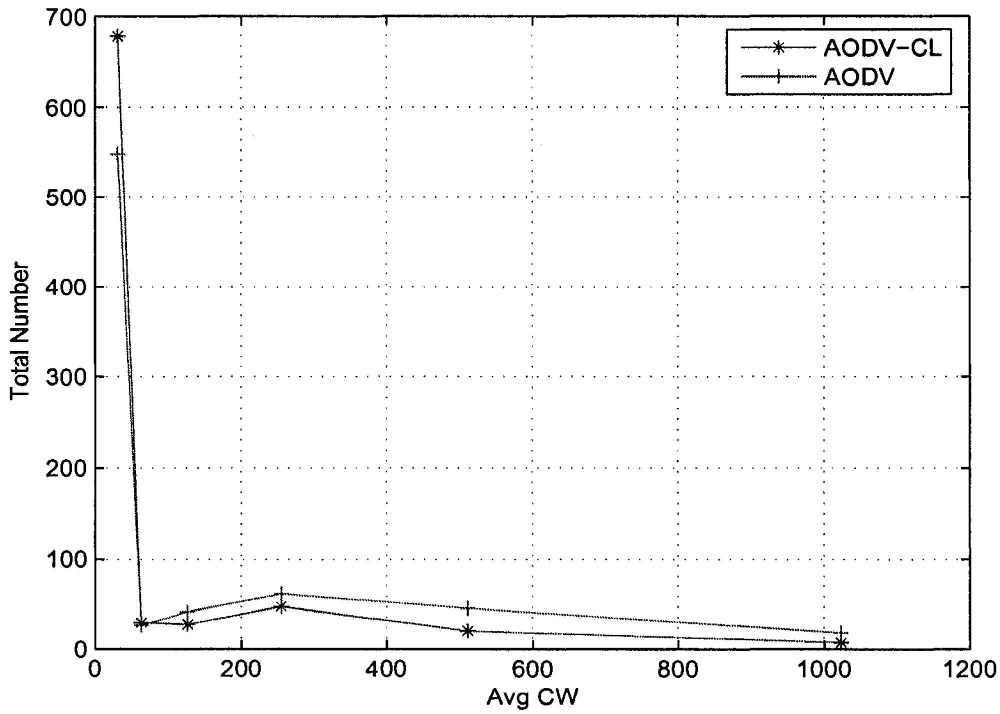

Figure 3.14: Average contention window size along routes

3.8 Comparison with a pure probabilistic protocol

The performance of AODV-CL protocol was compared with a probabilistic routing protocol. Some probabilistic schemes such as [12, 13] and [23] have been proposed for MANET. These schemes have already been explained in this chapter. The probabilistic protocol that AODV-CL is compared to is similar to the type described in [23]. Authors in [23] propose a protocol whereby nodes forward packets with a probability P, which is less than 1. The protocol being compared forwards request packets with a probability of 0.5. This probability scheme is called PROB in this thesis. The overhead performances of AODV, AODV-CL and PROB are shown in Figure 3.15. From the figure, it can be seen that AODV-CL outperforms PROB in terms of overhead though PROB outperformed AODV in this regard.

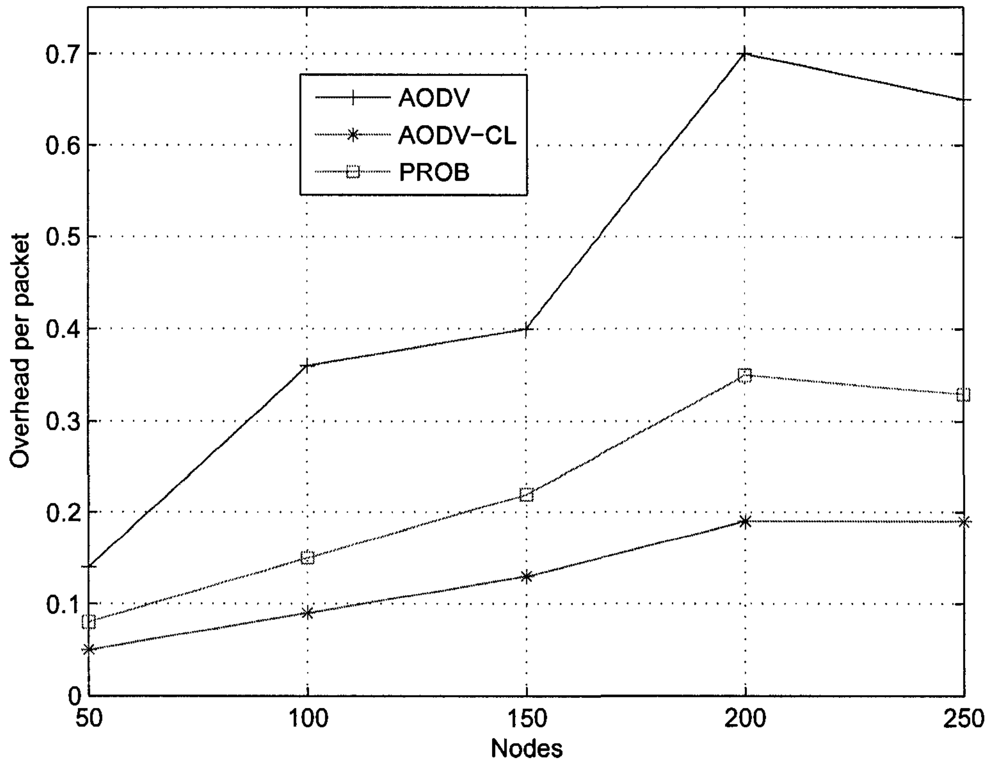

Figure 3.15: Overhead comparison with probability scheme

At network sizes of 200 nodes, PROB achieve a 50% reduction in packet overhead as compared to AODV while AODV-CL achieved a packet reduction of 72.8% over AODV. The delay performances for these three protocols are shown in Figure 3.16. The figure shows that AODV-CL has a better delay performance than PROB. This is due to the fact that AODV selects forwarding nodes in less congested areas of the network. Lesser overhead packet in AODV-CL also helps in achieving a better delay performance because the bandwidth is used efficiently.

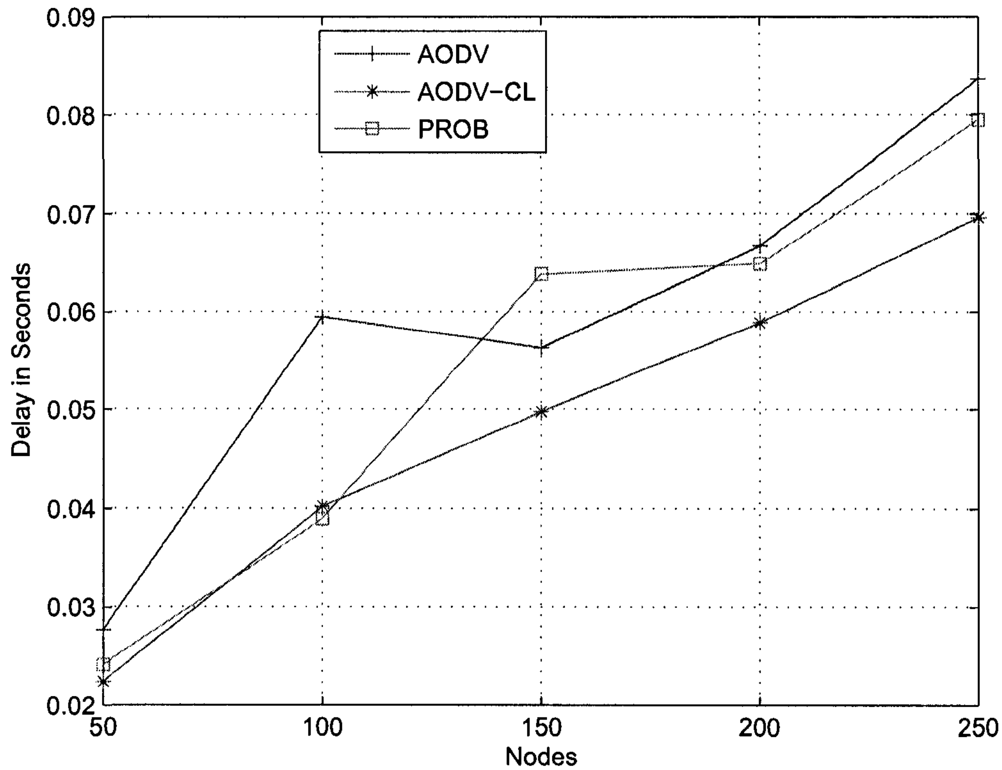

Figure 3.16: Delay comparison with probability scheme

3.9 Conclusions

This chapter presented two new protocols to improve routing efficiency and overall performance of MANET. One is based on FN selection and the other uses a cross-layer design. The first protocol is based on an algorithm called FN selection algorithm. In FN selection algorithm, nodes are classified as either mobile nodes or forwarding nodes. The algorithm works in a distributed fashion and dynamically at each node. It also works on-demand with no additional packet required for it operation. The FN selection algorithm has been implemented in AODV protocol. The FN selection algorithm was further improved by using a cross-layer design to select nodes in less congested areas of the network. The new protocol is called AODV with cross-layer design (AODV-CL).

Simulations result shows that AODV-CL improves network performance by reducing overheads, reducing delays and increasing network throughput. AODV-CL performs better than AODV in all network size.

Chapter 4

Conclusions and Future Work

4.1 Summary of Contributions

The main objective of this thesis has been to solve the 'flooding' problem and to select routes in less congested areas of MANET using cross-layer design. In Chapter 2, it has been shown that reactive routing protocols like Ad hoc On-demand Distance Vector (AODV) routing protocol and Dynamic Source Routing (DSR) uses a 'flooding' mechanism to discover paths to the destination. In the "flooding" mechanism, every node in the network broadcast route request packet to other nodes in the network. This "flooding" has been shown to bring about different problems that affect the overall performance of the network. Some of the problems are; (1) high packet collision, (2) redundant messages, and (3) high contention in the network. High packet collision leads to packet loss. Redundant messages occupy useful bandwidth. High contention leads to increase delay. Protocols have been proposed to mitigate the effect of flooding in MANET. Some of these protocols require some additions such as GPS, extra control messages and a location server [1, 3, 8, 9, 10, 12, 13] and [23]. Additions such as GPS and location servers add extra expense. Extra control messages add overheads to the network thereby further degrading the performance of the network. In Chapter 3, two new protocols were introduced. One is based on the FN selection algorithm introduced in [2] and the other is Ad hoc On-demand Distance Vector with Cross-layer Design (AODV-CL). AODV-CL works by combining the FN selection algorithm with a cross-layer design. It does not require any of the additions such as GPS and location servers that have been mention above. It classifies nodes as mobile nodes (MN) and forwarding nodes (FN). MN's are usually the source nodes and destination nodes while FNs are the nodes that forward data packets between the source and destination. Since only FN participates in the forwarding of data packets, overhead are significantly reduced in the network. The FNs are selected using the FN selection algorithm which has been combined with a cross-layer design that uses MAC layer congestion information. This combination allows FN algorithm to select FN in less congested areas of the network. Simulation results showed that there was significant performance improvement over AODV when AODV-CL was used.

The performance of AODV-CL protocol was compared with a probabilistic routing protocol called PROB. PROB forwards request packet with a probability of 0.5. Simulations results showed that AODV-CL had better performance than PROB though PROB showed performance improvement over the AODV.

The simulation results presented in this thesis have proved that the objective of this thesis which is to mitigate the flooding problems of MANET and to select routes in less congested areas of the network were met. AODV-CL protocol can still be improved in the future to mitigate other problems that occur in MANET such as energy constraint.

4.2 Future work

In this thesis, the proposed protocol has been simulated using NS-2 network simulator. In all the simulations carried out, network nodes were static. The protocol can be extended and tested in a mobile environment.

The mobile scenario does add additional complexity because nodes can move in and out of congested zones due to the dynamic nature of the topology. The effect of this change in the topology needs to be investigated and adjustments need to be made to the algorithm. The node selection algorithm used in AODV-CL apparently increases the number of hops to a destination than the AODV protocol. This can increase the delay. This problem needs to be looked into in order to further improve the delay performance of AODV-CL.

Energy efficiency is a critical issue in MANET. MANET will mainly be deployed using hand held devices such as PDAs, cell phones, and smart phones which all have limited energy resources. The performance of AODV-CL in terms of energy efficiency has not been investigated in this thesis. This needs to be investigated and if there is a need, a modification of the protocol for energy optimization can be done.

The protocol have been implemented and tested only on simulators. Implementing and testing AODV-CL in a real wireless environment will be interesting. This will allow for the comparison of AODV-CL performance in simulated environment with real scenarios

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