Mobility Models and Efficient Multihop Routing Methods in MANETs

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ABSTRACT

Many routing protocols are proposed in the literature on mobile ad hoc networks (MANETs). Some of those protocols which have been investigated under different assumptions are unable to capture the actual characteristics of MANETs. Therefore, there is a necessity to investigate the performance of MANETs under a number of different protocols with various mobility models.

The first part of this study evaluates the performance of the single path routing protocols Ad hoc On Demand Distance Vector (AODV), Dynamic Source Routing Protocol (DSR) and Destination Sequenced Distance Vector (DSDV), in the presence of different network loads and under four well-known mobility models, which are the Random Waypoint Mobility Model (RWPM), the Gauss Markov Mobility Model (GMM), the Manhattan Grid Mobility Model (MGM), and the Random Point Group Mobility Model (RPGM). Our findings show that DSR routing protocol has a better performance compared to other protocols with respect to various metrics.

In the second part of my thesis, a new mobility model has been implemented and investigated with a multipath routing protocol. Our proposed model partitions an area under simulation into clusters. An extensive simulation has been conducted to investigate the performance of the proposed model, together with well known mobility models with Ad hoc On-demand Multipath Distance Vector (AOMDV) routing protocol to be utilized in different network clusters (ad hoc configurations).

Using the simulation results, we are able to formulate a novel mobility model that could be used with different routing protocols.

Keywords: Wireless mobile ad hoc networks, routing protocols, mobility modeling, performance.

ÖZ

Literatürde, hareketli özel amaca yönelik ağlar (MANETs) üzerinde birçok yönlendirme protokolleri önerilmiştir. Farklı varsayımlar altında incelenen bazı protokollerle MANET'lerin gerçek özelliklerini yakalamak mümkün değildir. Bu nedenle, MANET'lerin performansını farklı protokoller ile farklı hareketlilik modelleri kullanılarak araştırma zorunluluğu vardır.

Bu çalışmanın ilk bölümünde, tek yollu yönlendirme protokollerinden özel amaca yönelik talebe bağlı mesafe vektörü (AODV) protokolü, dinamik kaynak yönlendirme (DSR) protokolü ve hedef sıralı uzaklık vectorü (DSDV) protokolünün performansı farklı ağ yapılarında, iyi bilinen dört hareketlilik modellerinden olan, rastgele geçiş noktası hareketlilik modeli (RWPM), Gauss Markov hareketlilik modeli (GMM), Manhattan ızgara hareketlilik odeli (MGM) ve rastgele nokta grup hareketlilik modeli (RPGM) ile birlikte değerlendirilmiştir. Bulgularımız, DSR yönlendirme protokolünün performansının farklı ölçütlerde diğer protokollere göre daha iyi olduğunu göstermektedir.

Tezin ikinci bölümünde ise, yeni bir hareketlilik modeli çok yollu bir yönlendirme protokolü ile uygulanmış ve incelenmiştir. Önerilen model benzetim alanını parçalayarak kümelere (clusters) böler. Önerilen modelin performansını araştırmak için, özel amaca yönelik talebe bağlı çokyollu mesafe vektörü (AOMDV) protokolü iyi bilinen hareketlilik modelleri ile farklı özel amaca yönelik ağ yapılarında kapsamlı simulasyonlar yapılmıştır. Elde edilen benzetim sonuçlarından, farklı yönlendirme protokolleri ile kullanılabilecek yeni bir hareketlilik modeli formüle edebiliceğimiz ortaya çıkmıştır.

Anahtar Kelimeler: Kablosuz hareketli özel amaca yönelik ağlar, yönlendirme protokolleri, hareketlilik modelleme, performans.

To my family, I specially dedicate this work.

(Huda, Afnan, Abdul Rahman)

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LIST OF ABBREVIATIONS

MANET	Mobil Ad hoc Network
WLAN	Wireless Local Area Network
MN	Mobile Node
AODV	Ad hoc On demand Distance Vector
DSR	Dynamic Source Routing Protocal
DSDV	Distination Sequenced Distance Vector
AOMDV	Ad hoc On-Demand Multipath Distance Vector
TORA	Temporally Ordered Routing Algorithm
ZRP	Zone Routing Protocol
WARP	Wireless Ad hoc Routing Protocol
RWPM	Random Waypoint Mobility Model
GMM	Guass Markov Mobility Model
MGM	Manhattan Grid Mobility Model
RPGM	Random Point Group Mobility Model
RREP	Route Request Packet
RREQ	Route Replay Packet
RERR	Route Error Packet
RTC	Request To Sent
CTS	Clear To Sent
ACK	Acknowledgment
LBCM	Location-Based Cluster Mobility Model
Ns2	Network Simulator 2
MAC	Medium Access control

CMU	Carnegie-Mellar University
DCF	Distributed Coordination Function
CSMA	Carrier Sense Multiple Access
CA	Collision Avoidance
FIFO	First In First Out
LL	Link Layer
PHY	Physical Layer
IFq	Interface queue
NetIF	Network Interface
CBR	Constant Bit Rate
TB	Terabyte
ISCN	International Symposium on Computer Networks
CSIT	Computer Sience Information Technologies
EEECS	Elecrtical and Electronic Engineering and Computer Systems
PICICT	Pelestinian International Conference on Infromation and Communication Technology
COMPELECENG	Computers and Electrical Engineering Journal

Chapter 1

INTRODUCTION

1.1 Background and Motivation

A mobile ad hoc network (MANET) is a collection of nodes that can move freely and communicate with each other using wireless devices. For nodes that are not within the direct communication range of MANET, other nodes in the network collaborate to relay packets. A MANET is characterized by its dynamic topological changes, limited communication bandwidth, and limited battery power of its nodes. The network topology of a MANET can change frequently and dramatically, since nodes in a MANET are capable of moving collectively or randomly. The link between any two nodes may be down/up, when they move out/in within the transmission range of each other. A MANET can be instable due to the signal fading interference from other signals, or the change of transmission power levels [1].

Routing protocols can be classified into three categories [2], namely, proactive which is table driven, reactive which is on-demand, and hybrid, depending on how the source finds a route to the destination. In proactive protocols, nodes advertise their routing state to the entire network to maintain a common complete topology of the network. One example is the conventional routing scheme, Destination Sequenced Distance Vector (DSDV) [3]. Reactive protocols establish paths only upon request, e.g. in response to a query, or an event; meanwhile, nodes remain idle in terms of routing behavior. Nodes forward each routing request to peers until it arrives at a destination; the latter will respond over the reverse communication path. Examples of reactive routing schemes are Adhoc On-demand Distance Vector (AODV) [4] and Dynamic Source Routing (DSR) [5]. Hybrid protocols use a combination of these two ideas.

AODV is a routing protocol used for MANETs, which is an on-demand, single path, loop-free distance vector routing protocol. AODV combines the on-demand route discovery mechanism in DSR with the concept of destination sequence numbers from DSDV. However, unlike DSR which uses source routing, AODV takes a hop-by-hop routing approach.

Some mobility models developed for wireless ad hoc networks have been studied recently. However, up to our knowledge, no extensive simulations and quantitative comparison of mobility models have been published. This thesis fills this gap by presenting a detailed performance evaluation and comparison of three single path routing protocols (AODV, DSR, and DSDV); under four well-known mobility models, which are the Random Waypoint Mobility Model (RWPM) [6], the Gauss Markov Mobility Model (GMM) [7], the Manhattan Grid Mobility Model (MGM) [8], and the Random Point Group Mobility Model (RPGM) [9].

Initially, a detailed simulation of single path routing protocols is presented. Then, performances of these routing algorithms are compared in terms of delivery ratio, average end to end delay, and routing overhead congestion. Finally, comprehensive studies of different sets of mobility models are presented with selected routing protocols.

1.2 Thesis Layout

The rest of the thesis is organized in the following manner.

Chapter 2 presents a general concepts about MANETs and ad hoc routing protocols in general. A section on mobility models also included in Chapter 2.

Chapter 3 includes classifications of the routing protocols. First we classified it according the cast property. Second, it classified according the route selection property. In this thesis, we have selected four routing protocols which are DSR, AODV, DSDV, and AOMDV which are presented in short.

In Chapter 4, we present a short literature survey on mobility models. In addition to that, the mobility models classification is discussed in brief. The four selected mobiliry models RWPM, RPGM, MGM, and GMM models also presented in brief.

Chapter 5 contains our own location based cluster mobility model, how we are motivated to design and construct this mobility model. The mobility architecture is presented in detail.

The simulation environment setup is presented in Chapter 6. This includes the simulation model in ns2. The detailed setup for the generation of the traffic model and the mobility model is discussed in this chapter. We have added the performance metrics that we have used in our simulation.

Chapter 7 contains two main parts. The first part is the performance analysis of the mobility models on routing protocols. Whereas the second part is the performance on our mobility model against other mobility models discussed in the pervious chapters.

Chapter 8 conclude this dessirtation and some other suggestions for future work are summarized.

1.3 Contribution of the Thesis

The result from my thesis are reported and summarized in one journal paper and five conference papers that I finished during my PhD studies:

1- In 2006, Compition-based Load Balancing for Distributed Systems, Proc. Of the Seventh IEEE International Symposium on Computer Networks, (ISCN'06), 16-18 June 2006, Istanbul, Turkey, Oz, G., and Kostin, A., IEEE 2006 pp. 230-235.

2- In 2009, In 2009, Application-Layer Testbed for Real-World Experimentation in Wireless Ad Hoc Networks, Proc. Of theWorkshop on Computer Science and Information Technologies (CSIT'2009) October 5-8, 2009 in Crete, Greece. Oz, G., and Ozen,Y.

3- In 2010, Experimental Study od Data Dissemination in Wireless Ad Hoc Networks, Proc. Of theWorkshop on Computer Science and Information Technologies (CSIT'2010), Russia, Moscow – St.Petersburg, September 13-19, 2010. Oz, G., and Komili, M., Ufa State Aviation Technical University, 2010, pp. 108-114.

4- In 2010, Performance Evaluation of Real – World Wireless Mobile Ad Hoc Networks, Sixth IEEE International Symposium on Electrical and Electronics Engineering and Computer Systems, (EEECS'10), 25-26 November 2010, Lefke, Northern Cyprus, Oz, G., and Akkoc, M., European University of Lefke.

5- In 2013, Experimental Study of Pure Flooding Method for Localizing an Anycast Server in Wireless Ad Hoc Networks, Palestinian International Conference on Information and Communication Technology (PICICT'2013), 14-16 April 2013, Gaza, Palestine, Oz,G., Islamic University of Gaza, pp. 83-89.

6- In 2013, Abdul Karim ABED, Gurcu OZ and Isik Aybay, Influence of Mobility Models on the Performance of Data Dissemination and Routing in Wireless Mobile Ad Hoc Networks, Computers and Electrical Engineering (compeleceng) Journal, available on line 30 April 2013, http://dx.doi.org/10.1016/j.compeleceng.2013.03.022.

Chapter 2

BACKGROUND

2.1 Introduction

A Mobile Ad hoc Networks, (MANET) is a wireless network that transmits data from one host to another, where any host willing to send or receive data can join the network anytime. In addition the node can leave the network without any restrictions.

The need for the rapid deployment of independent mobile hosts certainly created a network with no predefined infrastructure. In this network, all nodes can function as routers. This gives the MANETs two of its most desirable characteristics; being adaptable and quick to deploy. Figure 2.1 shows a MANET sample. Suggested areas of use will include establishing efficient communication networks for mobile workers in isolated regions or in disaster areas where existing networks have been destroyed or do not exist. As a consequence of this dynamic topology, the design of efficient routing protocols is a demanding challenge and a crucial problem [1].

MANETs can be used alone (for example in the military) or as a hybrid together with the Internet or other networks. Different MANET applications have different needs, and hence the various MANET routing protocols may be suitable for different applications. The size of the network and the frequency of the change in topology are factors that affect the choice of the protocols. There is no best protocol for all applications.

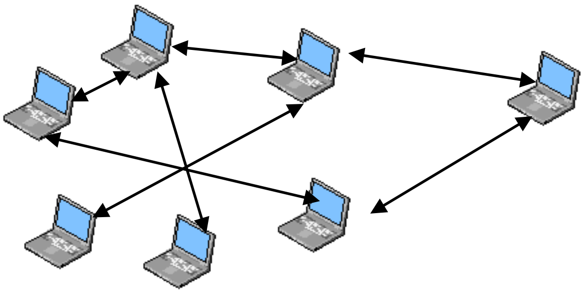

Figure 2.1. MANET example

The frequency of change in topology comes from the mobility model chosen. Each model has its own characteristics, where the node's motion depends on. These characteristics have many parameters that can be set that will influence the node's mobility and frequency of the change in the topology.

2.2 General Concepts of MANETs

A MANET is an autonomous collection of mobile hosts that communicate over relatively "slow" wireless links. Since the nodes are mobile, the network topology may change frequently, rapidly and unpredictably over time. The network is decentralized, where all network activity, including discovering the topology and delivering messages must be executed by the nodes themselves. Hence routing functionality will have to be incorporated into the mobile nodes.

Since the nodes communicate spontaneously over wireless links, they have to contend with the effects of radio communication, such as noise, fading, and interference. In addition, the links typically have less bandwidth than a wired network. Each node in a wireless ad hoc network functions as both a host and a router, and the management of the network is distributed among the nodes. The network topology is in general dynamic, because the connectivity among the nodes may vary with time due to new node arrivals, node departures, and the possibility of having mobile nodes. The mobility pattern of the nodes depends on the type of the node, its time and place where it is moving [1].

An ad hoc wireless network should be able to handle the possibility of having mobile nodes, which will most likely increase the rate at which the network topology changes. Accordingly, the network has to be able to adapt quickly to changes in the network topology. This implies the use of efficient handover protocols and auto configuration of arriving nodes.

In ad hoc networks, messages sent by a node may be received simultaneously by all nodes within its transmission range, i.e. by its neighbours. Messages requiring a destination outside this local neighbourhood zone must be hopped or forwarded by these neighbours, which act as routers, to the appropriate target address. As a result of node mobility, fixed source/destination paths cannot be maintained for the lifetime of the network. Consequently, a number of routing protocols have been proposed and developed for wireless ad hoc networks. These protocols have been derived from distance vector and link state techniques and involve determining the shortest path to a destination in terms of distance or link cost. Such protocols are classified as proactive, reactive or hybrid, depending on how route maintenance and discovery is performed.

2.3 Ad Hoc Routing Protocols

An ad-hoc routing protocol must be distributed as each node should be involved in route discovery making the routing information and link costs more reliable. With a wireless environment and mobile nodes all links should be considered as possibly being unidirectional and a protocol should be able to adapt to this constraint. In terms of battery consumption, a protocol must be energy efficient as the sending/receiving of routing information consumes battery power. Also quality of service issues such as time-delay and throughput are factors considered by real-time applications. To sumup, the significant characteristics of an ad-hoc routing protocol are [3,4]:

1. Dynamic Topology
2. Restricted Bandwidth
3. Erratic Capacity Link, possibly unidirectional
4. Energy Constraints

Based on when and how route discovery is initiated, there are three main classes of MANET routing protocols [1,3,4]:

1. Table Driven (Proactive) – each node maintains a table of all possible paths to every node within a network.
2. On Demand (Reactive) – Route discovery is only initiated when there is a need to establish a communications link between nodes.
3. Hybrid – this is a fusion of proactive and reactive protocol techniques.

2.4 Mobility Models

A mobility model is a set of rules used to generate trajectories for mobile entities. Mobility models are used in network simulations to generate network topology changes due to the node movement. A network simulator must know the position of a Mobile Node (MN) at any moment of time. Using the exact node position, the simulator can compute signal fading from one node to another and take actions based on the current network topology (e.g., determine the set of nodes that will receive a certain packet) [10].

A mobility model uses an environment description to define the bounds of the simulated world. In addition to the bounds, the environment description can include obstacles or restrictions within the simulated environment (e.g., walls, streets, etc.). These restrictions directly influence the way of nodes movement: simulated humans must not walk trough walls, simulated cars must stay on the streets, etc [11].

At a high level of abstraction, mobility has two components: a spatial component and a temporal component. The spatial component describes where the mobile entity is moving, and the temporal component describes when an entity is moving and at which speed [12]. Thus, when developing a mobility model, these two components of the mobility must be clearly defined. The general set of parameters required by a mobility model to build the simulated world contains: the simulated population size, the simulation time, the environment description, the spatial mobility characteristics, and the temporal mobility characteristics.

It has been shown that cluster architecture guarantees basic performance achievement in a Mobile Ad hoc NETwork (MANET) with a large number of MNs

[13, 14]. A cluster structure, as an effective topology control means [15], provides at least three benefits [16, 19, 20]:

1- A cluster structure facilitates the spatial reuse of resources to increase the system capacity [19, 21]. With the non-overlapping multi-cluster structure, two clusters may deploy the same frequency or code set if they are not neighboring clusters [20]. Also, a cluster can better coordinate its transmission events with the help of a special MN, such as a cluster-head residing in it. This can save resources used for retransmission by reduced transmission collision [17, 18].

2- The set of cluster-heads and cluster-gateways can normally form a virtual backbone for inter-cluster routing, and thus the generation and spreading of routing information can be restricted in this set of nodes [22, 23].

3- A cluster structure makes an ad hoc network appear smaller and more stable in the view of each MN [16]. When a MN changes the cluster it is attached, only MNs residing in that cluster need to update the information [24, 25]. Thus, local changes need not be seen and updated by the entire network, and information processed and stored by each MN is greatly reduced.

Chapter 3

CLASSIFICATION OF AD HOC ROUTING PROTOCOLS

Network Management is the key issue in the implementation of MANETs keeping in mind the various constraints due to the lack of infrastructure and high flexibility of nodes. Again, owing to the limited transmission range of the mobile nodes, it is indispensable that each node executes a routing algorithm to establish and maintain routes to other nodes in the network.

Routing protocols plays a vital role in mobile wireless ad hoc networks. Over the years, many researchers have investigated the performance of the simple and multi-path routing protocols with some mobility models. Almost all researchers agree on the significance contribution of these routing protocols [26-33].

3.1 Previous Studies

Routing in wireless mobile ad hoc networks has been studied for many years. Although most protocols are designed to be adaptive to the mobility and activity of the nodes, few researchers present comprehensive sets of mobility models to test against their protocols.

In [34], Mittal and Pinki compared AODV, DSR and DSDV single path routing protocols using the Random Waypoint Mobility model (RWPM). Their simulations showed that DSR is able to achieve remarkable packet delivery fraction and the same for the throughput. They compared for 20, 30, and 75 nodes only and they show that DSR is the best for all.

In [35], Maan and Mazhar compared AODV, DSR, DSDV, OLSR, and DYMO which are reactive and proactive single path routing protocols with RWPM, Random Point Group Mobility model (RPGM) and Column Mobility model (CM). However, the RPGM and CM models are derived from each other so they belong to the same group. Maan and Mazhar have observed that an increase in the network size and number of nodes have similar impact on all protocols under various mobility patterns. MANET protocols generally provide optimum performance for small networks of around 50 nodes in an area of 700m x 700m.

Kuman, Sharma and Suman [36] evaluated the impact of three mobility models i.e. File Mobility model (FM), RWPM model and RPGM model on proactive routing protocols only. FM model and RWPM are in the same group of routing protocols.

In other recent studies [37], Said, El-Emary and Kadim have compared AODV and DSDV with only RWPM model under different parameters. They concluded that the AODV gives less fluctuation results and better performance as compared with DSDV, with respect to some identified parameters like routing overhead, throughput, end-to-end delay. Other researchers [38, 39] have used AODV and DSDV in addition to DSR routing protocol in their work.

Simulation results have shown that the choice of the mobility model makes a difference in the physical link dynamics and performance [40]. There is limited work done to create a set of models that can be easily used to evaluate protocols. For example, Sanchez [41] considers different human or robotic moving behavior in different situations, formulating such models as the Brownian motion, the Column model (Scanning, Searching), the Pursue model (Target Tracking), and the Nomadic community model.

Research in mobility models have resulted in a number of models ranging from probabilistic to completely deterministic ones. Random mobility models represent an (almost) probabilistic approach since the movements of the nodes is only bound to a few parameters such as the variance of a Gaussian distribution or some constraints which keep the nodes in a bounded area; see [42] for a survey and simulation based comparison of several random mobility models and [43] for a concise categorization of mobility models in general.

A simulation based analysis about the impact of mobility models on the performance of node-disjoint and link-disjoint routing algorithms is given in [44]. In this study, Cooper and Maghanathan used their own Java simulator to simulate mobility models and the two Dijkstra algorithms as routing protocols. They did not use group mobility models. In our study, Reference Point Group Mobility Model has been taken as the representative of that type of protocols.

Researchers studying mobility models tend to apply their mobility model to one, or at most three routing protocols, which in most cases, do not capture the characteristics of the mobility model as well as the characteristic of the routing protocol. In this study, we have used three routing protocols (DSR, DSDV, and AODV) and considered one mobility model from each four major class mentioned in [42] as RWPM, GMM, MGM, and RPGM.

3.2 Classification of Routing Protocols Based on the Forwarding/ Messaging Property

A preliminary classification of the routing protocols can be done via the type of cast property, i.e., whether they use a

1. Unicast,
2. Multicast,
3. Broadcast,
4. Anycast forwarding.

Unicast forwarding means a one-to-one communication, i.e., one source transmits data packets to a single destination. This is the largest class of routing protocols found in ad hoc networks.

Multicast routing protocols come into play when a node needs to send the same message, or stream of data, to multiple destinations.

Broadcast is the basic mode of operation over a wireless channel; each message transmitted on a wireless channel is generally received by all neighbors located within one-hop from the sender. The simplest implementation of the broadcast operation to all network nodes is by naïve flooding, but this may cause the broadcast storm problem due to redundant re-broadcast.

Anycast routing protocols are used when a node needs to send a message, or stream of data, to a single destination in a group.

3.3 Classification of Routing Protocols Based on the Route Selection Property

Another major concern of routing protocols is whether the nodes in the ad-hoc network should keep track of routes to all possible destinations, or instead, keep track of only those destinations of immediate interest. A node in an ad hoc network does not need a route to a destination until that destination is to be the recipient of packets sent by the node, either as the actual source of the packet or as an intermediate node along a path from the source to the destination. There are three classes of ad hoc routing protocols proactive, reactive, and hybrid as shown in Figure 3.1.

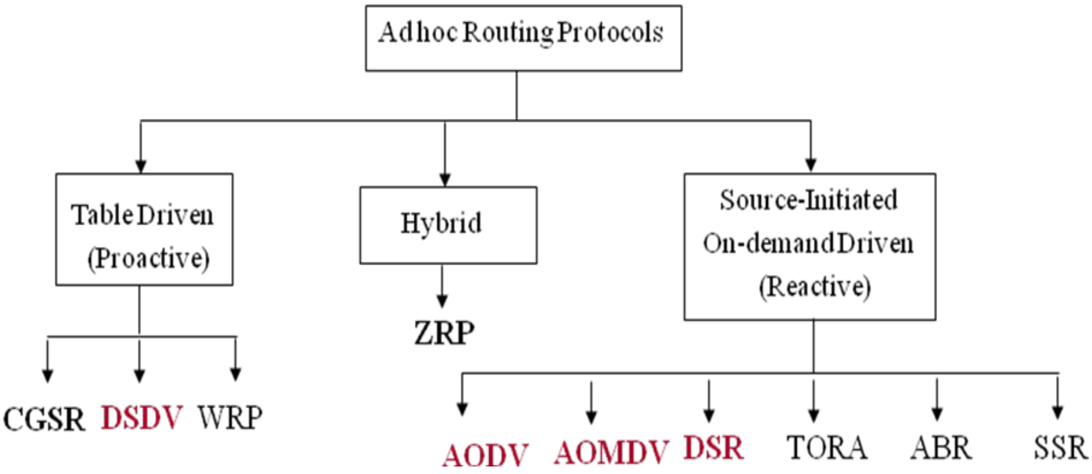

Figure 3.1. Routing protocols according the route selection property.

Proactive protocols or table-driven protocols keep track of routes for all destinations in the ad hoc network, as the routes can be assumed to exist in the form of tables. Proactive protocols have the advantage that communications with arbitrary destinations experience minimal initial delay from the point of view of the application. When the application starts, a route can be immediately selected from the route table. However, the disadvantage is that, additional control traffic is needed to continually update stale route entries. Unlike the Internet, an ad-hoc network contains numerous mobile nodes and therefore links are continuously broken and reestablished. If the broken route has to be repaired, even though no applications are using it, the repair effort can be considered wasted. This wasted effort can cause scarce bandwidth resources to be wasted and can cause further congestion at intermediate network points as the control packets occupy valuable queue space. Since control packets are often put at the head of the queue, the likely result will be data loss at congested network points. Data loss often translates to retransmission, delays, and further congestion.

Examples of proactive routing pProtocols include:

1- Destination-Sequenced Distance Vector (DSDV) [46]

2- Wireless Routing Protocol

3- Global State Routing

4- Fisheye State Routing

5- Hierarchical State Routing

6- Zone-based Hierarchical Link State Routing Protocol

7- Cluster head Gateway Switch Routing Protocol

In contrast, the reactive protocols acquire routing information only when it is actually needed. These protocols often use far less bandwidth for maintaining the route tables at each node, but the latency for many applications will drastically increase. Most applications are likely to suffer a long delay when they start because a route to the destination will have to be acquired before the communications can begin. Due to the high uncertainty in the position of the nodes, however, the reactive protocols are much suited and perform better for ad-hoc networks [47].

Examples of reactive routing protocols include:

1- Dynamic Source Routing (DSR) [47]

2- Ad-Hoc On-Demand Distance Vector Routing (AODV) [48, 49]

3- Ad-Hoc On-Demand Multipath Distance Vector Routing (AOMDV) [50, 51]

4- Temporally Ordered Routing Algorithm (TORA)

5- Associativity Based Routing

Since proactive and reactive routing protocols each work best in oppositely different scenarios, there is good reason to develop hybrid routing protocols, which use a mix of both proactive and reactive routing protocols. These hybrid protocols can be used to find a balance between the proactive and reactive protocols.

The basic idea behind hybrid routing protocols is to use proactive routing mechanisms in some areas of the network at certain times and reactive routing for the rest of the network. The proactive operations are restricted to a small domain in order to reduce the control overheads and delays. The reactive routing protocols are used for locating nodes outside this domain, as this is more bandwidth-efficient in a constantly changing network.

Examples of hybrid routing protocols include:

- Zone Routing Protocol (ZRP)
- Wireless Ad hoc Routing Protocol (WARP) - based on ZRP with additional enhancements for Quality of Service, or QoS support).

Again, since the medium in ad-hoc networks is common, simultaneous communication will collide. A suitable MAC layer protocol avoids the collision. The transmission of Unicast packet is preceded by a Request-to-Send/Clear-to-Send (RTS/CTS) exchange that reserves the channel for transmission of the data packets. When any packet is received correctly by the destination, this destination will send an acknowledgment (ACK) to the sender. During this time the originator will transmit the same packet a limited number of times until receiving the ACK from the destination. If the virtual and physical carrier senses indicate that the medium is clear then broadcast packets are sent. In this case they will not send a RTS/CTS and will not be acknowledged by the destinations. Routing protocols are used to set up and maintain the route between the source and destination by means of Route-Request/Route-reply (RREQ/RREP) packet exchange. Route-Error (RERR) packet is used to detect link/route failure.

3.4 Selected Routing Protocols

For the evaluation of the performance of the mobility models the following protocols are selected.

1- Dynamic Source Routing (DSR) [47]

2- Ad-Hoc On-Demand Distance Vector Routing (AODV) [48, 49]

3- Ad-Hoc On-Demand Multipath Distance Vector Routing (AOMDV) [50, 51]

4- Destination-Sequenced Distance Vector (DSDV) [46]

The DSR, AODV, and AOMDV are reactive routing protocols but DSDV is a proactive routing protocol.

These have been selected to be representative of the main classes in Figure 3.1 and most of the authors in the literature have been chosen these for their simulations. In this way, the comparison of our results be in consistant with protocols most of the authors found in this area.

3.4.1 Dynamic Source Routing (DSR)

The main feature of DSR [47] is the use of source routing. That is, the sender knows the complete hop-by-hop route to the destination. These routes are stored in a route cache. The data packets carry the source route in the packet header. When a node in the ad hoc network attempts to send a data packet to a destination for which it does not already know the route, it uses a route discovery process to dynamically determine such a route. Route discovery works by flooding the network with route request (RREQ) packets. Each node receiving an RREQ rebroadcasts it, unless it is the destination or it has a route to the destination in its route cache. Such a node replies to the RREQ with a route reply (RREP) packet that is routed back to the original source. RREQ and RREP packets are also source routed. The RREQ builds up the path traversed across the network. The RREP routes itself back to the source by traversing this path backward. The route carried back by the RREP packet is cached at the source for future use. If any link on a source route is broken, the source node is notified using a route error (RERR) packet. The source removes any route using this link from its cache. A new route discovery process must be initiated by the source if this route is still needed. DSR makes very aggressive use of source routing and route caching.

3.4.2 Ad-Hoc On-Demand Distance Vector Routing (AODV)

AODV [48,49] discovers routes on an as needed basis via a route discovery process similar to DSR. However, AODV adopts a very different mechanism to maintain routing information. It uses traditional routing tables, one entry per destination. This is in contrast to DSR, which can maintain multiple route cache entries for each destination. Without source routing, AODV relies on routing table entries to propagate an RREP back to the source and, subsequently, to route data packets to the destination. AODV uses sequence numbers maintained at each destination to determine freshness of routing information and to prevent routing loops. All routing packets carry these sequence numbers.

An important feature of AODV is the maintenance of timer-based states in each node, regarding utilization of individual routing table entries. A routing table entry is expired if not used recently. A set of predecessor nodes is maintained for each routing table entry, indicating the set of neighboring nodes which use that entry to route data packets. These nodes are notified with RERR packets when the next-hop link breaks. Each predecessor node, in turn, forwards the RERR to its own set of predecessors, thus effectively erasing all routes using the broken link. In contrast to DSR, RERR packets in AODV are intended to inform all sources using a link when a failure occurs. Route error propagation in AODV can be visualized conceptually as a tree whose root is the node at the point of failure and all sources using the failed link as the leaves.

3.4.3 Ad-Hoc On-Demand Multipath Distance Vector Routing (AOMDV)

Ad Hoc On-Demand Multipath Distance Vector Routing (AOMDV) [50,51] is based on a prominent and well-studied on-demand single path protocol known as ad hoc on-demand distance vector (AODV). AOMDV extends the AODV protocol to discover multiple paths between the source and the destination in every route discovery. Multiple paths computed, this was guaranteed to be loop-free and disjoint. AOMDV has three aspects compared to other on-demand multipath protocols. First, it does not have high inter-nodal coordination overheads like some other protocols. Second, it ensures disjointness of alternate routes via distributed computation without the use of source routing. Finally, AOMDV computes alternate paths with minimal additional overhead over AODV; it does this by exploiting already available alternate path routing information as much as possible.

3.4.4 Destination-Sequenced Distance Vector (DSDV)

The Destination-Sequenced Distance-Vector (DSDV) [46] Routing Algorithm is based on the idea of the classical Bellman-Ford Routing Algorithm with certain improvements. Every mobile station maintains a routing table that lists all available destinations, the number of hops to reach the destination and the sequence number assigned by the destination node. The sequence number is used to distinguish stale routes from new ones and thus avoid the formation of loops. The stations periodically transmit their routing tables to their immediate neighbors. A station also transmits its routing table if a significant change has occurred in its table from the last update sent. So, the update is both time-driven and event-driven.

The routing table updates can be sent in two ways: a “full dump” or an incremental update. A full dump sends the full routing table to the neighbors and could span many packets whereas in an incremental update only those entries from the routing table are sent that has a metric change since the last update and it must fit in a packet. If there is space in the incremental update packet then those entries may be included whose sequence number has changed. When the network is relatively stable, incremental updates are sent to avoid extra traffic and full dumps are relatively infrequent. In a fast-changing network, incremental packets can grow big so full dumps will be more frequent.

Chapter 4

CLASSIFICATION OF MOBILITY MODELS

4.1 Previous Works

A variety of mobility models have been studied by both simulation and analytical analysis in literature. The most common homogeneous mobility models are the Random Walk Mobility Model [52] and Random Waypoint Mobility Model [55]. A good survey of ad hoc mobility models like the random direction model, the random Gauss-Markov model, and the Brownian walk can be found in [13, 52]. Hyytia et al. [53] state an expression that represents the nodes' position distribution of Random Waypoint in an arbitrary convex domain and propose a modified Random Waypoint model that forms comparable distribution with Random Waypoint. Nevertheless, works such as the one described by Yoon et al. [54] state that "random waypoint is considered harmful", because it does not give a uniform distribution of nodes in a simulation environment. This in turn affects the connectivity graph on which the assessments of the simulated MANET protocols depend.

A great deal of attention has been paid towards finding out a realistic mobility model for MANETs and the performance of ad hoc protocols under these mobility models. Such examples include [56-58]. In [56], the Obstacle Mobility Model simulates real world topographies with obstacles and pathways. It is also designed to model very specific scenarios and incorporates the propagation of radio signals according to the obstacles placed. In [56], pathways were constructed by using a Voronoi diagram of the vertices of polygonal obstacles. In this last model, the mobility model considers a simple mobility restricted on the created Voronoi graph.

Stepanov et al. [59] proposed the graph-walk mobility model similarly to the random waypoint model with the difference that in their model, the movement is restricted on a graph. After the graph-walk model, Stepanov et al. [59] developed the CANUMobisim framework [60], a powerful realistic mobility trace generator. The Graph-based Mobility Model [59] maps the topology of a scenario by using a graph to define the motion of the nodes, but it does not consider clusters with different topologies and densities.

Hollick et al. [61] proposed a macroscopic mobility model for wireless metropolitan area networks, where a simulation field is divided into multiple zones with different attributes such as workplace, commercial and recreation zones. Also, each MN has an attribute: resident, worker, consumer or student. Given trips with destinations for user nodes, an existing urban transportation planning technique is used to estimate the user density in each zone.

Many realistic mobility models including our proposed methodology have intended to model the environment in the real world. Our proposed methodology is closest to the work presented in [61-63], which tries to reproduce the real-world’s geography and movement of nodes. In [63], five clusters are used for the terrains. They include types of nodes such as pedestrians, automobiles, and static nodes. The number of each kind of node is different and it is determined according to real data. Each cluster has a predefined activity area, speed range, pause time range, capacity and weights for each purpose. In the design of our proposed methodology, there is no limit on the number of clusters, and each cluster has it own speed range.

4.2 Selected Mobility Models

In this section, selected mobility models will be explained briefly.

4.2.1 Random Waypoint Mobility Model (RWPM)

In RWPM [65], the nodes are distributed uniformly all over the simulation area Figure 4.1. Then each node chooses a random destination and starts to mode to it with a speed uniformly distributed over [Vmin, Vmax]. On reaching the destination, the nodes pauses for a specified period of time, then it chooses another speed and direction to move to. The properties of the random waypoint model have been extensively studied [66, 67, 68, and 69].

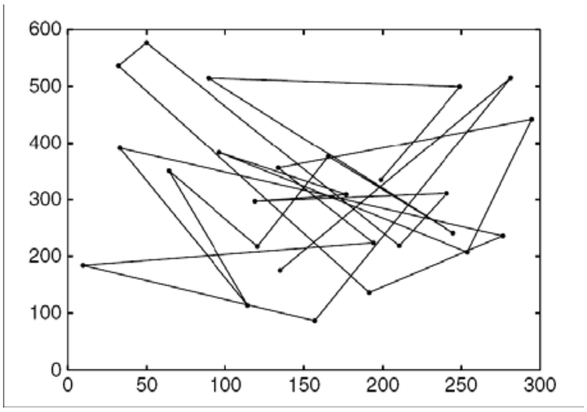

Figure 4.1. Random waypoint mobility model: example [73]

The poor choice of velocity distribution [73] will lead to a situation where each node stops moving when network reach a stationary state. Also from the previous studies mentioned above, the nodes tend to congregate in the center of the simulation area, resulting in a non-uniform network density, because the nodes tend to follow a cyclic pattern during the lifetime of he network.

4.2.2 Reference Point Group mobility Model (RPGM)

In [70], Hong et al. described the RPGM. The nodes in the simulated area constitute a number of groups. Each node in a group follows its group leader. The different nodes use their own mobility model and are added to the reference point which drives them in the diection of the group as shown in Figure 4.2. During simulation, each node has a speed and direction that is derived by randomly deviating from that of the group leader.

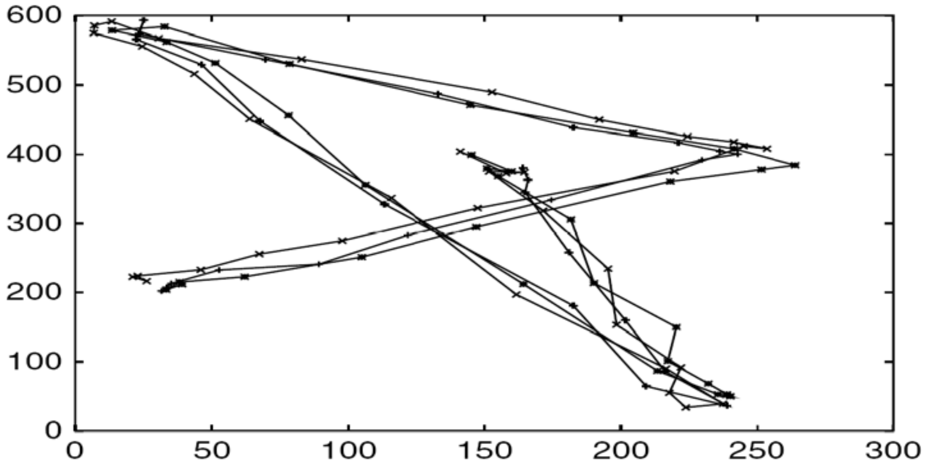

Figure 4.2. Reference point group mobility model: example [73]

4.2.3 Gauss Markov Mobility Model (GM)

In GM [71] model the speed and direction at any time (t) depends on the previous step in time (t – 1). Initially for each node position, speed and direction are chosen uniformly distributed. The movement of each node is variated after an interval Δt. The new values are chosen based on a first-order autoregressive process. See [27] for detailed information on this process. An example of the Guass Morkov mobility model is shown in Figure 4.3.

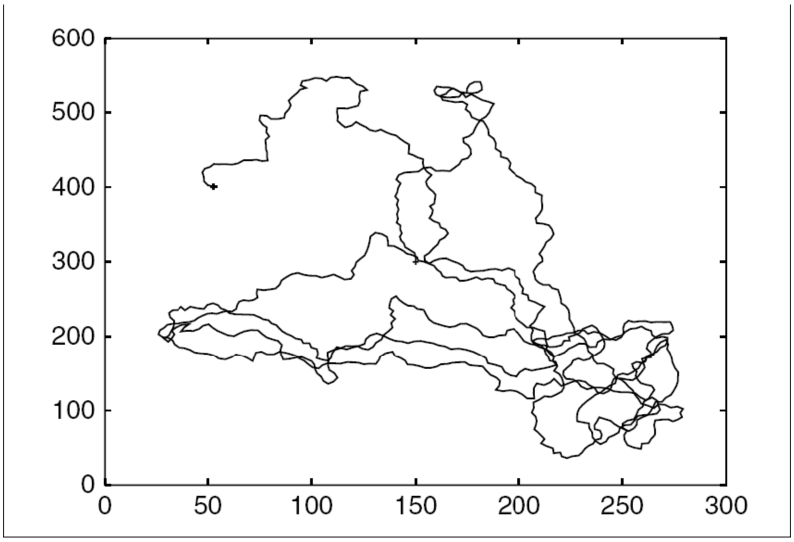

Figure 4.3. Gauss-Markov mobility model: example [73]

4.2.4 Manhattan Grid Mobility Model (MGM)

The simulation area in Manhattan Grid Mobility Model [72] is divided into vertical and horizontal lines that represent streets on a city or urban map. So, each node is allowed to move in one of these directions (horizontal or vertical) as shown in Figure 4.4. When a node arrives at an intersection, it can turn left, right or straight ahead. A probability is assigned for each case, the probability of turning right is 0.25, turning left is 0.25 and going straight ahead on the same street is 0.5. The speed of the node depends on and restricted by the speed on the node in front of it, which is moving in the same lane. Also its speed at any instance of the time depends on the previous instance of time.

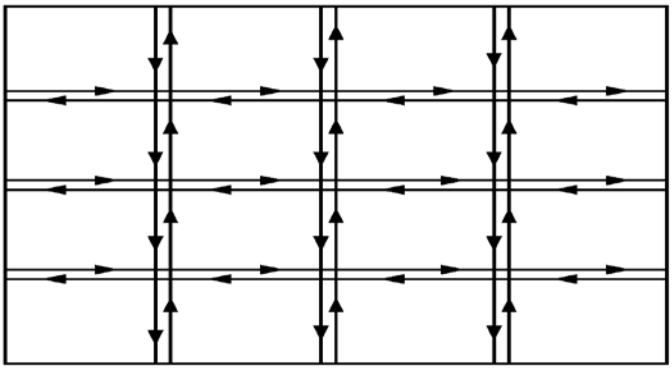

Figure 4.4. Manhattan Grid Mobility Model: example [73]

Chapter 5

LOCATION-BASED CLUSTER MOBILITY MODEL (LBCM)

5.1 Motivation

An ad hoc network is formed of a number of stand alone hosts which are termed as mobile nodes. Each mobile node covers a small geographical area which is part of a uniquely identified cluster. By integrating the coverage of each of these mobile nodes, a wireless ad hoc network provides radio coverage over a much wider area. Nodes are always on the move and may stop at any moment for some duration.

Many researchers try to configure, understand, analyze, and simulate these unpredicted movements of nodes. As a consequence, many mobility models are used to simulate the performance of mobile wireless systems [74]. The challenge is to develop a realistic mobility model that emulates the real movement of a specific application. Each mobile application has its own characteristics (humans, cars, buses, animals, etc.). These characteristics depend on location and time. If we take the human's case, from the time of waking up in the morning, till sleeping at night, the x and y coordinates of a person changes, as the time changes.

The most widely used mobility models are based on random individual movement. The simplest one is the Random Walk mobility model (equivalent to Brownian motion). It is used to represent purely random movements of the entities of a system.

However, with empirical observations one can see that the random mobility models generate behavior that is most un-human-like.

Some researchers tried to develop mobility models with human-like mobility, but with some extra assumptions [53]. Others modeled the behavior of individuals moving in groups and between groups. Clustering is used in the typical ad hoc networking deployment scenarios of disaster relief teams, platoons of soldiers, groups of vehicles, etc.

In this work, a new mobility model, which we claim is more realistic than the previously proposed models, has been developed and investigated using a number of well known performance metrics. This new model can generate some of our daily movement behaviors. The movements of the mobile node have to be consistent with its position. The movement of the node is different when it is in a park than when it is inside a car in a highway as an example. So, the nodes within clusters have to be configured accordingly.

5.2 LBCM Design

In this section, the design of the proposed mobility model is described in detail. Firstly, the position of the mobile node is modeled according to spatial components and temporal components. In LBCM spatial components the nodes is distributed to the clusters. These mobile nodes will start moving according to the temporal components associated to each mobile node. Secondly, the construction of the model is done, and the related specifications are discussed. Thirdly, an algorithm, which is the basis of the mobile node movements, is described. Finally, the performance of the mobility model is investigated according to the performance metrics specified.

5.2.1 LBCM Construction

The pictorial view of a representation of a simulation area can be as the following:

Figure 5.1. Typical city section.

Figure 5.2. Small area in a city section.

Looking in detail in this representative city section Figure 5.1, it can be observed that the movement is mostly in straight long lines. These straight lines are perpendicular to each other. So, many will argue that one has to use the Manhattan Grid mobility model only, for the representations. However, it is impossible to generalize the Manhattan Grid mobility model to all city clusters. This is because we have parks where children can play freely with their parents also we have big schools that have playgrounds with students and teachers. The same will be applied to students at a university and so on for any person that may have a mobile node with him.

Considering a small area of a city in Figure 5.2, it’s perceptible that every so often, a person can go straight, with a curve, with different angles, and can even move in a Brownian motion, which depends on the position and time. Examples for these clusters are students in a school, families in a park, workers in a factory, or people in a hospital.

A realistic mobility model like that acquires all movement possibilities is inevitable. The coordinates of the clusters should be an important parameter of the LBCM model.

Each cluster of the city has its own characteristics, and it should be modeled separately. In our case, many mobility models (depending on the locations) can be used in the simulation. So, LBCM is a merge of some mobility models. Manhattan Grid mobility model can be employed for the coordinates that specify the highways and streets with a vehicle’s speed. The Random Point Group mobility model can be manipulated for clusters like a museum, with people considered to walk with an average walking speed. The Random Waypoint mobility model can be employed on a childrens on the parks. Whereas, the Guass Markov mobility model can be manipulated on the players on the stadiums as they change their directions so often. In addition, GMM can be used in the schools where students take their breaks. Hence, our proposed model can cover all these locations with its accurate coordinates and velocities.

5.2.2 Positions as Input

In this model, the geographic representation of the simulated clusters, such as buildings, street, markets, highways, parks, etc., are determined as shown in Figure 5.3. Each geographic cluster should have a dimension. According to these dimensions, the behavior of the mobile nodes in the mobility model can be specified. In the Figure, A means an open area, B means a street, C means a building, D means a museum, and H means a high way.

A mobile node has its own private mobility model in each one of these clusters. Depending on its cluster, the node is assigned a different speed. Hence, the state of the mobile node must be analyzed according to the spatial components and temporal components assigned to it.

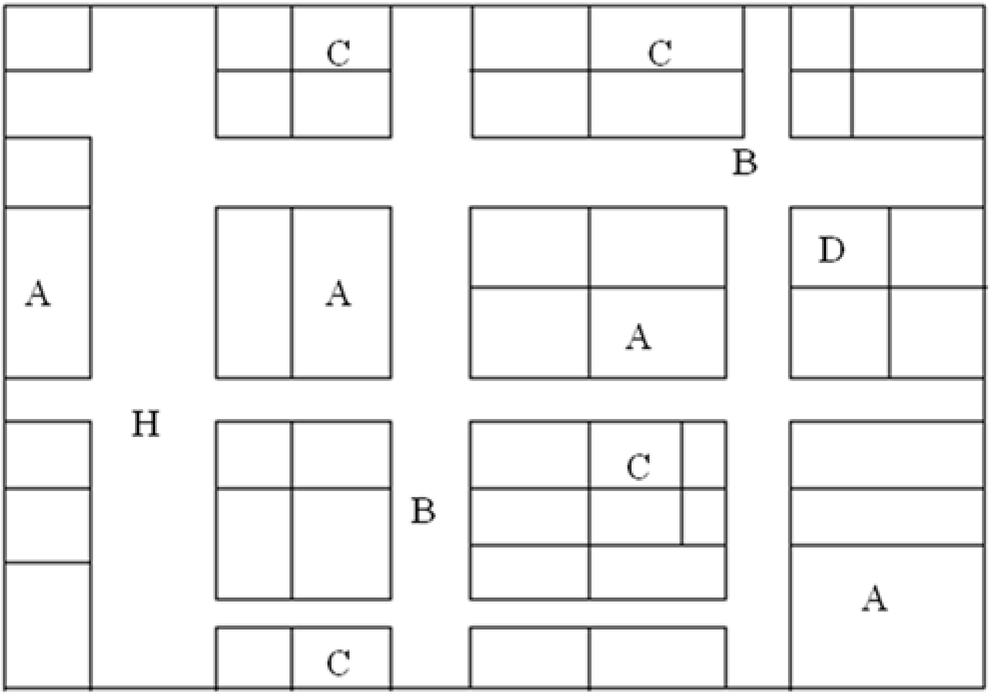

Figure 5.3. Cluster representation of the simulated area

5.3 LBCM Architecture

In the LBCM model, node’s environment patterns and movement patterns are considered. Naturally, different nodes have different mobility specifications. For example, in a museum environment, mobile nodes move in groups with a walking speed whereas mobiles nodes in a car move with a car speed.

In constructing the architecture of LBCM the following assumptions have been made.

1- The speed in each cluster will be different from others. For example speed in the building clusters will be different from the speed of the highway clusters.
2- Each cluster has a different capacity. For example, the maximum number of mobile nodes in a park area will be different from those in a school section.
3- Mobile nodes will have different pause times when arriving to destinations, according to the cluster the mobile node is currently in.

4- The path selection method for mobile nodes is different. For instance, walking mobiles prefer shortcuts whereas mobiles in cars prefer sparser paths even if it takes more time to travel.

In the proposed model, initially, each node will be distributed to a cluster according to a normal distribution. So, each node will behave according to the mobility configuration of the cluster. Figure 5.4. shows the UML activity diagram of the operation in the LBCM model.

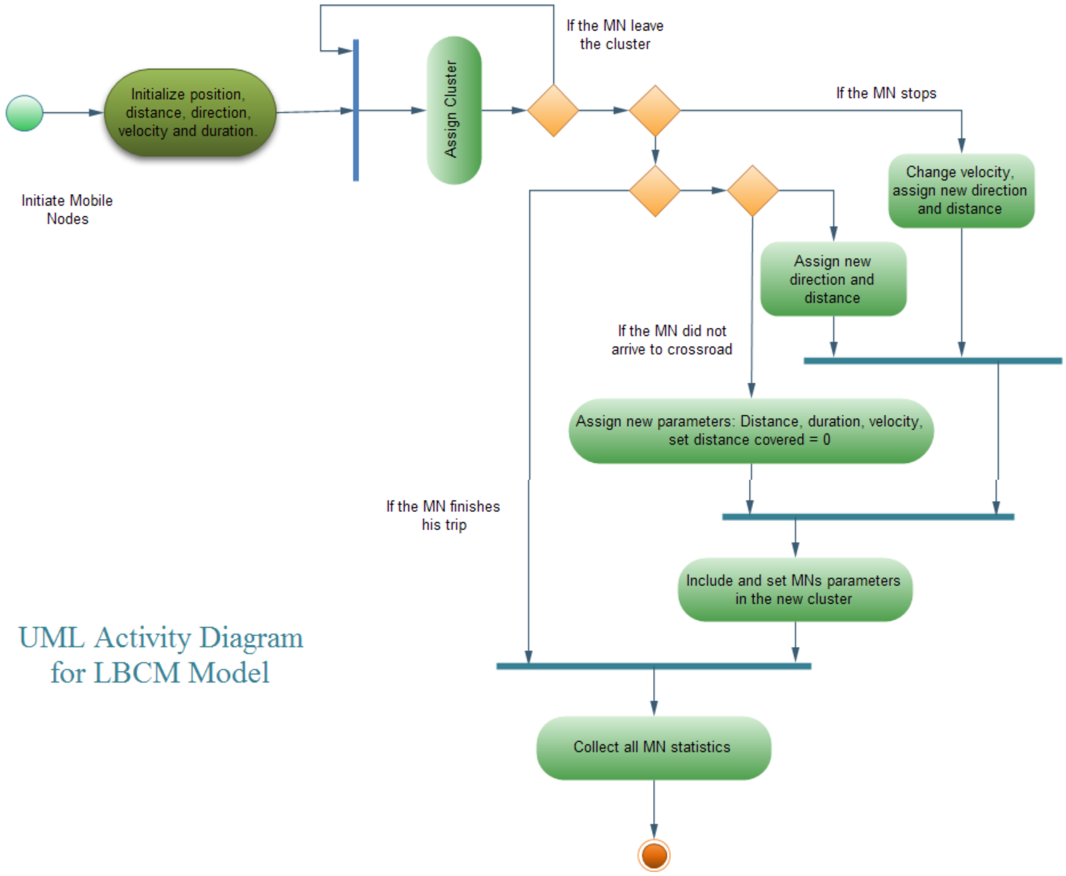

Figure 5.4. UML activity diagram of the LBCM model

The worst-case time complexity of an algorithm is expressed as a function

$$T : N \rightarrow N$$

where T(n) is the maximum number of “steps” in any execution of the algorithm on inputs of “size” n. Intuitively, the amount of time an algorithm takes depends on how large is the input on which the algorithm must operate: Sorting large lists takes longer than sorting short lists; multiplying huge matrices takes longer than multiplying small ones. The dependence of the time needed to the size of the input is not necessarily linear: sorting twice the number of elements takes quite a bit more than just twice as much time; searching (using binary search) through a sorted list twice as long, takes a lot less than twice as much time [71].

The time complexity function expresses that dependence. Note that an algorithm might take different amounts of time on inputs of the same size. We have defined the worst-case time complexity, which means that we count the maximum number of steps that any input of a particular size could take.

In order to have an idea of how our algorithm performs, we have to measure the cost of the algorithm using the time complexity. From Figure 5.4 we have the following:

```
c1 * |node| + 1.
{
    c2 * |node|
    c3 * |node|
    c4 * |node|
    c5 * |node|
    c6 * |node|
```

```
    c7 * |node|
    c8 * |node|
    c9 * |node|
    c10 * |node| * |node|
}
```

From that we can write the following equation

$$T(n) = c1 * |node| + 1 + c2 * |node| + c3 * |node| + c4 * |node| + c5 * |node| + c6 * |node| + c7 * |node| + c8 * |node| + c9 * |node| + c10 * |node| * |node| \tag{5.1}$$

From equation 2.1, we can write it in the following manner

$$T(n) = C * |node| * |node| \text{ , where C is a constant} \tag{5.2}$$

So, the general case (worst) of the time complexity of our algorithm as the following

$$\text{So General case is } T(n) = O(|node|^2) \tag{5.3}$$

Chapter 6

SIMULATION ENVIRONMENT SETUP

In the second part of this study, we have implemented a detailed simulation model and used the simulation program ns-2 (version 2.34) in the evaluation of routing protocols and mobility models. We also made use of support for simulating multi-hop wireless networks, complete with physical layer, and medium access control (MAC) layer models on ns-2 [75] developed by the Monarch research group at Carnegie-Mellon University (CMU).

6.1 Simulation Model for Wireless LAN in ns-2

The Distributed Coordination Function (DCF) of IEEE 802.11 for wireless LANs is used as the MAC layer protocol. A Carrier Sense Multiple Access (CSMA) technique with Collision Avoidance (CSMA/CA) is used to transmit the data packets. The radio model uses characteristics similar to a commercial radio interface, Lucent's WaveLAN. WaveLAN is modeled as a shared-media radio with a nominal packet rate of 2 packets/s and a nominal radio range of 250m.

The simulated protocol maintains a send buffer of 64 packets. This buffer contains all data packets waiting for a route, such as packets for which route discovery has started, but no reply has arrived yet. To prevent buffering of packets indefinitely, packets are dropped if they wait in the send buffer for more than 30 seconds. All packets (both data and routing) sent by the routing layer are queued at the interface queue of MAC layer until the MAC layer can transmit them (Figure 6.1), DSR is one example. The interface queue has a maximum size of 50 packets and is maintained as a priority queue with two priorities, each priority level served in FIFO order. Routing packets get higher priority than data packets.

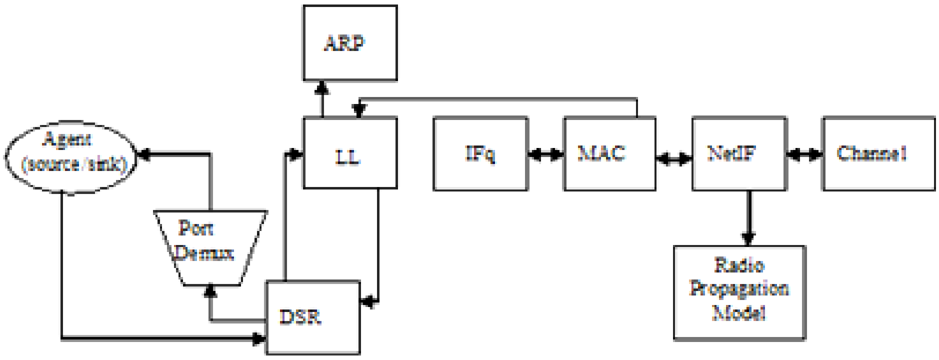

Figure 6.1. Simulating DSR routing protocol.

The network simulator (ns-2) implements several propagation models, Free Space, Two Ray Ground, and Shadowing to predict the signal power received by the receiver. The signal strength is used to determine whether the frame is transmitted successfully. The Free Space model is used to simulate path loss of wireless communication when line-of-sight path exists between transmitter and receiver. The Two Ray Ground model is used when line-of-sight path exists and reflection of ground is considered. The Shadowing model simulates shadow effect of obstructions between the transmitter and receiver. It is mainly used to simulate a wireless channel in in-door environment.

The simulator uses thresholds to determine whether one frame is received correctly by the receiver. ns-2 sets one signal strength threshold (CSThresh_) [75] to determine whether a frame is detected by the receiver. If the signal strength of the frame is less than CSThresh_, this frame is discarded in PHY (Physical layer) module and will not be visible to MAC layer. It has another threshold (RxThresh_) for the signal strength of one frame received by the receiver. If a frame is received and received signal strength is stronger than RxThresh_, the frame is received correctly. Otherwise, the frame is tagged as corrupted and the MAC layer will discard it. In this study, the parameters in Table 1 are used to simulate a 802.11b channel in ns-2.

6.2 The Traffic and Mobility Models for Wireless LANs

The source-destination pairs are considered to be distributed randomly over the network. Constant Bit Rate (CBR) traffic sources are considered in the simulations. Only 512-byte data packets are used in all simulations. The number of source-destination pairs and the packet sending rate in each pair can be varied to change the offered load in the network. The main configuration parameters that are used in the simulation are given in Table 6.2. The joint parameters are kept the same in all models. This is to create similar simulation situations in all considered cases.

One of the parameters used for the RWPM model is the minimum speed which is equal to 0.5 m/s. The nodes move along the x and y directions only. In the RPGM model, the average number of nodes per group is 3, the group change probability is 0.01 and the maximum distance to group center is 2.5m. The minimum speed is 0.5 m/s.

Table 6.1 Parameters used to simulate 802.11b channel in ns-2.

Item	**Value**	**Explanation**
The antenna height of transmitter and receiver	1.5m	
The propagation model	TwoRayGround model	
Antenna/OmniAntenna	set Gt_ 1	Transmit antenna gain
Antenna/OmniAntenna	set Gr_ 1	Receive antenna gain
Phy/WirelessPhy	set L_ 1.0	System loss factor
Phy/WirelessPhy	set freq_ 2.472e9	channel-13. 2.472GHz
Phy/WirelessPhy	set bandwidth_ 11Mb	Data rate
Phy/WirelessPhy	set Pt_ 0.031622777	Transmit power
Phy/WirelessPhy	set CPThresh_ 10.0	Collision threshold
Phy/WirelessPhy	set CSThresh_ 5.011872e-12	Carrier sense power
Phy/WirelessPhy	set RXThresh_ 5.82587e-09	Receive power threshold; calculated under TwoRayGround model by tools from ns2
*Mac/802_11	set dataRate_ 11Mb	Rate for data frames
*Mac/802_11	set basicRate_ 1Mb	Rate for control frames

In configuring the MGM model, the number of blocks along x and y axis is 10, the minimum speed is 0.5 m/s, and the mean speed is 1.0 m/s. The speed standard deviation is 0.2, speed change probability is 0.2 and by default nodes goes straight and the turn left or right probability is 0.5. The value of parameters used in the GMM model are 0.5 m/s, 0.4 and 2.5 for the speed, angle standard deviation and speed update frequency respectively.

Table 6.2. General configuration parameters for the mobility models used.

Parameter	**Values**
Number of nodes	varies from 10 to 100
X coordinate	1000 m
Y coordinate	1000 m
Simulation interval	1000 s
Number of seconds to skip	500 s
Maximum speed (slow motion)	1.5 m/s
Maximum pause time	60 s
Traffic sources	CBR
Data Packet size	512 bytes
Routing Packet size	32 bytes
Packet sending rate	2 packets/s
Maximum Transmission range	250 m
Number of traffic pairs	10

6.3 Generation of Traffic and Mobility Models

In order for ns-2 to simulate the wireless mobile nodes, the traffic properties and the movement of the nodes have to be supplied. Instructions of ns-2 can be used to define the topology structure of the network and the motion mode of the nodes, to configure the service source and the receiver, and to create the statistical data track file.

Random traffic connections of CBR were set up between mobile nodes using a traffic-scenario generator script. This traffic generator script is available under ~ns/indep-utils/cmu-scen-gen and is called cbrgen.tcl. It was used to create CBR traffic connections between wireless mobile nodes.

The node-movement generator is available under the ~ns/indep-utils/cmu-scen-gen/setdest directory and consists of setdest{.cc,.h} and a makefile.

The node-movement generator mentioned above, that comes with ns-2, is for the RWPM model only. Our simulations were carried out with more complex scenarios, so, the BonnMotion Generator [76] is used to generate the node movement scenarios for other mobility models, which are the RPGM model, the GMM model, and the MGM model. To have fair results, the movement for the RWPM model was also generated by the BonnMotion Generator.

6.4 Performance Metrics

The popular performance metrics, delivery ratio, average end-to-end delay, routing overhead are used to evaluate the efficiency and effectiveness of ad hoc networks. These performance metrics that can be used to quantitatively assess MANET routing protocols are discussed below.

In the simulations, the calculation of the delivery ratio is expressed as,

$$Delivery\ ratio\ \% = \frac{Packet_{recv}}{Packet_{snd}} \times 100 \tag{6.1}$$

where Packetrev is the total number of received packets at destination nodes and Packetsnd is the total number of packets sent by source nodes during a simulation. This metric defines the delivery rate experienced by the application data and is related to the data throughput of the network.

The end-to-end delay is measured as the time delay between sending a packet from the source node to the destination node. This metric describes the packet delivery time: the lower the end-to-end delay, the better is the application performance.

Once the time difference between every received and sent packet is recorded, dividing the total time difference over the total number of packets received at destination nodes provides the average end-to-end delay for all received packets.

$$Average\ end-to-end\ delay = \frac{\sum_{1}^{n} \left(Packet_{recvTime} - Packet_{sndTime} \right)}{\sum_{1}^{n} Packet_{recv}} \tag{6.2}$$

where PacketrecvTime is the time the packet is received at the destination node and PacketsndTime is the time, the packet was sent from the source node.

The bandwidth consumed by all the control packets of the routing protocol is defined as the routing overhead. This quantity helps to determine the scalability of a given routing protocol. A lower control packet overhead with a higher throughput is a much desired optimization in MANETs. The routing overhead can be computed as:

$$Routing\ overhead = \frac{Number\ of\ routing\ packets\ sent}{Number\ of\ data\ Packets\ received} \tag{6.3}$$

The number of nodes a packet traverses to reach from the source node to the destination node is the number of hops for the packet. This quantity helps to determine the path optimality of a given routing protocol.

The sum of path hop count taken by each packet over the total number of received packets at destination nodes provides the average number of hops.

$$Average\ number\ of\ \ hops = \frac{\sum_{1}^{n} Packet_{hopcnt}}{Packet_{recv}} \tag{6.4}$$

where Packethopcnt is the number of hops for a packet from the source node to the destination node.

A Framework for analyzing the network performance was constructed as shown in Figure 6.2 to have a clear idea of what is needed in our studies.

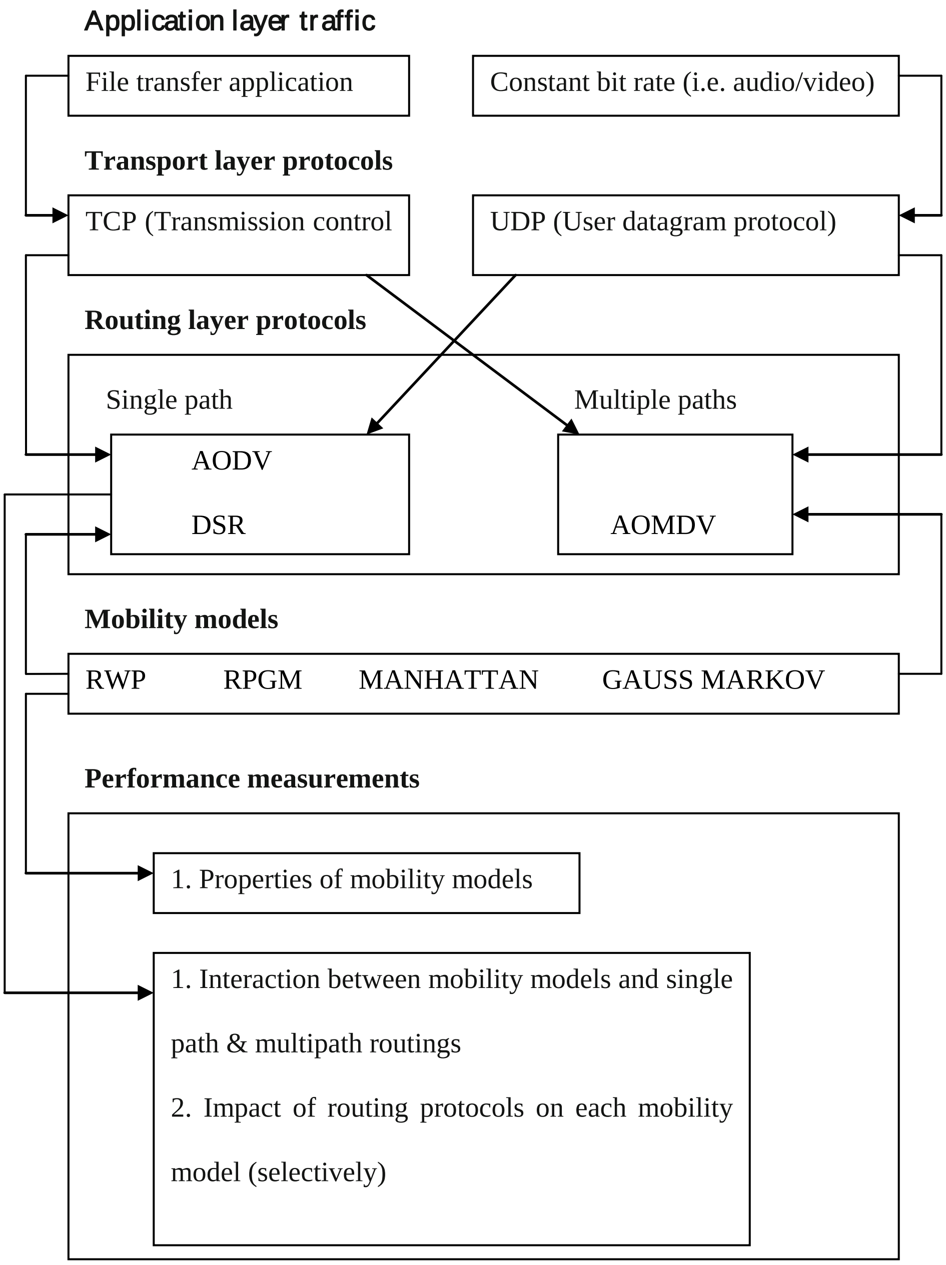

Figure 6.2 Framework for analyzing network performance.

Chapter 7

SIMULATION RESULTS

In this chapter, the performance of the DSR, DSDV, and AODV routing protocols are evaluated and compared under different mobility models. In addition, the performance of LBCM against other mobility models is evaluated using the AOMDV routing protocol.

7.1 Influence of Mobility Models on Routing Protocols

The influences of mobility models on routing protocols have been investigated in detail. In this context, the performance metrics, including delivery ratio, average end-to-end delay, and routing overhead are compared separately to have a detailed picture of how each protocol behaves under each mobility model. As a result, we can have an understanding of which routing protocol is most suitable under various conditions.

7.1.1 Delivery Ratio

A group of experiments were conducted to investigate the dependence of delivery ratio on number of nodes varied in the range 10 up to 100. Four different mobility models, GMM model, MGM model, RPGM model and RWPM model with four routing protocols, DSR, DSDV, AODV, and AOMDV were used. The delivery ratio versus number of nodes results are presented in Figures 7.1a, 7.1b, 7.1c and 7.1d.

Considering Figure 7.1a and 7.1b the GMM model and MGM delivers more than 60% of the packets when the number of nodes is 30. As the number of nodes increases, the delivery ratio also increases.

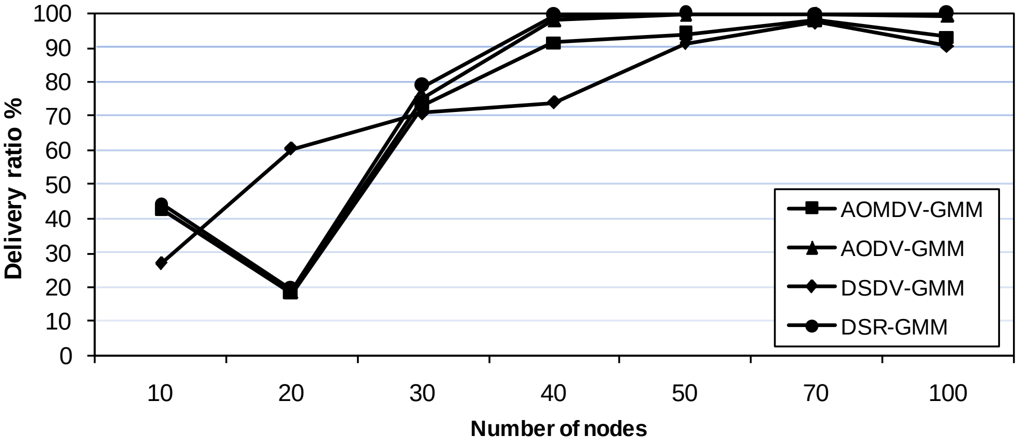

Figure 7.1a. Delivery ratio versus routing protocols with GMM model

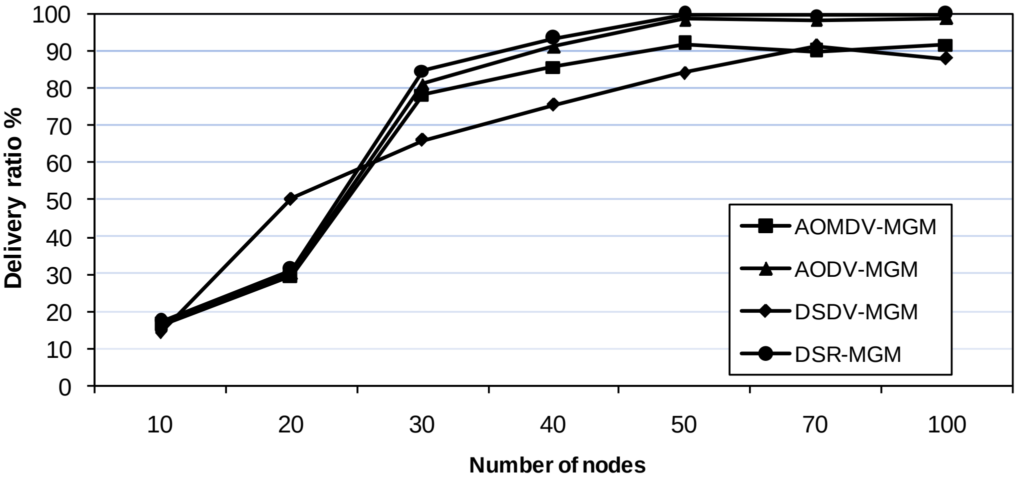

Figure 7.1b. Delivery ratio versus routing protocols with MGM model

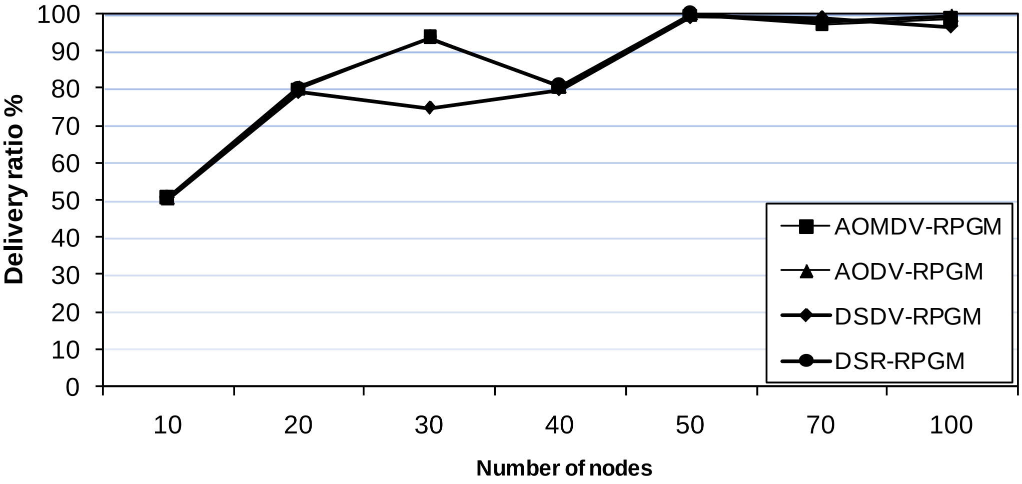

Figure 7.1c. Delivery ratio versus routing protocols with RPGM model

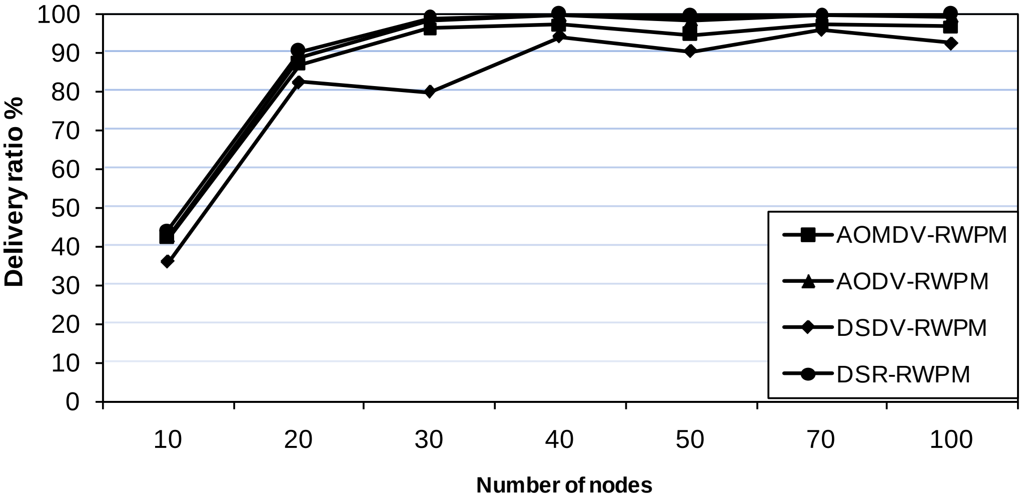

Figure 7.1d. Delivery ratio versus routing protocols with RWPM model

From the graphs of these mobility models, it may be noted that the best ratio is obtained by the RWPM. In Figure 7.1d, two protocols delivered 90% of the packets when the number of nodes is 20 and above. The same for the AOMDV protocol. However, the DSDV protocol delivered 90% of the packets, when the number of nodes is 40.

Another noticeable point in Figure 7.1c is that, in case of the RPG mobility model, all protocols deliver more than 98% of the packets for more than 50 nodes.

Wireless ad hoc networks establish autonomous networks and can be easily built without any infrastructure. Therefore, to deliver most of the data packets requires no concern for delay or routing overhead. With the RWPM model the DSR routing protocol is the best choice considering delivery ratio (Figure 7.1d).

Considering the packet delivery ratio in [10] Mittal and Pinki have done their simulations over 30 seconds, which is a very short time. When the simulation time is increasing, the trace file produced by ns-2 takes a considerable amount of storage space. In our work, for some cases, for one simulation time only, the trace file required more than one terabyte (TB) of storage space.

In other studies, there was no consideration for the stability of the system. In our work we have started the simulation and then collected results after 500 seconds. In addition to that, the speed of the nodes was taken as 100m/s in [10], which is not logical to consider that for a mobile node all the time. The results we obtained were more logical as we have considered other mobility models like MGM model, GMM model, and RPGM model in addition to the RWPM model.

7.1.2 Average End-to-End Delay

Figures 7.2a, 7.2b, 7.2c and 7.2d demonstrate the dependence of average end-to-end delay on the number of nodes with different routing protocols and mobility models. As graphs show, the average end-to-end delay is quite low in DSDV routing protocol with all mobility models, but it shows different characteristics from one mobility model to another. The RPGM model produces the lowest average end-to-end delay.

As a result, to send packets as quickly as possible, the use of RPGM model with DSR routing protocol can be a good alternative. This is obvious when using the AOMDV routing protocol.

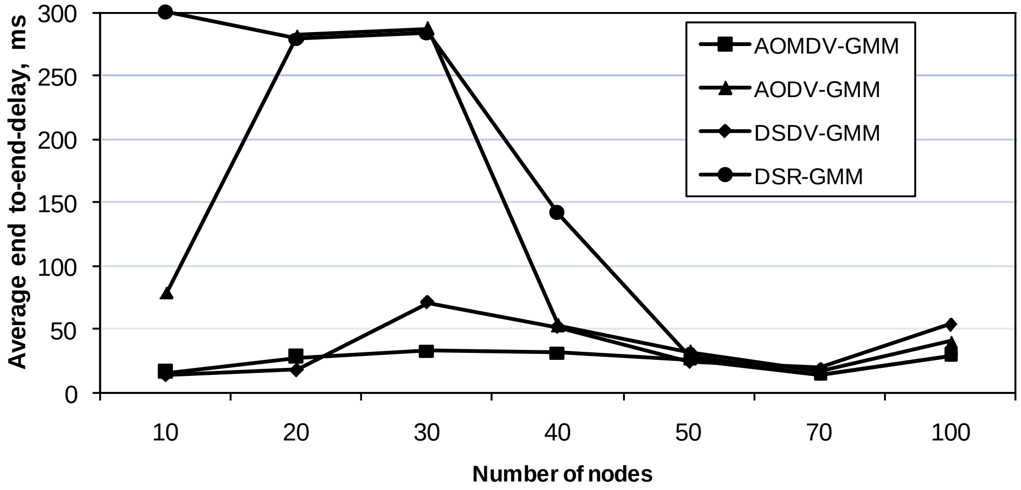

Figure 7.2a. Average end-to-end delay versus routing protocols with GMM model

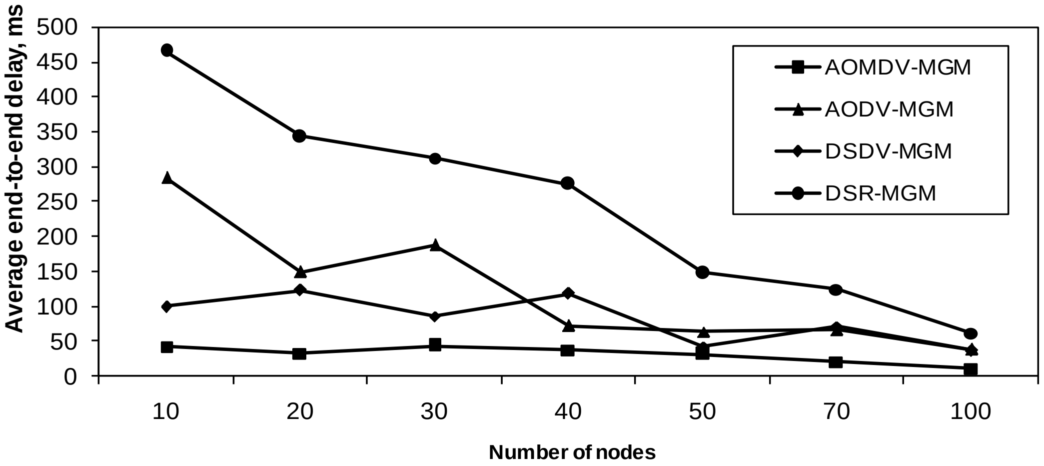

Figure 7.2b. Average end-to-end delay versus routing protocols with MGM model

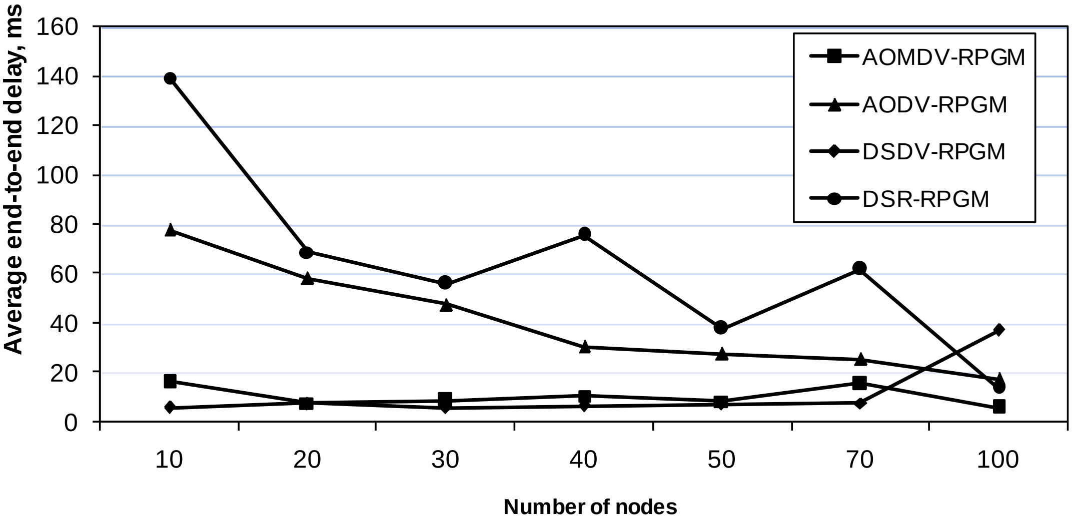

Figure 7.2c. Average end-to-end delay versus routing protocols with RPGM model

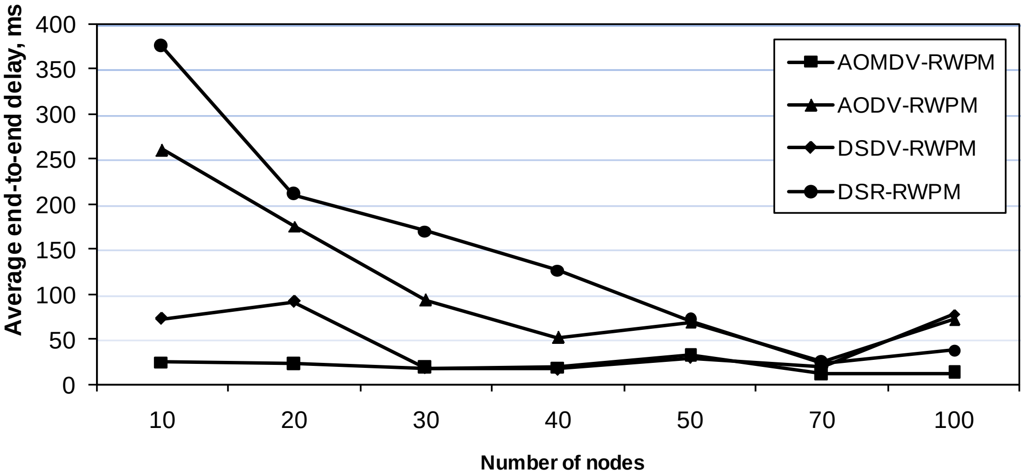

Figure 7.2d. Average end-to-end delay versus routing protocols with RWPM model

7.1.3 Routing Overhead

Figures 7.3a, 7.3b, 7.3c and 7.3d shows the performance metric "routing overhead" with respect to the number of nodes, using mobility models with different routing protocols. Routing overhead is the ratio of the number of control packets propagated by every node in the network to the number of data packets received by the destination nodes. Figure 7.3 indicates that the routing protocol (AODV) produces more control packets, as the production of disjoint paths requires such control packets. This is the case in all mobility models investigated. The MGM model produces the highest routing overhead with low and high dense ad hoc wireless networks specially with AOMDV routing protocol.

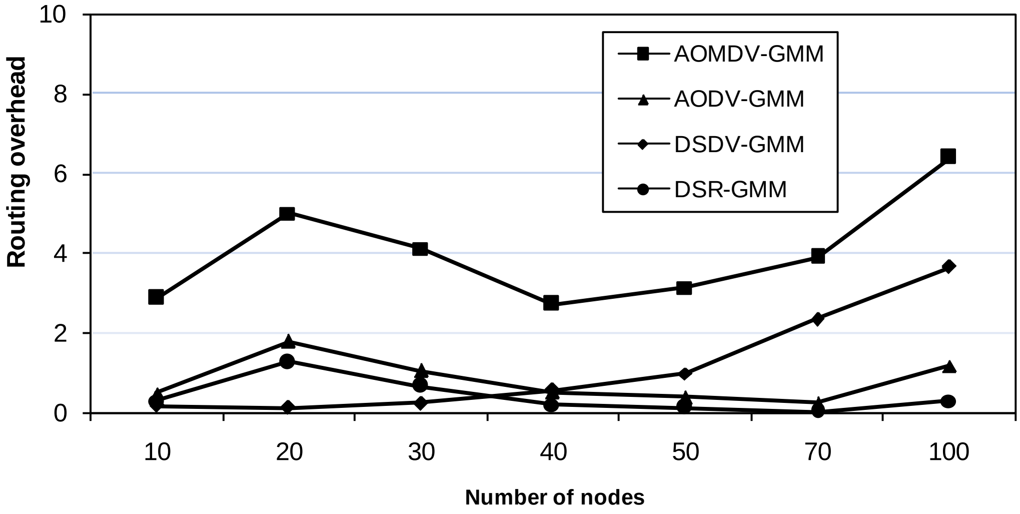

Figure 7.3a. Routing overhead versus routing protocols with GMM model

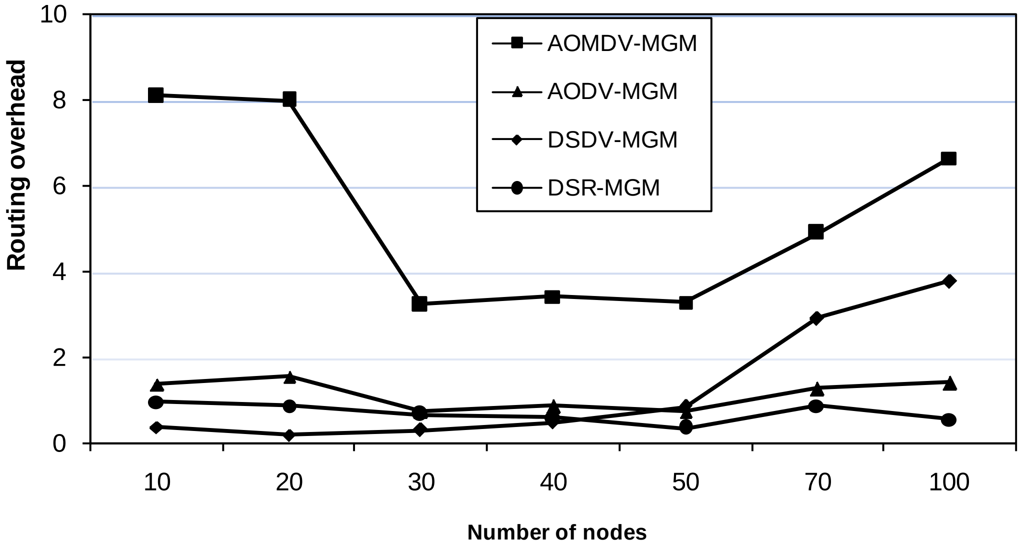

Figure 7.3b. Routing overhead versus routing protocols with MGM model

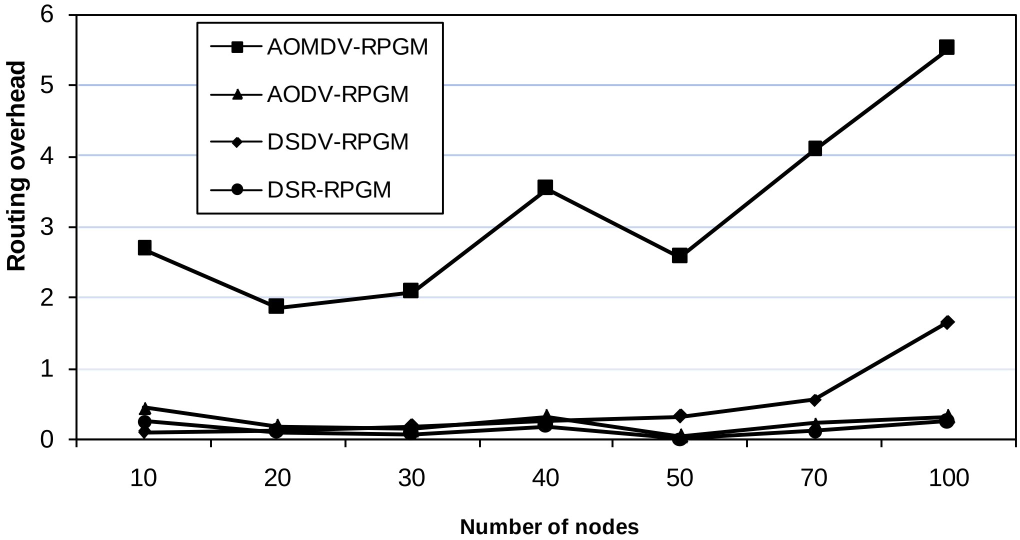

Figure 7.3c. Routing overhead versus routing protocols with RPGM model

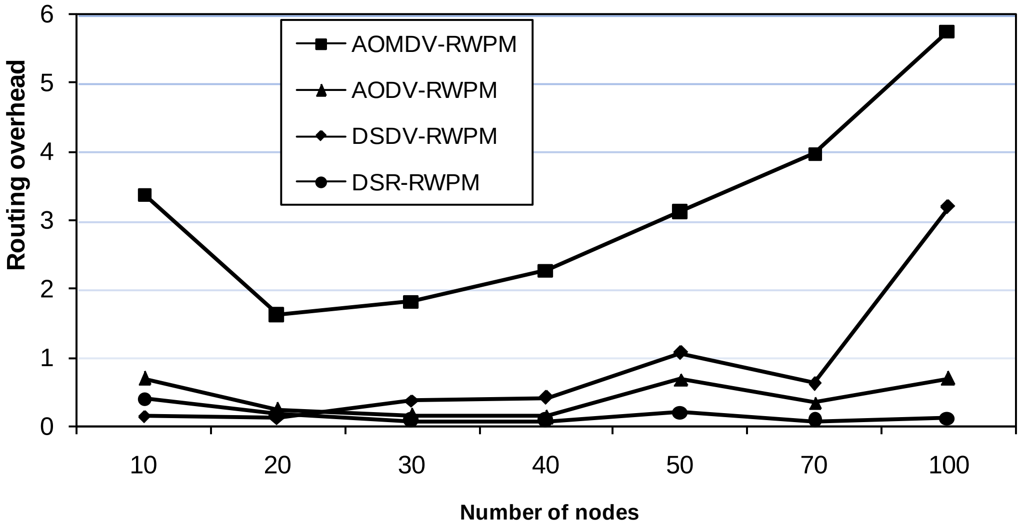

Figure 7.3d. Routing overhead versus routing protocols with RWPM model

DSDV uses both full and incremental updates of routing tables to reduce the routing overhead, which can be observed in all graphs of Figure 7.3 (see Section 3.1 for DSDV functionality).

Comparing our results with the work of Khiavi, Jamali and Gudakahriz [15] we may emphasize the following points:

1. Khiavi, Jamali and Gudakahriz have done their simulation for 500 seconds, only. We preferred to skip the first 500 seconds (for system stability) and then we have started the collection of results.
2. We have recorded better results for packet delivery ratio versus number of nodes.
3. Khiavi, Jamali and Gudakahriz produced the simulations for the RWPM model only. We have extended the work to include the MGM, GMM, and RPGM models.

4. Considering the average end-to-end delay, we have recorded a much better result.
5. In the case of routing overhead (normalizes routing load) we have got better results.

7.2 LBCM Performance

In this section, LBCM is compared with other mobility models using the AOMDV routing protocol.

7.2.1 Delivery Ratio

Initially we have analyzed the first performance metric which is the delivery ratio with respect to varied number of nodes. Figure 7.4 shows that the LBCM mobility model delivers the highest percentage of the generated packets. This is a very promising result obtained for our LBCM model. With all mobility models, we observed an increase in the delivery ratio as the number of nodes is increased. When the number of nodes is increased, the protocol finds more paths from one source to a destination, so, the packets have many optional paths to go through.

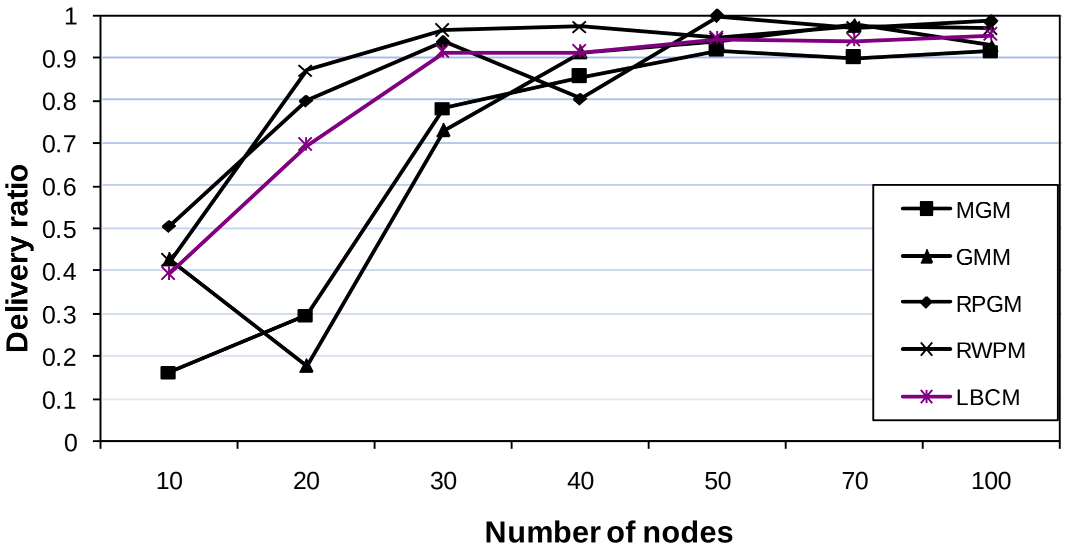

Figure 7.4. Delivery ratio versus number of nodes with the AOMDV protocol.

7.2.2 Average End-to-End Delay

The performance of the mobility models in terms of average end-to-end packet delay is examined with AOMDV protocol as well. The results are presented in Figure 7.5. In LBCM model, the average end-to-end packet delay decreases with the increase of the number of nodes. It gives one of the best results. The MGM model consumes the highest time in all cases. The RPGM model takes less time to deliver the packets compared to the other mobility models. Again, as the number of nodes increase, the end-to-end delay decreases.

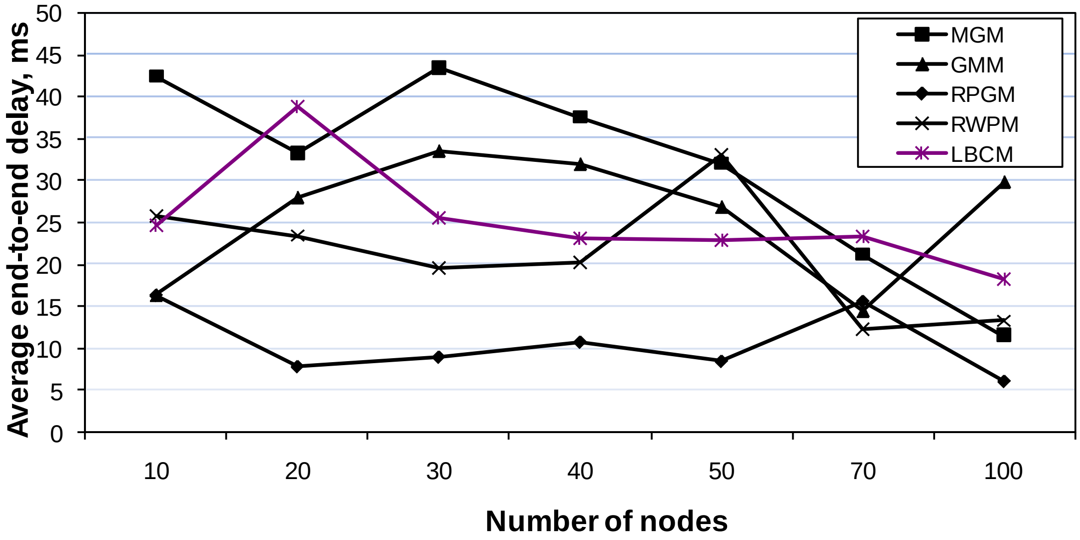

Figure 7.5. Average end-to-end delay versus number of nodes with the AOMDV protocol.

7.2.3 Average Number of Hops

Figure 7.6 shows the average number of hops versus the number of nodes. The RPGM model has the least average number of hops, since the number of nodes has been divided into a small number of groups. Considering this, it is noticeable that even when the number of nodes is large enough, the average number of hops did not go beyond 2. On the other hand, from the structure of the MGM model, the average number of hops is the largest as the nodes move in the rows and columns and there were some building blocks considered as obstacles. This is also noticeable in our LBCM model where the average number of hops is greater than RPGM model. We expected this to happen considering the architecture of the LBCM model. In order for a packet to arrive at a destination node, it must go around any obstacles on its way, to be delivered to the destination.

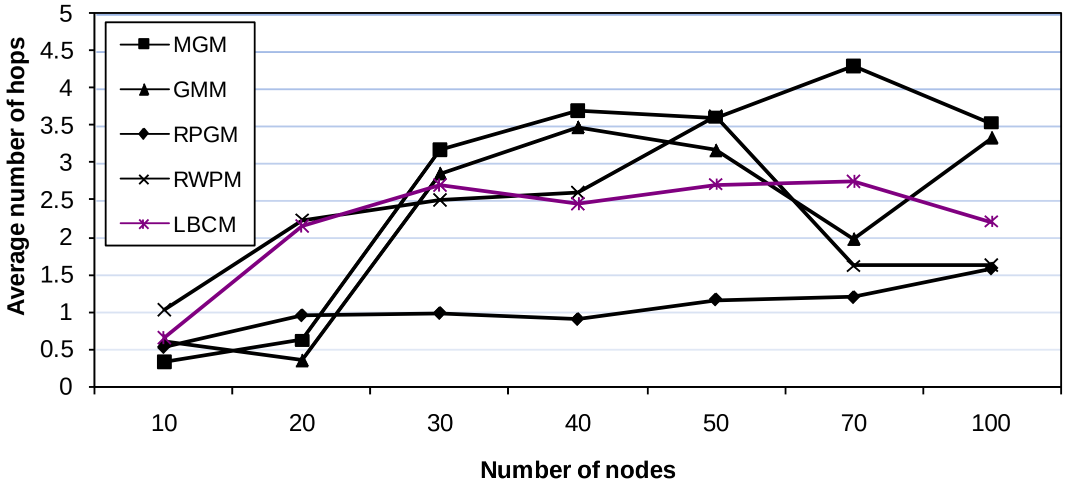

Figure 7.6. Average number of hops versus number of nodes with the AOMDV protocol.

7.2.4 Routing overhead

The bandwidth consumed by all the control packets of the routing protocol is measured as the routing overhead. So, the routing overhead or overhead is how much we did routing work compared to the work delivered. Figure 7.7 indicates that for the configuration given, the lowest routing work was done (except MGM), when the number of nodes is between 20 and 30. LBCM started with same routing as others then when the number of nodes is 30. LBCM did the average amount of routing among all mobility models. On the average, MGM has done a higher amount of routing work for number of nodes less than 30.

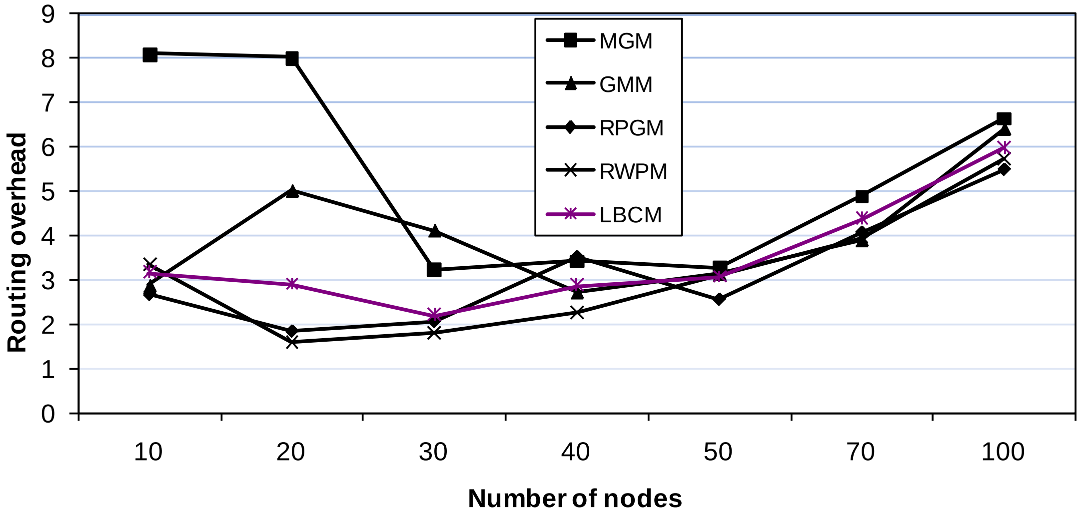

Figure 7.7. Routing overhead versus number of nodes with the AOMDV protocol.

The above results can be summarized in Table 7.1. This table represents the best mobility model that return the most addiquite with the best protocol. From that we can conclude the which mobility model works well with which routing protocol.

Table 7.1 Mobility models that return best according to each performance.

Routing Protocol	**Mobility models, that return best according to each performance metric**			
	Delivery ratio	Average end-to-end delay	Average number of hops	Routing overhead
DSR	RWPM	RPGM	RPGM	RPGM
AODV	RWPM	RPGM	RPGM	RPGM
AOMDV	RWPM	RPGM	RPGM	RWPM
DSDV	LBCM	RPGM	RPGM	RPGM

Table 7.2 Mobility models that return second best according to each performance.

Routing Protocol	**Mobility models, that return second best according to each performance metric**			
	Delivery ratio	Average end-to-end delay	Average number of hops	Routing overhead
DSR	LBCM	RWPM	RWPM	LBCM
AODV	LBCM	LBCM	LBCM	RWPM
AOMDV	RPGM	RWPM	RWPM	LBCM
DSDV	RWPM	RWPM	RWPM	LBCM

Table 7.2 shows the second best mobility model for each protocol. It is obvious that LBCM has the best routing overhead values for DSR, AOMDV, and DSDV routing protocols out of the tested four. Also it is better with DSR and AODV routing protocols in delivering packets. From the above results, the LBCM model is the best for the AODV routing protocol. So, we recommend that using the LBCM model with the AODV routing protocol will return the best results..

Chapter 8

CONCLUSION

In this thesis, we have investigated the performance of three routing protocols with four different classes of the most popular mobility models in wireless mobile ad hoc networks. In MANETs, the efficiency of routing protocols depends heavily on accurate characterization of the operating environment. The mobility models were chosen to represent the real characteristics of the operating environment in determining protocol performance. In addition, we have also concentrated on the performance of a single path routing protocols with different mobility models, which is a novel approach.

The simulation studies show that the performance of the examined routing protocols is different under different mobility models. The DSR routing protocol performs well with the RWPM model, but it performs fairly with the MGM model. The primary reason for this is that, in contrast to the RWPM model, the MGM model consists of an area with differing topologies and densities.

The RPGM model gives the lowest end-to-end delay in all routing protocols, but it is most beneficial with DSDV. Our delivery ratio simulations show that to deliver most of the sent data packets, without much concern about the end-to-end delay or routing overhead, the DSR routing protocol with the RWPM model is the best choice. Our analysis reveals that the four mobility models can be used effectively with a certain routing protocol. For example, RWPM works best with DSR and RPGM works best with DSDV. Finally, we believe that exploiting routing and mobility choices in MANETs results in a clear understanding of which combination of routing protocol and mobility model should be utilized under which conditions.

In the second part, a new mobility model, Location Based Cluster Mobility (LBCM) is presented. The proposed model is defined to be more realistic in many ways than any other mobility models available for wireless ad hoc networks. We believe LBCM more closely represents the realistic pattern movement of MNs in real-world.

The goals for this mobility model are met by having created a model that is easy to use and is able to produce user mobility scenarios without the researcher needing to have much background of mobility modeling. Investigations of the model have shown that the behavior generated is as expected and is representative of real-world behavior.

The LBCM is currently designed to model user movement on the scale of kilometers or hundreds of meters. It would be useful to create a similar model that is focused on much smaller scales, since such a model would be useful for much of the wireless LAN technology that is becoming so popular.

As further work, firstly, protocols presented in this thesis can be extended to include other routing techniques, like geographic routing. Also, mobility models can be further improved to develop more complex and realistic models.

Secondly, in our research study, up to 100 nodes were used in the simulation. An extension of probably to 1000 nodes may gave us another impression on the performance of the mobility models studied.

Thirdly, in the developed mobility model (LBCM), when we pass from a cluster to another we change the mobility model. We think that also changing the best routing protocol that uses that cluster be another improvement that can be done on the mobility model developed.

Finally, we have done a lot of real world experiments on routing and MANETs. So, we can validate our developed LBCM model with the experimental results found. This can be done with only 10 nodes and the RWPM model to be consistant with the real world experiments done.

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APPENDICES

APPENDIX A: Simulation Data for AODV Routing Protocol

A.1 GMM model with AODV routing protocol

Number of Nodes	10	20	30	40	50	70	100
send	17086	19003	18965	19045	19058	18960	19026
recv	7325	3460	14286	18608	18943	18898	18847
routingpkts	3728	6242	15456	9897	7519	4811	22351
Data-pkts	11311	7372	59680	70948	68830	42413	72788
PDR 100%	42.87	18.21	75.33	97.71	99.4	99.67	99.06
PDR	0.4287	0.1821	0.7533	0.9771	0.994	0.9967	0.9906
Highest packet id	17085	19002	18964	19044	19057	18959	19025
NRL	0.51	1.8	1.08	0.53	0.4	0.25	1.19
Average e-e delay(ms)	79.6	282.29	287.21	53.26	32.8	16.78	40.8
Average Hop Count	0.66	0.39	3.15	3.73	3.61	2.24	3.83
No. of dropped data (packets)	9669	15420	5293	1083	660	253	1101
No. of dropped data (bytes)	5143908	8203498	2840410	601618	374726	141788	625868
Packet Loss [%]	56.59	81.15	27.91	5.69	3.46	1.33	5.79

A.2 MGM model with AODV routing protocol

Number of Nodes	10	20	30	40	50	70	100
send	17135	19027	18990	18995	19020	19004	19006
recv	2844	5744	15425	17317	18727	18697	18763
routingpkts	3943	9008	11549	15025	14106	24013	26571
Data-pkts	7069	12216	64632	77234	76513	89561	76103
PDR 100%	16.6	30.19	81.23	91.17	98.46	98.38	98.72
PDR	0.166	0.3019	0.8123	0.9117	0.9846	0.9838	0.9872
Highest packet id	17134	19026	18989	18994	19019	19003	19005
NRL	1.39	1.57	0.75	0.87	0.75	1.28	1.42
Average e-e delay(ms)	283.97	149.51	188.39	72.23	64.24	66.51	39.58
Average Hop Count	0.41	0.64	3.4	4.07	4.02	4.71	4
No. of dropped data (packets)	14112	13229	4013	2609	1094	1324	1070
No. of dropped data (bytes)	7507700	7038930	2153592	1427254	613444	743982	601662
Packet Loss [%]	82.36	69.53	21.13	13.74	5.75	6.97	5.63

A.3 RPGM model with AODV routing protocol

Number of Nodes	10	20	30	40	50	70	100
send	17122	19008	19044	19013	18997	19049	18968
recv	8651	15268	17865	15314	18988	18577	18905
routingpkts	3924	2955	2460	4995	994	4298	6234
Data-pkts	8664	18402	19003	16896	22897	23933	31700
	50.53	80.32	93.81	80.54	99.95	97.52	99.67
PDR	0.5053	0.8032	0.9381	0.8054	0.9995	0.9752	0.9967
Highest packet id	17121	19007	19043	19012	18996	19048	18967
NRL	0.45	0.19	0.14	0.33	0.05	0.23	0.33
Average e-e delay(ms)	77.68	58.33	47.57	30.71	27.89	25.55	17.73
Average Hop Count	0.51	0.97	1	0.89	1.21	1.26	1.67
No. of dropped data (packets)	8360	3710	1152	3689	20	476	119
No. of dropped data (bytes)	4447520	1974358	612864	1963244	10640	253638	64294
Packet Loss [%]	48.83	19.52	6.05	19.4	0.11	2.5	0.63

A.4 RWPM model with AODV routing protocol

Number of Nodes	10	20	30	40	50	70	100
send	17159	19032	19027	19010	19053	18993	18983
recv	7337	16889	18735	18952	18757	18934	18867
routingpkts	5161	4423	3252	2914	12946	6596	13377
Data-pkts	17558	44757	50677	54862	76297	38369	38215
PDR 100%	42.76	88.74	98.47	99.69	98.45	99.69	99.39
PDR	0.4276	0.8874	0.9847	0.9969	0.9845	0.9969	0.9939
Highest packet id	17158	19031	19026	19009	19052	18992	18982
NRL	0.7	0.26	0.17	0.15	0.69	0.35	0.71
Average e-e delay(ms)	260.96	176.71	94.84	53.09	69.78	26.08	72.91
Average Hop Count	1.02	2.35	2.66	2.89	4	2.02	2.01
No. of dropped data (packets)	9761	2331	389	188	1127	150	201
No. of dropped data (bytes)	5193896	1247690	209268	103786	636220	81598	108614
Packet Loss [%]	56.89	12.25	2.04	0.99	5.92	0.79	1.06

A.5 LBCM model with AODV routing protocol

Number of Nodes	10	20	30	40	50	70	100
send	17118	18940	18958	19019	19050	18950	19009
recv	6875	13832	18172	18251	18900	18805	18882
routingpkts	3169	8361	6779	8638	9196	11141	16597
Data-pkts	11486	47022	55110	53785	57311	59596	46893
PDR 100%	40.16	73.03	95.85	95.96	99.21	99.23	99.33
PDR	0.4016	0.7303	0.9585	0.9596	0.9921	0.9923	0.9933
Highest packet id	17117	18939	18957	19018	19049	18949	19008
NRL	0.46	0.6	0.37	0.47	0.49	0.59	0.88
Average e-e delay(ms)	196.39	159.68	72.94	82.33	25.6	26.51	23.25
Average Hop Count	0.67	2.48	2.55	2.83	3.01	3.14	2.47
No. of dropped data (packets)	10180	5430	1165	1108	737	582	401
No. of dropped data (bytes)	5416398	2903202	633816	600476	416618	326444	221394
Packet Loss [%]	59.47	28.67	6.15	5.83	3.87	3.07	2.11

APPENDIX B: Simulation Data for AOMDV Routing Protocol

B.1 GMM model with AOMDV routing protocol

Number of Nodes	10	20	30	40	50	70	100
send	17146	19008	18964	19035	18988	19034	19008
recv	7315	3396	13845	17373	17786	18593	17648
routingpkts	21108	44232	57176	47542	56040	72698	113187
Data-pkts	10445	6707	54293	66243	60262	37663	63485
PDR 100%	42.66	17.87	73.01	91.27	93.67	97.68	92.85
PDR	0.4266	0.1787	0.7301	0.9127	0.9367	0.9768	0.9285
Highest packet id	17145	19007	18963	19034	18987	19033	19007
NRL	2.89	5.02	4.13	2.74	3.15	3.91	6.41
Average e-e delay(ms)	16.45	27.97	33.46	31.92	26.86	14.56	29.8
Average Hop Count	0.61	0.35	2.86	3.48	3.17	1.98	3.34
No. of dropped data (packets)	9909	15676	6497	3708	3146	1135	3929
No. of dropped data (bytes)	5272226	8340560	3487550	2011168	1717462	618726	2161452
Packet Loss [%]	57.79	82.47	34.26	19.48	16.57	5.96	20.67

B.2 MGM model with AOMDV routing protocol

Number of Nodes	10	20	30	40	50	70	100
send	17154	19067	19066	19051	19023	19042	18977
recv	2801	5652	14923	16306	17473	17120	17378
routingpkts	22685	45199	48409	56002	57508	83920	115517
Data-pkts	5706	11769	60275	70378	68536	81713	67064
PDR 100%	16.33	29.64	78.27	85.59	91.85	89.91	91.57
PDR	0.1633	0.2964	0.7827	0.8559	0.9185	0.8991	0.9157
Highest packet id	17153	19066	19065	19050	19022	19041	18976
NRL	8.1	8	3.24	3.43	3.29	4.9	6.65
Average e-e delay(ms)	42.47	33.25	43.5	37.62	32.02	21.17	11.51
Average Hop Count	0.33	0.62	3.16	3.69	3.6	4.29	3.53
No. of dropped data (packets)	14396	13602	5585	5014	3781	4803	4005
No. of dropped data (bytes)	7658962	7238236	2995696	2720518	2051802	2613544	2178974
Packet Loss [%]	83.92	71.34	29.29	26.32	19.88	25.22	21.1

B.3 RPGM model with AOMDV routing protocol

Number of Nodes	10	20	30	40	50	70	100
send	17107	18972	19033	18978	19041	19034	19017
recv	8646	15165	17832	15272	19008	18463	18754
routingpkts	23263	28171	37032	54014	49085	75450	103314
Data-pkts	9131	17989	18599	17128	22101	22672	29860
PDR 100%	50.54	80	93.69	80.47	99.83	97	98.62
PDR	0.5054	0.8	0.9369	0.8047	0.9983	0.97	0.9862
Highest packet id	17106	18971	19032	18977	19040	19033	19016
NRL	2.69	1.86	2.08	3.54	2.58	4.09	5.51
Average e-e delay(ms)	16.36	7.85	8.98	10.77	8.48	15.63	6.09
Average Hop Count	0.53	0.95	0.98	0.9	1.16	1.19	1.57
No. of dropped data (packets)	8464	3899	1211	3782	76	696	591
No. of dropped data (bytes)	4502848	2075776	644252	2012604	41012	370678	318530
Packet Loss [%]	49.48	20.55	6.36	19.93	0.4	3.66	3.11

B.4 RWPM model with AOMDV routing protocol

Number of Nodes	10	20	30	40	50	70	100
send	17152	19017	18977	18982	19042	19023	18984
recv	7241	16561	18282	18472	18023	18514	18380
routingpkts	24461	26784	33401	42205	56285	73654	105925
Data-pkts	17432	42434	47258	49263	68888	30700	30699
PDR 100%	42.22	87.09	96.34	97.31	94.65	97.32	96.82
PDR	0.4222	0.8709	0.9634	0.9731	0.9465	0.9732	0.9682
Highest packet id	17151	19016	18976	18981	19041	19022	18983
NRL	3.38	1.62	1.83	2.28	3.12	3.98	5.76
Average e-e delay(ms)	25.73	23.41	19.54	20.19	33.06	12.28	13.31
Average Hop Count	1.02	2.23	2.49	2.6	3.62	1.61	1.62
No. of dropped data (packets)	10050	2951	1190	1134	2882	1126	1387
No. of dropped data (bytes)	5347412	1577820	634646	609900	1586062	605354	748730
Packet Loss [%]	58.59	15.52	6.27	5.97	15.13	5.92	7.31

B.5 LBCM model with AOMDV routing protocol

Number of Nodes	10	20	30	40	50	70	100
send	17099	18970	19010	19017	18969	18976	19001
recv	6729	13192	17366	17346	17923	17817	18110
routingpkts	21401	38347	38297	50038	55142	78230	108638
Data-pkts	11214	40827	51047	46660	51480	52095	42051
PDR 100%	39.35	69.54	91.35	91.21	94.49	93.89	95.31
PDR	0.3935	0.6954	0.9135	0.9121	0.9449	0.9389	0.9531
Highest packet id	17098	18969	19009	19016	18968	18975	19000
NRL	3.18	2.91	2.21	2.88	3.08	4.39	6
Average e-e delay(ms)	24.68	38.9	25.53	23.18	22.97	23.36	18.27
Average Hop Count	0.66	2.15	2.69	2.45	2.71	2.75	2.21
No. of dropped data (packets)	10508	7071	2957	3005	2718	2705	2176
No. of dropped data (bytes)	5591300	3779288	1591858	1615074	1484198	1462376	1180890
Packet Loss [%]	61.45	37.27	15.55	15.8	14.33	14.25	11.45

APPENDIX C: Simulation Data for DSDV Routing Protocol

C.1 GMM model with DSDV routing protocol

Number of Nodes	10	20	30	40	50	70	100
send	17169	19004	18394	17910	18969	19000	18983
recv	4564	11441	12978	13201	17269	18447	17128
routingpkts	891	1754	3259	7694	17214	43472	62789
Data-pkts	6425	22504	47369	52274	54558	37565	55173
PDR 100%	26.58	60.2	70.56	73.71	91.04	97.09	90.23
PDR	0.2658	0.602	0.7056	0.7371	0.9104	0.9709	0.9023
Highest packet id	18067	20785	21730	25704	36257	62551	81839
NRL	0.2	0.15	0.25	0.58	1	2.36	3.67
Average e-e delay(ms)	14.02	18.27	71.46	52.08	24.45	19.93	53.96
Average Hop Count	0.37	1.18	2.58	2.92	2.88	1.98	2.91
No. of dropped data (packets)	13164	8754	9131	8819	3792	1304	4534
No. of dropped data (bytes)	7003488	4658230	4892456	4723702	2051724	708988	2474060
Packet Loss [%]	72.86	42.11	42.02	34.31	10.46	2.08	5.54

C.2 MGM model with DSDV routing protocol

Number of Nodes	10	20	30	40	50	70	100
send	17164	19009	19033	18994	19013	19074	19062
recv	2450	9566	12565	14330	15976	17406	16755
routingpkts	928	1965	3854	6953	13740	50778	63346
Data-pkts	5332	29282	48586	58920	58773	73342	57844
PDR 100%	14.27	50.32	66.02	75.44	84.03	91.26	87.9
PDR	0.1427	0.5032	0.6602	0.7544	0.8403	0.9126	0.879
Highest packet id	18114	21020	22994	26019	32845	69974	82517
NRL	0.38	0.21	0.31	0.49	0.86	2.92	3.78
Average e-e delay(ms)	99.74	122.67	86.33	118.02	42.45	71.95	37.2
Average Hop Count	0.31	1.54	2.55	3.1	3.09	3.85	3.03
No. of dropped data (packets)	15523	11598	10130	8585	6126	4081	5074
No. of dropped data (bytes)	8258932	6172562	5407730	4606240	3285570	2233838	2742628
Packet Loss [%]	85.69	55.17	44.05	32.99	18.65	5.83	6.15

C.3 RPGM model with DSDV routing protocol

Number of Nodes	10	20	30	40	50	70	100
send	17149	18981	19025	18984	18978	19018	18950
recv	8685	15014	14220	15134	18834	18847	18304
routingpkts	880	1808	2651	3975	5959	10642	30214
Data-pkts	8685	17807	14231	16793	21455	22300	27227
PDR 100%	50.64	79.1	74.74	79.72	99.24	99.1	96.59
PDR	0.5064	0.791	0.7474	0.7972	0.9924	0.991	0.9659
Highest packet id	18034	20792	21712	23011	25113	29789	49334
NRL	0.1	0.12	0.19	0.26	0.32	0.56	1.65
Average e-e delay(ms)	5.98	7.66	6.04	6.78	7.29	7.85	37.03
Average Hop Count	0.51	0.94	0.75	0.88	1.13	1.17	1.44
No. of dropped data (packets)	8671	4429	4867	4487	199	307	1099
No. of dropped data (bytes)	4613052	2357584	2589324	2388408	106164	163904	586198
Packet Loss [%]	48.08	21.3	22.42	19.5	0.79	1.03	2.23

C.4 RWPM model with DSDV routing protocol

Number of Nodes	10	20	30	40	50	70	100
send	10004	19066	2662	19020	18996	18988	19040
recv	3602	15712	2128	17891	17174	18196	17598
routingpkts	592	2101	800	7504	18575	11548	56353
Data-pkts	9935	37546	5522	44406	62171	28703	29021
PDR 100%	36.01	82.41	79.94	94.06	90.41	95.83	92.43
PDR	0.3601	0.8241	0.7994	0.9406	0.9041	0.9583	0.9243
Highest packet id	10618	21200	3512	26585	37636	30577	75430
NRL	0.16	0.13	0.38	0.42	1.08	0.63	3.2
Average e-e delay(ms)	74.01	92.24	19	17.91	30.49	20.96	78.82
Average Hop Count	0.99	1.97	2.07	2.33	3.27	1.51	1.52
No. of dropped data (packets)	7741	5031	786	2221	4322	1575	2515
No. of dropped data (bytes)	4119746	2684144	418762	1187210	2343508	840322	1353898
Packet Loss [%]	72.9	23.73	22.37	8.35	11.48	5.15	3.33

C.5 LBCM model with DSDV routing protocol

Number of Nodes	10	20	30	40	50	70	100
send	8351	10946	19065	9076	19002	19046	19009
recv	2670	6533	15903	8232	17698	17908	18882
routingpkts	478	1254	4603	3639	21864	47962	16597
Data-pkts	5654	21781	44001	18069	47958	48020	46893
PDR 100%	31.97	59.68	83.41	90.7	93.14	94.02	99.33
PDR	0.3197	0.5968	0.8341	0.907	0.9314	0.9402	0.9933
Highest packet id	8842	12237	23763	12797	40995	67103	19008
NRL	0.18	0.19	0.29	0.5	1.24	2.68	0.88
Average e-e delay(ms)	24.2	33.04	47.48	17.12	25.3	34.28	23.25
Average Hop Count	0.68	1.99	2.31	1.99	2.52	2.52	2.47
No. of dropped data (packets)	6444	6949	5806	2932	3145	2400	401
No. of dropped data (bytes)	3429016	3710694	3104818	1566616	1717248	1302090	221394
Packet Loss [%]	72.87	56.78	24.43	22.91	7.67	3.58	2.11

APPENDIX D: Simulation Data for DSR Routing Protocol

D.1 GMM model with DSR routing protocol

Number of Nodes	10	20	30	40	50	70	100
send	17151	18976	19072	19007	18933	19104	19050
recv	7583	3604	14989	18820	18896	19076	18984
routingpkts	2443	4630	10299	4154	2878	933	5863
Data-pkts	10557	7494	55621	69263	62208	38250	63378
PDR 100%	44.21	18.99	78.59	99.02	99.8	99.85	99.65
PDR	0.4421	0.1899	0.7859	0.9902	0.998	0.9985	0.9965
Highest packet id	4429667	7935296	2798378	170147	21223	19712	21748
NRL	0.32	1.28	0.69	0.22	0.15	0.05	0.31
Average e-e delay(ms)	299.84	279.6	283.73	141.61	29.93	15.06	29.74
Average Hop Count	0.62	0.39	2.92	3.64	3.29	2	3.33
No. of dropped data (packets)	9583	15459	5175	909	989	391	1368
No. of dropped data (bytes)	5098312	8231230	2850978	513726	569634	220422	792878
Packet Loss [%]	0.22	0.19	0.18	0.53	4.66	1.98	6.29

D.2 MGM model with DSR routing protocol

Number of Nodes	10	20	30	40	50	70	100
send	17148	19018	19047	19019	19062	19031	19010
recv	2982	5949	16124	17771	19026	18947	18946
routingpkts	2892	5213	10828	10766	6707	16766	10531
Data-pkts	6636	13965	63767	75433	71622	82658	69975
PDR 100%	17.39	31.28	84.65	93.44	99.81	99.56	99.66
PDR	0.1739	0.3128	0.8465	0.9344	0.9981	0.9956	0.9966
Highest packet id	7068837	7328818	1786902	915425	26826	26253	24231
NRL	0.97	0.88	0.67	0.61	0.35	0.88	0.56
Average e-e delay(ms)	464.69	342.97	312.08	274.48	147.82	124.28	61.71
Average Hop Count	0.39	0.73	3.35	3.97	3.76	4.34	3.68
No. of dropped data (packets)	14277	13266	4221	3037	1243	2070	1938
No. of dropped data (bytes)	7600680	7072272	2328954	1716138	711618	1188782	1109574
Packet Loss [%]	0.2	0.18	0.24	0.33	4.63	7.88	8

D.3 RPGM model with DSR routing protocol

Number of Nodes	10	20	30	40	50	70	100
send	17153	19082	19026	18970	19031	19042	19015
recv	8702	15382	17808	15327	19018	18601	18890
routingpkts	2281	1634	1364	2882	247	2155	4686
Data-pkts	8734	18507	18158	17760	21822	22404	29235
PDR 100%	50.73	80.61	93.6	80.8	99.93	97.68	99.34
PDR	0.5073	0.8061	0.936	0.808	0.9993	0.9768	0.9934
Highest packet id	4707163	2495394	768317	1788045	19657	290905	21684
NRL	0.26	0.11	0.08	0.19	0.01	0.12	0.25
Average e-e delay(ms)	139.23	68.79	56.21	75.82	37.99	61.83	14.14
Average Hop Count	0.51	0.97	0.95	0.94	1.15	1.18	1.54
No. of dropped data (packets)	8462	3796	1237	3749	28	551	397
No. of dropped data (bytes)	4502052	2022738	659776	2002910	15970	299940	225072
Packet Loss [%]	0.18	0.15	0.16	0.21	0.14	0.19	1.83

D.4 RWPM model with DSR routing protocol

Number of Nodes	10	20	30	40	50	70	100
send	17134	19062	18964	19068	19012	19042	19043
recv	7613	17214	18748	19040	18899	18961	19003
routingpkts	3110	3122	1506	1450	3917	1466	2413
Data-pkts	17046	43670	47900	47843	69570	30875	30619
PDR 100%	44.43	90.31	98.86	99.85	99.41	99.57	99.79
PDR	0.4443	0.9031	0.9886	0.9985	0.9941	0.9957	0.9979
Highest packet id	5109600	1195691	169156	22535	91181	20313	21053
NRL	0.41	0.18	0.08	0.08	0.21	0.08	0.13
Average e-e delay(ms)	375.25	211.61	170.78	127.67	71.97	25.06	38.89
Average Hop Count	0.99	2.29	2.53	2.51	3.66	1.62	1.61
No. of dropped data (packets)	9558	2306	437	248	1385	341	375
No. of dropped data (bytes)	5087908	1251616	239178	139902	793744	189052	208128
Packet Loss [%]	0.19	0.19	0.26	1.1	1.52	1.68	1.78

D.5 LBCM model with DSR routing protocol

Number of Nodes	10	20	30	40	50	70	100
send	17048	19030	18988	19061	18991	19001	19086
recv	7108	14248	18478	18483	18952	18937	18974
routingpkts	2837	6928	4433	3836	2794	4988	3243
Data-pkts	12829	45504	53010	47468	51216	51594	45075
PDR 100%	41.69	74.87	97.31	96.97	99.79	99.66	99.41
PDR	0.4169	0.7487	0.9731	0.9697	0.9979	0.9966	0.9941
Highest packet id	5134894	2605087	381176	358663	20646	22074	21283
NRL	0.4	0.49	0.24	0.21	0.15	0.26	0.17
Average e-e delay(ms)	887.31	960.15	296.65	241.07	23.44	30.85	19.4
Average Hop Count	0.75	2.39	2.79	2.49	2.7	2.72	2.36
No. of dropped data (packets)	10095	5674	1247	1274	1059	1151	749
No. of dropped data (bytes)	5376350	3069122	692236	704388	606980	648190	419430
Packet Loss [%]	0.2	0.22	0.33	0.36	5.13	5.21	3.52