A STUDY OF THE DESTINATION GUIDED MOBILITY MODELS

by

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Abstract

Mobility models play a critical role in the simulation studies of Mobile Ad hoc Networks (MANETs). They greatly influence the performance of MANET routing protocols. For MANET simulations, random mobility models have been used in nearly all research studies in the past. In recent times, several studies have criticised the use of random mobility models in the performance studies of MANETs for the lack of realism in modelling mobility. Therefore, questions have been raised regarding the credibility of MANET simulation studies.

Realism and simplicity are two attractive properties of mobility models; achieving both together in modelling mobility has been a challenging task. Recently, a framework of mobility models called Destination Guided Mobility (DGM) models for MANETs with a basic software tool was proposed [1]. This framework can be used to develop several simple DGM models with improved realism.

This thesis is primarily interested in studying DGM models for their suitability in modelling mobility in various MANET scenarios. Our study requires a suitable simulation testbed for DGM models. Designing such a tool, referred to as DGMGen, with suitable functionality to study DGM models is the secondary objective of this thesis.

More specifically, after the design and implementation of DGMGen, we study: i) the generality of the DGM models by modelling different real world scenarios; ii) the connectivity analysis of three basic DGM models in comparison with the widely used Random Waypoint (RWP) mobility model; iii) how to model a real life scenario using DGM models, based on the trace collected from that scenario; and iv) the impact of DGM models on the Ad hoc On-demand Distance Vector (AODV) routing protocol using NS2.

Our study shows that i) the DGM framework is powerful in capturing various MANET scenarios simply and more accurately, ii) DGM models confirm higher level connectivity prevailed in most real world scenarios, iii) DGM models can generate approximately the similar trace based on the insights of a real trace, and iv) the mobility models can influence the performance of the routing protocol under study.

Dedicated To

my parents,
my wife,
my son,
and
my sister Mehrun Nesa and my brother-in-law,
Yunus Ali, whose sacrifice and support will never be forgotten.

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Chapter 1

Introduction

1.1 Introduction

1.1.1 Background

Traditional communication networks such as Internet and cellular networks, have established infrastructure and well regulated controls to facilitate communication between the nodes in those networks. Mobile Ad hoc Network (MANET) is a new class of communication networks where nodes are mobile and they communicate with each other without any pre-existing infrastructure [2]. That is, MANETs are expected to be set up spontaneously in an ad hoc fashion using a collection of mobile nodes to establish communication. They are typically set up for specific purposes under special circumstances. In particular, MANETs are suitable for the scenarios where no established infrastructure is available or even possible. Some scenarios or applications envisioned for MANETs are: disaster management where the infrastructure is partially or completely destroyed, communication network for scientific or business conferences held in remote resorts and locations, military communication network set up in enemy regions during war times, etc. Quick deployment with minimal configuration makes MANETs suitable and attractive for many real-life applications. In recent times, in addition to their potential applications, technological advancements in communication and computing have generated a great deal of interest in MANETs [3–5].

Despite their potential use and technological feasibility, setting up and managing MANETs effectively are complex tasks. The topology of MANETs is highly dynamic as the nodes are expected to move unpredictably. Also, the size of the network could vary time to time as nodes can join and leave the network at any time. Due to the complexity, most research studies in MANETs are based on simulations [3, 5, 6].

MANETs are primarily set up for message communication and message routing is an essential component of message communication. Routing of a message between two nodes, say A and B, in a network is a process of transferring the message from node A to node B, often involving other intermediary nodes in the network. As the nodes in MANETs are mobile, the mobility of nodes heavily influences the routing of a message. Therefore, mobility is one of the fundamental characteristics of MANETs.

As indicated earlier, most research studies on MANETs are done using simulation. Modelling and simulation of MANETs intrinsically involve the modelling of mobility. Mobility models generate a trace of the mobility of the nodes in the network; that, in turn, is used in the performance study of routing and related activities in the network.

A survey conducted in 2005 showed that most of the earlier research studies on MANETs were conducted using random mobility models (80% of studies are based on random mobility models.) [3]. Such research studies have been widely criticized for the lack of rigour and accuracy in modelling the network. Hence, questions have been raised regarding the validity of the simulation results [3, 7–9]. As modelling the mobility of the nodes plays an integral role in the modelling and simulation of

MANETs, using the random mobility models is primarily responsible for the inaccuracies and criticisms. We believe the main reasons for the continued use of random mobility models are: (i) the simplicity and hence ease of use; (ii) widely supported in the existing MANET simulation tools; and (iii) lack of mobility generation and analysis tools supporting alternative and more realistic mobility models.

In response to the criticisms of MANETs simulations, several ideas have been proposed in the literature to increase realism in modelling mobility by including real life objects such as roads, building, etc. [2, 4, 5, 10–13]. Although these proposals improve the appearance of realism, they have increased the complexity of modelling and implementation of mobility in the simulation studies of MANETs. Therefore, the use of these refined models has been limited and most simulation studies on MANETs continue to use the random mobility models [14] even though their use is widely questioned [3, 7–9].

Recently, a framework of mobility models called Destination Guided Mobility (DGM) models was proposed [1]. The basic idea behind DGM models is that a fixed number of destinations are assumed to be an integral part of the network and the nodes only move between those destinations with specified transition probabilities. This set-up is reasonable, realistic, and useful in that it is seldom that MANET nodes walk randomly in the network region (as modelled by the random mobility models). By suitably controlling the number and positions of the destinations and the mobility of nodes between them, several interesting mobility models with improved realism can be modelled and studied.

The framework proposed in [1] was primarily aimed at addressing the concerns expressed in [3, 7–9] by providing guidelines for mobility model specification and a software tool to generate suitable mobility trace for the performance studies of MANETs.

It was claimed that the framework is simple and capable of modelling mobility in a variety of real life scenarios. However, despite the appeal of the idea behind the proposed framework in modelling various mobility patterns, the work presented in [1] is limited at least in two aspects: (i) The work presented is preliminary and lacks detailed analysis and study of the proposed mobility models; and (ii) the software tool presented to generate different DGM mobility models has limited functionality. We feel that more study on DGM models is needed to explore the strengths and weaknesses of the DGM models so they can be understood well before widely adopted for the performance study of MANETs. This thesis is an extension of the work presented in [1] in the two directions identified above. More specifically, we are interested in studying the versatility and some performance aspects of DGM models.

1.1.2 Motivation

As discussed earlier, most past research on the performance study of the protocols for MANETs have used random mobility models [3, 9]. However, the mobility of the nodes in real life MANETs cannot be completely random to be modelled using random mobility models. More specifically, we believe, using random mobility as the default model for MANETs is a dubious approach to study the performance of MANETs. Also, as indicated earlier, MANETs are application specific and therefore modelling of a MANET is dependent on the scenario that it intended to capture. Hence, we concur with the observation reported in the literature [3,7–9] that the performance studies on MANET protocols using random mobility models are not realistic and therefore lack accuracy and credibility. Therefore, for the research studies on MANETs to be credible and useful, they must be conducted based on more realistic mobility models. In this context, realism refers to the closeness of actual scenario to be modelled. Furthermore, a model to be widely understood and used, it must be simple and generic.

We consider a model as generic if, with suitable tuning, it can model a large number of common scenarios. The question here is:

- How generic is the DGM framework in modelling mobility of the nodes in MANETs under different scenarios?

Exploring the above question is the primary objective of this thesis. This exploration involves several sub-questions that need to be addressed including:

- What are the representative scenarios in which MANETs could be viable?
- Is the DGM framework capable of generating mobility traces closer to the real traces?
- How do we illustrate or test whether the DGM framework is capable of modelling a chosen scenario?
- How the proposed DGM mobility modelling tool can be enhanced to support a variety of representative mobility models?

Mobility models can be best understood only by studying the behaviour and performance of the nodes in the system. Connectivity is a fundamental requirement for communication between nodes [15–21]. Establishing a stable connection between nodes of MANETs is necessary for their communication. Mobility of the nodes and their communication range influence the connectivity between them. Since connectivity has such a fundamental influence on the performance of the protocols in MANETs, a systematic study on the connectivity aspects of more realistic mobility models is critical and necessary. The question here is:

- What are the interesting connectivity metrics involved in MANETs and how they can be implemented in mobility generation and analysis tool to study connectivity analysis of supported DGM models?

Although it is hard to define the characteristic of MANETs, the scale-free property and the clustering coefficient have been found to be defining characteristics of various real life networks that MANET is intended to model [22]. Scale-free property relates to a power-law distribution of the degrees of the nodes, and clustering coefficient defines the propensity of nodes to be gathered in small groups that are highly interconnected. These observed basic characteristics of real life networks have been seldom studied in the context of MANETs. An interesting problem here is:

- How to implement and explore the scale-free property and clustering coefficient for a selected set of DGM models?

Message routing is an important task in computer networks and it is a process of transferring message from a source node to a destination node. Among the routing protocols of MANETs, Ad hoc On-demand Distance Vector (AODV), Dynamic Source Routing (DSR), and Destination Sequence Distance Vector (DSDV) are the most popular and widely studied. AODV and DSR are reactive protocols that establish a route to a destination only on demand. In contrast, DSDV is a proactive protocol which maintains a routing table at each node containing destination node, next hop, hop count, and other metrics for every other node. These tables of all nodes are updated periodically. We may ask:

- How does AODV perform under some representative DGM models as compared to the RWP model?

The above questions are the main motivations for this thesis.

1.2 Contributions

The objective of this thesis is to explore the behaviour of the DGM models. The main contributions of this thesis are:

1. Enhancement of the DGM mobility generation tool presented in [1]. The tool is enhanced in four main directions:

   - Redesign of the destination and mobility generation in a way that a large number of scenarios can be modelled by setting suitably chosen parameters.
   - Implementation of a comprehensive set of performance metrics to analyse the mobility trace.
   - Design and integration of a model and comparison with real traces.
   - Design and integration of a component to visualize the result of the performance of mobility models.

   We refer to the enhanced mobility generation and analysis tool as DGMGen.

2. An illustration of the generality of the DGM framework provided by modelling various real world scenarios.

3. An experimental evaluation of performance metrics such as average number of contacts, average number of connection changes, average contact time, contact time distribution, inter-contact time distribution, node degree distribution, clustering coefficient, and k-hop paths, etc., for a set of DGM models is conducted and compared with that of the RWP model.

4. An experimental evaluation of the traces generated by the studied models is conducted and compared with the traces observed in real scenarios.

5. A study on the performance impact of the DGM models on one of the popular routing protocols (AODV) of MANET is presented using NS2.

1.3 Organization of This Thesis

The documentation of this research work is distributed in the remaining five chapters. Chapter 2 provides the literature review related to this thesis work. More specifically, it provides the literature review on mobility models, connectivity analysis, real traces, performance analysis of routing protocols, and mobility generation tools. The selected performance metrics for analysing mobility models and evaluating the performance of routing protocols under the influence of DGM models have been presented in Chapter 3. Chapter 4 presents the trace generation and network exploration tool we enhanced for analysing the traces. A set of experiments for showing the versatility of the DGM models and for evaluating the performance of the DGM models including RWP model and their impact on the performance of the AODV routing protocol is presented in Chapter 5. Finally, Chapter 6 summarizes this research effort and outlines the directions for further research.

Chapter 2

Literature Review

The work presented in this thesis is related to mobility models for MANETs, real trace analysis, software tool for mobility trace generation and analysis, network performance analysis, and MANET routing protocols. This chapter provides the literature survey related to the above five topics. Section 2.1 and Section 2.2 review related mobility models and the importance of real mobility traces for the study of MANETs. Section 2.3 reviews the related mobility trace generation and analysis tools. Section 2.4 describes the network performance analysis emphasizing the connectivity metrics. Finally, Section 2.5 provides a brief survey on MANET routing protocols.

2.1 Mobility Models

Mobility models play an influential role in the simulation studies of MANETs, and they are used to represent the movement patterns of mobile nodes for the MANET scenarios to be studied. There are several surveys available for mobility models proposed for MANETs [2,11,13,23,24], and a comprehensive survey can be found in [5]. In this chapter, to set the context, we review only a representative set of mobility models.

Brownian motion [25] is one of the simplest and oldest basic mobility models to represent the unpredictable movement of the entities of a system. In this model, each entity moves from its current location to new location by choosing a random direction and a random speed until it hits another entity or the boundary. This model was proposed to mimic the movements of particles in a fluid. The Random Direction Mobility Model (RDMM) [26,27] can be considered as a variation of Brownian motion. In the RDMM, each mobile node moves from its current location to a new location by randomly choosing a direction θ from the interval $[0, 2\pi)$ using a uniform distribution and randomly choosing a speed using a normal distribution in some given range. Then the node travels for a selected time period and the process is repeated. In this model, when a node hits the boundary of the simulation field, the node is bounced back in the simulation region with an angle of $-\theta$ or $(\pi - \theta)$ if the node hits the horizontal boundary. A number of simplified derivatives of this model has been introduced in [28]. One of the important derivatives is Random Walk Mobility Model [11], where each mobile node chooses a direction θ from the interval $[0, 2\pi)$, selects the speed between 0 and 10 m/s, and then travels either for a fixed number of steps or fixed time period such as 60 seconds. Then the process repeats. Another variation is Random Drunken Mobility Model [29] where a node periodically moves to a position chosen randomly from its immediate neighbouring positions as long as the new position is within the coverage area. The frequency of the change of nodes' positions can be controlled based on user-defined parameters.

The Random Waypoint (RWP) model introduced in [30], is the most widely used random mobility model in MANET simulations where each mobile node randomly selects one point (waypoint) in the simulation area as the destination and then travels to the chosen destination with constant speed chosen from a given range using uniform distribution. Upon reaching the destination, the node pauses for a fixed period called *pause time* which is chosen uniformly from a specific range. After this duration, the node chooses another random point in the simulation area and continues in the same way until the simulation time period is over. RDMM and RWP are the basic random mobility models used in MANETs. All other random mobility models proposed later are variations of these two models.

It is observed in [2] that in varying velocity range and pause time in RWP model, various mobility scenarios with different levels of nodal speed can be generated. For example, we can generate a relatively stationary network if we choose speed within a range of smaller velocities and long pause time; similarly we can create a highly dynamic network by choosing speed within a range of higher velocities and small pause time. Several variations have been proposed to increase realism by controlling the speed, the direction, and/or the destination. Two important variations of the RWP model are the Random Borderpoint Model [31] and the Realistic Mobility Model [32].

The objective of the Random Borderpoint Model [31] is to create hot spots in the simulation area where clusters of nodes can be located at any time. In this model, destinations are only located at the border region of the simulation area. Although the model is simplified for mathematical derivations, due to the restriction of destination to the border area it creates some non-uniform node distribution in the simulation region.

The basic idea behind the Realistic Mobility Model [32] is that the nodes select an initial speed and a direction of movement. At discrete time steps, which are determined by the simulation environment, the speed and direction of movement are re-evaluated, based on the current state of the mobile node, and using a Markovian process.

The Gauss-Markov Mobility Model [33] and the Smooth Random Mobility Model [26] are temporal dependent mobility models where the velocity of mobile node is correlated over time. The Gauss-Markov model uses memory history to represent the degree of dependency and a variety of mobility models can be generated based on the weak or strong memory history. In Smooth Random model, in a given range, a set of speed values with fixed probabilities are specified and the remaining speeds are chosen using a uniform distribution. Along the way, acceleration and deceleration are introduced and they are chosen uniformly within the given ranges. The movement direction is uniformly distributed in the interval $[0, 2\pi]$.

The Freeway Mobility Model [34], the Manhattan Mobility Model [34], the City Section Mobility Model [35] and the Obstacle Mobility Model [6] go one step further to represent reality by introducing real life objects to the implementation. But these models are very scenario specific and require considerable effort in incorporating real life objects into the model. In most of these models, the selection of a destination and initial distribution follows the RWP model.

To capture the battle field scenarios, the disaster management scenarios and the other scenarios where a group of people work to achieve one objective, a number of mobility models such as the Reference Point Group Mobility (RPGM) Model [36], the Reference Velocity Group Mobility (RVGM) Model [37], the Column Mobility Model [11, 38], the Pursue Mobility Model [11, 38], and the Nomadic Community Mobility Model [11,38] have been introduced. In these models, a group of nodes shares a common mobility pattern. More specifically, each group has a logical center which controls the movement patterns (i.e., speed, direction, acceleration, deceleration, etc.) of all its member nodes. In the RVGM model, a mean velocity of a group is used as the velocity for that group. However, in these models, the logical center is chosen based on the RWP model. The Virtual Track Based Mobility Model [39] is another group mobility model where a group of nodes moves as a group along a track. This model captures the two important group dynamics such as split and merge.

Recently a generic framework is proposed in [1] that can generate a set of mobility models called the DGM models. The basic idea behind DGM models is that a fixed number of destinations are assumed to be an integral part of the network and the nodes only move between the destinations. This is a reasonable, realistic, and useful assumption that seldom MANET nodes walk randomly in the network region (as modelled by the random mobility models). By suitably controlling the number and positions of the destinations, and the mobility of nodes between them, several interesting mobility models with increased realism can be modelled and studied. Since this thesis is primarily interested in studying DGM models, we reproduce the definition of MANET incorporating DGM models given in [1].

Definition 1 *A MANET is a sextuple* $< \mathfrak{N}, \mathfrak{R}_{\mathfrak{m}}, \mathfrak{D}, \mathfrak{F}_{\mathfrak{D}}, \mathfrak{F}_{\mathfrak{s}}, \mathfrak{F}_{\mathfrak{c}} >$, *where*

$\mathfrak{N}$ - *a finite set of mobile nodes.*

$\mathfrak{R}_{\mathfrak{m}}$ - *mobility space where the mobile nodes can move.*

$\mathfrak{D}$ - *a finite set of destinations within* $\mathfrak{R}_{\mathfrak{m}}$.

$\mathfrak{F}_{\mathfrak{D}}$ - *a function to choose a destination from* $\mathfrak{D}$.

$\mathfrak{F}_{\mathfrak{s}}$ - *a function to choose travel speed.*

$\mathfrak{F}_{\mathfrak{c}}$ - *a function from* $\mathfrak{D} \times \mathfrak{D}$ *to* $\{0, 1\}$.

$\mathfrak{F}_{\mathfrak{c}}(d_i, d_j) = 1$ means the destinations d_i and d_j are connected and therefore communicate. With suitable implementation of $\mathfrak{F}_{\mathfrak{c}}$, various types of MANETs can be designed. If $\forall i \forall j [\mathfrak{F}_{\mathfrak{c}}(d_i, d_j) = 0]$ then the described MANET has no communication infrastructure.

Definition 2 *A* **pause** ρ *of a node is a period in which it is stationary.*

Definition 3 *A* **leg** τ *is a continuous movement from its current location to a new location in* $\mathfrak{D}$.

Using ρ and τ, we define the mobility of an individual node in $\mathfrak{R}_m$ as follows.

Definition 4 **Mobility** *of a node* i *in* $\mathfrak{R}_m$ *is a sequence* $M_i = \tau_{i1}, \rho_{i1}, \tau_{i2}, \rho_{i2}, \ldots, \tau_{in}, \rho_{in}$ *alternating between two states leg and pause, where* τ_{ik} *and* ρ_{ik} *respectively are the* k^{th} *leg and pause of the node* i.

We can generate several mobility models with desired realism by choosing suitable implementations for ρ and τ. In physical world, destinations are key aspects and they are a set of fixed locations within $\mathfrak{R}_m$ with associated attributes. Each mobile node is associated with a fixed destination as its home station where it originates.

By introducing the set $\mathfrak{D}$ of destinations as an integral part of the model and defining communication infrastructure based on it, we believe that DGM models capture the realism in a much simpler and convenient way.

The destination selection function $\mathfrak{F}_{\mathfrak{D}}$ and the speed selection function $\mathfrak{F}_s$ are the next most significant components in DGM models. Both functions essentially model the transition probabilities and are highly abstract. The functions $\mathfrak{F}_{\mathfrak{D}}$ and $\mathfrak{F}_s$ can introduce realism by properly controlling the probability of choosing the next destination to move and the next speed to be followed respectively.

Another important optional feature of DGM models is the consideration of destinations as stationary transmission nodes. This consideration enhances the capability of DGM models to capture networks beyond the traditional MANETs where no communication infrastructure is assumed. The assumption of some sort of on and off communication support within the network region is becoming increasingly valid as many public and business locations offer complementary Internet service to their customers.

2.2 Analysis of Real Mobility Traces of MANETs

To understand the true behaviour of a routing protocol, the preferred method could be evaluating the protocols using the trace collected from real networks. For this purpose, several organizations [40–45] have started collecting real trace data and make it available for research purpose. CRAWDAD [46] is one such centralized site that maintains links to these data sources that can be accessed publicly for research purpose.

Despite the attractiveness of using real trace, there are several limitations to this approach. First, traces are often not readily available especially for large MANETs. Second, only history of traces is available. So it is difficult to use for future as forthcoming networks and requirements keep changing. Also, collecting real traces involves some other issues such as privacy and cost. Finally, as most of these are collected based on WLAN access points, their accuracy is often limited. Therefore, most research studies have used synthetic mobility models. Very few studies have been done using real traces [4, 20, 36]. These studies include analysing the real traces for some performance metrics and using the traces to validate the accuracy of synthetic mobility models. A survey on the studies related to real traces can be found in [4].

For this thesis, we use a real trace to illustrate the generality of DGM model. Specifically, by suitably adjusting the modelling parameters, we a generate mobility trace using a DGM model which is closer in terms of inter-contact time distribution and contact time distribution to a real trace obtained from [46].

2.3 Mobility Trace Generation and Analysis Tools

There are several network simulators such as NS2 [47], GloMoSim [48], QualNet [49], OPNET [50] and OMNeT++ [51] available for the modelling and simulation of computer networks. Among them, NS2 is the widely used simulator within the network research community. Most of the MANET simulators have included a component to generate basic random mobility of nodes in the network. Later, realizing the inadequacy of the supported mobility models in these network simulators, several independent tools have been proposed to generate mobility models. We review the widely known mobility generator tools below.

- **BonnMotion [52]:** BonnMotion is an open source tool which can be used to create and analyse mobility traces. It was initially developed at the University of Bonn, Germany. Recently, a set of mobility models have been added. Of them, most are random mobility models, four are random group mobility models and others are specific like disaster area, static model, chain scenario and TIMM (Tactical Indoor Mobility Model). These models are implemented as separate components. The tool also provides support for some statistical analysis metrics such as relative mobility, average node degree, the average number of partitions, the degree of separation, the average link duration, and the total number of links. It lacks support for connectivity analysis such as inter-contact time distribution, contact-time distribution and clustering coefficient.

- **IMPORTANT [34]:** The IMPORTANT is a mobility generator that supports the Random Waypoint, the Reference Point Group, the Freeway, and the Manhattan models. It has limited support for statistical analysis which can be used to compute the number of link changes, link duration and path availability.

These metrics can be used to evaluate the impact of the mobility models on the routing protocol performances in wireless ad hoc networks.

- **RMobiGen [53]:** The RMobiGen is mobility generator tool that can be used to specify, visualize, analyse, and generate mobility traces for various random mobility models such as Random Destination-Speed, Random Destination-Time, Random Direction-Speed-Distance, Random Direction-Speed-Time and Random Direction-Time-Distance models. This tool also provide some statistical analysis - the number of leg movements, the average speed, the standard deviation, the average motion time and the idle time, etc.; and connectivity analysis - the number of connection changes, the session duration, and the link duration.

- **VanetMobiSim [24]:** VanetMobiSim is an extension to CanuMobiSim [54], a generic mobility simulator, to support the vehicular mobility. Vehicular network emphasizes on road and traffic regulations. VanetMobiSim can import maps from TIGER [55] database and generate random maps by creating a Voronoi tessellation on a set of non-uniformly distributed points. It models both macro-mobility such as the road topology, the road structure (unidirectional or bidirectional, single or multi-lane), the road characteristics (speed limits, vehicle classes restrictions) and the presence of traffic signs (stop signs, traffic lights), as well as micro-mobility such as an individual car's speed and acceleration.

- **CityMob [56]:** The CityMob is again a mobility trace generator for vehicular ad hoc network, and has implemented three mobility models. In the CityMob, there is no such facilities to create user-defined road topology or extract road topology from any GIS database. It does not provide any support for trace analysis.

- **GMSF [57]:** The Generic Mobility Simulator Framework (GMSF) is another simulation tool for simulating and analysing the node mobility in vehicular ad hoc networks. The GMSF extracts the road topology from the official Swiss nation map and generates mobility trace within the extracted road topology using one of its implemented mobility models. The implemented models are Random Waypoint model, GIS model, Manhattan model and MMTS model. As the network topology is extracted from the road topology which is accessible only by vehicles, the movements of the nodes are constrained to those roads which are accessible by vehicles.

- The other widely known mobility generator tools specially designed for vehicular ad hoc networks are STRAW [58], FreeSim [59], SUMO [60], and MOVE [61]. They all generate traces using the RWP model or Dijkstra's shortest path strategy on the road topology extracted either from a database like Tiger [55] or OSM [62] or from user defined topology.

The main objective of most of these tools was to produce mobility trace, not to analyse the trace. However, our objective is also to provide performance analysis features in our developed tool so that the user can observe dynamically the characteristics of their studied scenarios and then can use the traces for performance study of the networks. Also, these tools support mostly random mobility models and only a few tools support specific scenarios such as Manhattan grid.

The DGMGen differs from other mobility generator tools in several aspects:

- DGMGen is based on the concept of destinations as the main guiding principle of generating traces. That is, DGMGen is designed to generate and analyse the traces of mobility generated by DGM models. None of the above mentioned tools generate mobility trace of a DGM model.

- DGM framework is generic and therefore capable of modelling a variety of real life scenarios. In this sense, the DGMGen is more generic in generating and analysing mobility trace of a variety of real life scenarios.
- DGMGen supports a comprehensive set of trace analysis metrics.
- DGMGen provides a feature to model and compare with real trace.

2.4 Network Performance Analysis

We are interested in studying the performance of the network related to mobility. Specifically, the performance metrics include connectivity, clustering coefficient, and scale-free property.

The connectivity is a fundamental property of a network that reflects the existence of the connection between two nodes [63]. A network is connected if there is a path between every pair of nodes in the network. A network is k-connected if there exist k-disjoint paths between each pair of nodes in the network. The k-connectivity of an ad hoc network ensures that each node can be reached even if any $k-1$ nodes are removed from the network [19, 21]. Several theoretical and some simulation-based analysis related to connectivity, mainly based on RWP mobility model, have been reported in the literature [15–17, 19, 21, 52, 64–66]. Our study on connectivity uses simulations on DGM models, in comparison with the RWP mobility model.

The work [15] studied analytical analysis on the connectivity metrics such as *the number of neighbours of a given node (node degree)*, *the probability of having a path between node pairs*, and *the probability that the entire network is connected* of wireless multi-hop networks in which the nodes move according to the RWP mobility model.

The paper [16] defined and developed the analytic expression for four connectivity metrics, such as *the single-hop connectivity number (node degree)*, *the multi-hop connectivity number*, *connectivity distance* and *the connectivity hops*, in vehicular network environments. The first two metrics indicate how many nodes are reachable by 1-hop path and by multi-hop path respectively from a particular node. The connectivity distance represents the geographic distance between vehicles and the connectivity hops corresponds the number of hops required to reach all nodes in the connected network.

The *k-connectivity*, *contact-time of the connectivity*, and *inter-contact time of the connectivity* of an ad hoc network have been theoretically analysed in [19]. In their studied network, the nodes move according to RWP mobility model. They provided an analytical approximation for estimating the probability that a network is k-connected. Like [19], the work [21] also provided an analytical approximation for the probability that a network is k-connected. Moreover, this paper investigated *the existence of the cluster in their analysis.*

The study in [34] defined some connectivity metrics such as *(average) number of link changes*, *(average) link duration*, *(average) path availability* for analysing the effect of mobility on connectivity graph between mobile nodes. Based on [34], the paper [66] developed four k-hop metrics such as *number of connected node pairs*, *number of connected periods*, *path duration*, and *fraction of connected time* for evaluating the connectivity of nodes in vehicular ad hoc networks.

The work [67] studied real-world mobility and defined metrics such as *inter-contact time* and *contact time*, for observing the possibilities of opportunistic data forwarding. They analysed distributions of these two metrics on real data sets. To analyse connectivity graph of mobile multi-hop wireless networks, the work [52] used *node degree*, *partitions* and *k-connectivity* in their simulation-based study. The study in [53] also conducted simulation based analysis of two connectivity metrics such as *(average)* *number connection of changes* and *link/session duration.*

The authors in [17] contrasted connectivity profiles obtained from RWP and Manhattan grid model against the profiles extracted from a realistic traffic simulator, and showed that widely used MANET mobility models are inadequate to capture the specific properties of VANETs in urban environments. They used *average node degree* and *transitive connectivity* metrics and highlighted multi-hop connectivity in delay tolerant applications in sparse networks. Though this work led the preliminary idea that classical mobility models do not represent realistic connectivity profiles, they didn't show through connectivity analysis and provide what would be impact of the observation on routing protocols.

To characterize mobility models, the work [64] proposed five metrics such as *network diameter*, *neighbourhood instability*, *nodes distributions*, *repetitive behaviour*, and *clustering coefficient.* Using these metrics, mobility models can partially be differentiated. The authors in [65] showed the relationship of input parameters (e.g., transmission range, simulation area, speed) and performance metrics (e.g. total links, link duration). Their simulation results revealed that sometimes based on the configuration, only some metrics are not able to differentiate mobility models. Therefore, we need to study the models based on the more representative set of metrics.

The scale free network describes the class of networks in which the degree distribution of the nodes obeys the power law. The work [68] proposed the *scale-free metric* to measure what extent of a graph/network is scale-free.

Based on the connectivity metrics found in literature, we have presented a representative set of connectivity metrics in the next chapter.

2.5 MANET Routing Protocols

From the literature, we found Ad hoc On-Demand Distance Vector (AODV), Dynamic Source Routing (DSR) and Destination Sequenced Distance Vector (DSDV) are the most widely studied MANET routing protocols [69–72]. Through simulation study, it is shown that the reactive protocols (AODV, DSR) perform significantly better than the proactive protocol DSDV. The author in [73] analysed the performance of DSR protocol under the Reference Point Group Mobility (RPGM) model, and showed that the protocol performance is highly dependent on the mobility behaviour adopted by nodes in MANETs. They used different mobility models where the leader is moved as levyWalk, random direction, probabilistic random direction and random walk models.

Between AODV and DSR, AODV is the more studied routing protocol and it is found that AODV performs better than DSR at higher traffic loads. We are interested in studying AODV protocols under DGM models in comparison with RWP model. Also, we analysed AODV for a set of performance metrics under some representative DGM models.

2.6 Summary

This chapter provided the literature review related to this thesis work. We reviewed mobility models, analysis of real mobility traces of MANETs, mobility trace generation and analysis tools, network performance analysis and MANET routing protocols. Collecting real trace is getting attention among MANETs research community for observing the true behaviour mobile nodes. We discussed the collection, storage, and use of real traces in MANET research. We also reviewed some important mobility generation and network analysis tools and showed how the DGMGen is different from those tools. We also provided a brief survey of the performance metrics (especially connectivity) for analysing the mobility models. Finally, we briefly explained how and why AODV routing protocol has been chosen for our study.

Chapter 3

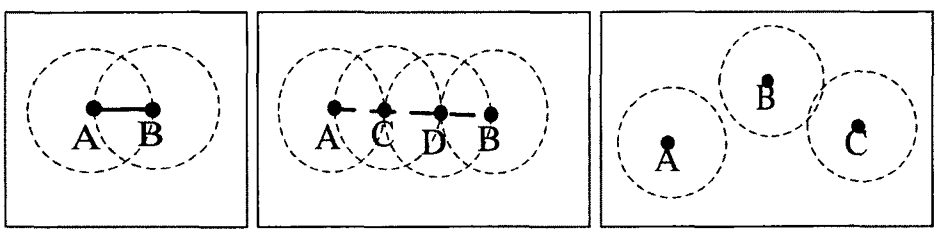
Performance Metrics

Performance metrics of a system indicate how well the system performs. Performance metrics could be quantitative or qualitative. This chapter describes the different quantitative performance metrics for analysing mobility models and routing protocols for MANETs. In this context, the performance of mobility models is measured based on how well the communication is achieved between nodes in the system. This heavily depends on the connectivity between the nodes in the system. Therefore, our focus is mainly connectivity and related metrics for analysing mobility models. For routing protocols, we use packet delivery ration, data loss, and end-to-end delay.

Section 3.1 describes the fundamental concept of connectivity. Following that, we describe the terminology and metrics for connectivity analysis in Section 3.2. Section 3.4 explains some metrics for evaluating the performance of the MANET routing protocols. Finally, we conclude the chapter by providing a brief summary.

3.1 Connectivity Metrics

Connectivity is a fundamental property that reflects the existence of the connection, the link or the path between nodes. For example, if two nodes are within their communication range, they are connected by a link shown in Fig. 3.1(a). If they are not within their communication range but there are some intermediate nodes that help to build a path between the two nodes, then they are connected by a path shown in Fig. 3.1(b). If there exists a set of nodes that are not connected either by a link or by a path, then they are considered as isolated nodes as shown in Fig. 3.1(c). In a static wireless network, the connectivity is primarily influenced by the density of the nodes, the nodes' transmission range, and the network areas. However, in dynamic ad hoc networks including vehicular ad hoc networks, there are some other important parameters that influence the connectivity of the networks. These include the mobility pattern generated by the mobility models, the speed, and the pause time.



(a) Link (b) Path (c) Isolated Nodes

Figure 3.1: Connection by Link and Path or Isolated Nodes

To analyse the connectivity of any network using simulation, we need a good set of connectivity metrics. In the literature, there exists a number of works [15,16,18,19,21, 64] for analysing the connectivity properties of ad hoc networks. Some of them have done analytical studies and the others are simulation-based analyses. Most of these works have done their analysis based on just one or a few metrics for evaluating the connectivity of their studied networks. The work [15] presents the network topology in three viewpoints: single node, two nodes and complete network view, and studies. We have summarized the metrics found in the literature and use some of them to study DGM models.

The following sections describe all the depicted metrics. We, first, define the terminology and then describe the metrics for connectivity analysis based on the defined terminology.

3.2 Terminology

Here, we introduce some terminology needed in defining the performance metrics.

Definition 5 *A link is said to exist between two transmission nodes i and j if and only if they are within their transmission range.*

Definition 6 *A communication path between the nodes i and j is a set of nodes $n_1, n_2, n_3, n_4, ...n_m$ such that $i = n_1$ and $j = n_m$, and a link exists between n_{l-1} and n_l, $1 \leq l \leq n$. The length of this path is $m - 1$.*

Definition 7 *A path is said to be a k-hop path if its length is k.*

Let T be the duration of the experiment, $t \in T$ and N be the number nodes in a network. We define the following functions.

- $P(i,j,t)$: A path at time t. Formally,

$$P(i,j,t) = \begin{cases} 1 & \text{if there exists a path between } i \text{ and } j \text{ at time } t \\ 0 & \text{otherwise} \end{cases}$$

- $P_k(i,j,t)$: A k-hop path at time t. Formally,

$$P_k(i,j,t) = \begin{cases} 1 & \text{if there exists a } k\text{-hop path between } i \text{ and } j \text{ at time } t \\ 0 & \text{otherwise} \end{cases}$$

- $P(i,j)$: A path exists at least once during the simulation time. Formally,

$$P(i,j) = \begin{cases} 1 & \text{if } \exists t \in T \ni P(i,j,t) = 1 \\ 0 & \text{otherwise} \end{cases}$$

- $P_k(i,j)$: A k-hop path exists at least once during the simulation time. Formally,

$$P_k(i,j) = \begin{cases} 1 & \text{if } \exists t \in T \ni P_k(i,j,t) = 1 \\ 0 & \text{otherwise} \end{cases}$$

- $C(i,j)$: The number of contacts between i and j during the simulation time. Formally,

$$C(i,j) = \sum_{t=1}^{T} (1 - P(i,j,t-1)) \cdot P(i,j,t).$$

- $C_k(i,j)$: The number of contacts with k-hop path between i and j during the simulation time. Formally,

$$C_k(i,j) = \sum_{t=1}^{T} (1 - P_k(i,j,t-1)) \cdot P_k(i,j,t).$$

- $N_b(i,t)$: The set of neighbours of node i at time t. Formally,

$$N_b(i,t) = \{j : P_1(i,j,t) \wedge j \neq i\}.$$

- $E_b(i,t)$: The set of edges in the neighbour set $N_b(i,t)$. Formally,

$$E_b(i,t) = \{e_{uv} : u \in N_b(i,t) \wedge v \in N_b(i,t) \wedge P_1(u,v,t) \wedge u \neq v\}.$$

Using the above terminology, next we introduce the connectivity metrics that we intend to study using simulation of nodes mobility in DGM models.

3.3 Connectivity Metrics

- *Repetitive visit:* It is the ratio of time a node spends at its initial service area (or its initial few locations) as compared to the simulation time. The value closer to 1 represents that the model exhibits strong repetitive visit.

- *Node degree (ND):* The node degree of a node at a particular time in a dynamic network represents the number of nodes to which that node is connected with. Formally, the node degree of a node i at time t can be defined as:

$$ND_{(i,t)} = | N_b(i,t) | .$$

  The average node degree of a node i can be defined as:

$$ND_A(i) = \frac{1}{T}\sum_{t=1}^{T} | N_b(i,t) | .$$

  At a particular time, the node degree distribution of an ad hoc network is the distribution of the node degree of all nodes.

- *Clustering coefficient (CC):* The clustering coefficient of a node in a network is the ratio between the number of connections among its neighbours and the number of connections if the neighbours of the node were fully connected. Formally, the clustering coefficient of node i at time t can be defined (when network is undirected) as:

$$CC_{(i,t)} = \frac{2* \mid E_b(i,t) \mid}{n*(n-1)},$$

where $n = \mid N_b(i,t) \mid$ is the number of neighbours of i at t. The node clustering coefficient is termed as local clustering coefficient. In case of ad hoc network, at a particular time, the network clustering coefficient is the average of the clustering coefficients of all nodes at that time. Formally, the clustering coefficient of an ad hoc network consisting of N nodes at time t can be defined as:

$$CC_{Net} = \frac{1}{N}\sum_{i=1}^{N} CC_{(i,t)}.$$

- *Number of connected pairs (N_P):* This is the number of node pairs connected at least once during the simulation period. Formally,

$$N_P = \sum_{i=1}^{N-1}\sum_{j=i+1}^{N} P(i,j).$$

Similarly, the number of node pairs connected at least once with k-hop length path during the simulation time can be defined as

$$N_{P_k} = \sum_{i=1}^{N-1}\sum_{j=i+1}^{N} P_k(i,j).$$

- *Number of contacts (N_C):* This is the total number of contacts among the nodes. Formally,

$$N_C = \sum_{i=1}^{N-1}\sum_{j=i+1}^{N} C(i,j).$$

The average number of contacts is the average of the number of contacts existed in all nodes in the entire simulation time. Formally, the average number of contacts can be defined as

$$N_{AC} = \frac{N_C}{N_P}.$$

The number of contacts with k-hop path can be defined as

$$N_{C_k} = \sum_{i=1}^{N-1} \sum_{j=i+1}^{N} C_k(i,j).$$

- *Number of connection changes (N_{CC}):* It is the number of the link/path apparition and disappearance. This metric intrinsically represents the neighbourhood instability [64].

- *Contact duration (contact time):* It is the time period during which two nodes are connected by a link or a path. The contact duration between a node pair i and j can be defined as

$$CD_{(i,j)} = CD(i, j, t1, t2),$$

where $t1$ is the start time of the contact and $t2$ is the end time of the contact. Therefore, contact duration $t = (t2 - t1)$.

  - **Average contact duration between a pair:** It is the average of all the contact times existed between a node pair.

  - **Contact duration distribution between a node pair:** The contact time distribution between a node pair is the distribution of their contact times during the entire simulation time.

  - **Average contact duration:** It is the average of average contact duration of each node pair in the network.

  - **Contact duration distribution in a network:** The contact-time distribution of a network is the distribution of the contact times happened among all the nodes during the entire simulation time.

- *Inter-contact time:* The interval between two successive contacts between nodes i and j. Suppose, there are two contacts such as $CD(i, j, t1, t2)$ and $CD(i, j, t3, t4)$, happened at $t1$ and $t3$ and finished at $t2$ and $t4$ between nodes i and j respectively. The inter-contact time between nodes i and j can be defined as

$$IC_{(i,j)} = t3 - t2.$$

  - **Average inter-contact time between a node pair**: The average inter-contact time is the average over all inter-contact times computed for a pair of nodes.
  - **Inter-contact time distribution between a node pair:** It is the distribution of all the inter-contact times computed between a node pair during the entire simulation time.
  - **Average inter-contact time in a network:** It is the average over all the inter-contact time computed for the nodes in the entire simulation time.
  - **Inter-contact time distribution in a network:** It is the distribution of the inter-contact time computed for nodes during the entire simulation time.

- *Scale-free metric:* Scale free network describes the class of networks in which the degree distribution of the nodes obeys a power law distribution. More specifically, in a scale-free network, the probability that a node has exactly x neighbours/links follows a power law distribution [74]. That is, there is a $\lambda > 0$ such that

$$P(x) \approx x^{-\lambda}$$

for large x. An important property of scale-free networks is the *preferential attachment and growth.* Social networks, cellular metabolism, research collaborations, world wide web and protein interaction are some examples of scale-free networks. To measure at which extent a network is scale-free, the scale-free metric is proposed in [68]. A more explanation regarding this metric can be found in [68, 74, 75].

To define the scale-free metric in a simplified way, let

- $G = (V, E)$ be a graph where V and E are the sets of nodes and edges, respectively,
- e_{ij} denotes an edge between nodes i and j,
- $deg(i)$ is the degree of node $i \in V$,
- H denotes the set of all the graphs having the identical node degree distribution of G.

the metric $s(G)$ is defined [75] as

$$s(G) = \sum_{e_{ij} \in E} deg(i) \cdot deg(j).$$

The value of $s(G)$ is maximized when high degree nodes are connected to other high degree nodes and $s(G)$ depends only on the graph G not the process of how G has been constructed. Therefore, the scale-free metric can be defined as

$$S(G) = \frac{s(G)}{S_{max}},$$

where S_{max} is the maximized value of $s(H)$. If $S(G)$ closes to 0, the graph/network is *scale-rich* and if $S(G)$ closes to 1, the network is *scale-free* [68, 75].

3.4 Performance Metrics for Routing Protocols

To compare the impact of the DGM models in comparison to the RWP model on performance of routing protocols (e.g., AODV) in MANETs, we use the following metrics.

- *Data loss (D_L):* It is the ratio between the number of lost packets (N_L) and the number of generated data packets (N_T). That is,

$$D_L = \frac{N_L}{N_T}.$$

- *Data delivery ratio (D_R):* It is the ratio between the number of received data packets (N_R) and the number of generated data packets. Formally,

$$D_R = \frac{N_R}{N_T}.$$

- *End-to-end delay (E_D):* It is the time between send and receipt of the data packet.

Data loss and data delivery ration are usually estimated in percentage (i.e., ($D_L \cdot 100\%$) and ($D_R \cdot 100\%$), respectively).

3.5 Summary

In this chapter, we described the performance metrics for analysing the connectivity of the mobility models and evaluating the performance of the MANET routing protocols. First, we explained the basic concept of connectivity that reflects the presence of the connection between nodes. Then, we summarized some important connectivity metrics. These metrics are used to evaluate DGM models. Three performance metrics for analysing MANET routing protocol performance were also discussed.

Chapter 4

Trace Generation and Network Exploration Tools

This chapter describes the architecture and the functionality of the mobility generation and analysis tool, DGMGen. It also describes the architecture of the routing protocol performance suite designed for analysing the performance of a MANET routing protocol. Section 4.1 describes the higher level architecture of DGMGen and its main components. Section 4.2 explains DGMGen from users' point of view. Section 4.3 presents the higher level architecture of the routing protocol performance suite. Finally, Section 4.4 gives a brief summary of this chapter.

4.1 DGMGen - Architecture

DGMGen is a software tool that can be used to generate the trace of mobile nodes in a MANET using DGM models and analyse the trace by visualizing the movements and performance metrics. The tool has a graphical user interface to set input parameters, to visualize the movements, to compute performance metrics, and to show the results dynamically. Internally, it has components to model the destinations and the mobility of nodes, to create mobility trace, to compute performance and animation geometries, and to parse real traces. The higher level architecture of DGMGen is given in Fig. 4.1.

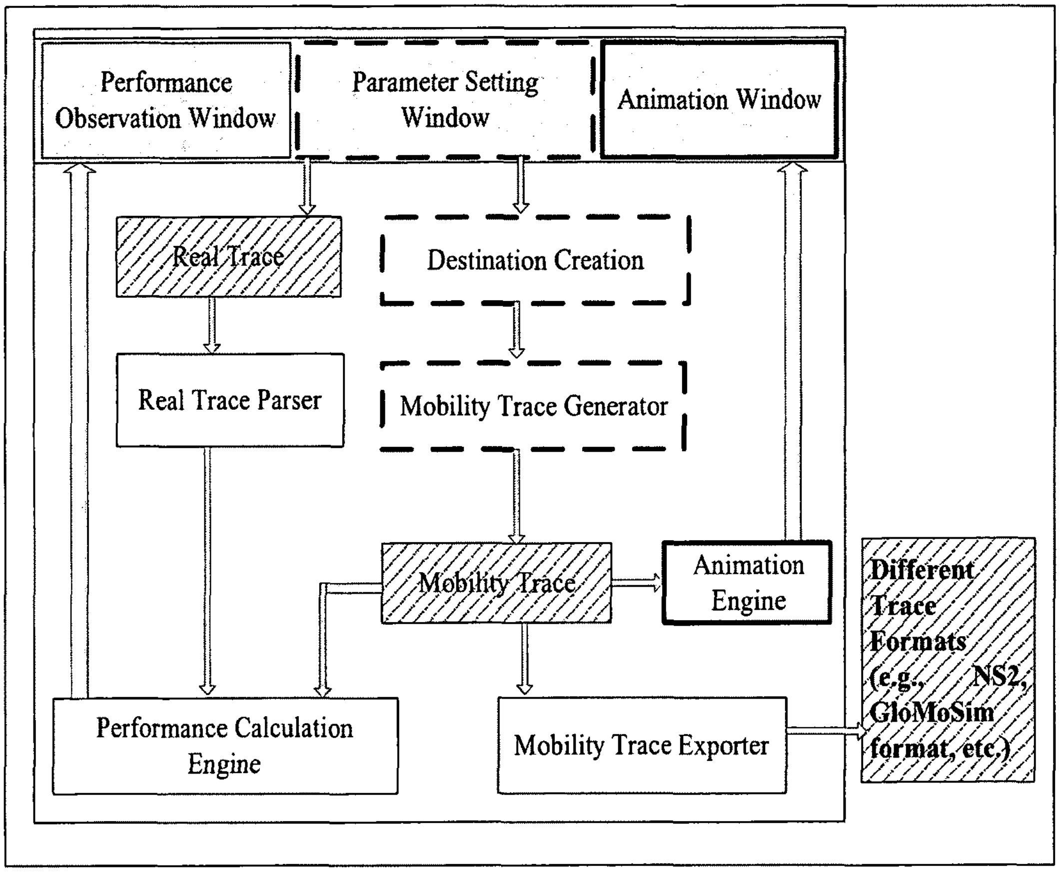


Figure 4.1: Higher Level Architecture of the DGMGen Tool

The development of the DGMGen started in [1], as a part of the effort to present a DGM framework to model and generate mobility traces. In that effort, five components *Parameter Setting Window*, *Destination Creation*, *Mobility Trace Generator*, *Animation Engine*, and *Animation Window* were implemented. These components are shown in bold (solid and dotted) rectangles. The remaining components have been added to increase its functionality. The dotted bold rectangles indicate that the components have been redesigned to enhance the capability of generating more variations of DGM models. The shaded rectangles such as *Real Trace*, *Mobility Trace* and *Different Trace Formats* represent simple files containing the mobility traces in different formats.

The functionality of the main components of our developed tool are briefly described as follows:

- **Parameter Setting Window:** This component is used for initializing the simulation parameters like simulation area, simulation start and end times, specification of mobility, speed and pause-time ranges, probability distributions for choosing speed and pause, and starting the basic simulation environment. It is also used to import real trace files as well as previously saved parameter setting files.

- **Destination Creation:** This component basically helps to create destinations in two modes: (i) one at a time and (ii) as random clusters. The tool also allows addition or deletion of destinations, individually or at a cluster level. While creating a random cluster of destinations, the steps of addition and deletion can be repeated until a desired scenario of destinations is created.

- **Mobility Trace Generator:** The mobility trace generator is accountable for placing the mobile nodes and generating their mobility trace based on the defined parameters. The generated trace, referred to as *Mobility Trace*, contains information required for visualization and statistical and/or connectivity information for further analysis in the *Performance Calculation Engine.*

- **Animation Engine:** This component refines the mobility trace and makes the trace in a presentable form for the *Animation Window.*

- **Animation Window:** This window is used for animating the nodes' movement and visualizing the traces for individual node, as well as for all the nodes together.

- **Real Trace:** Real trace is a mobility trace collected from a real-world network or a practical system. For this thesis, we obtained the real trace from the CRAWDAD repository [76].

- **Real Trace Parser:** This is a parser module which takes the raw real trace data as input from a file, parses it, and produces the trace into a format convenient for the *Performance Calculation Engine* module.

- **Performance Calculation Engine:** The *Performance Calculation Engine* is responsible for analysing the mobility trace (real or synthetic). It takes different synthetic traces generated by mobility models and refined real trace from the *Real Trace Parser* module, computes the performance metrics of these traces and stores the results in different data structures for graphical representation.

- **Mobility Trace Exporter:** This component allows users to export the mobility trace into a desired format (e.g., NS2, NAM) so that it can further be used in the simulation studies of the MANET routing protocols.

- **Performance Observation Window:** This window is used for observing the different performance metrics graphically. It takes the numerical result of each performance metric from the *Performance Calculation Engine* and presents it graphically. The results can be viewed for individual run as well as for multiple runs at the same time.

DGMGen has four main logical functions that are typically invoked in the order for a typical use.

- **Destinations Creation:** To create desired destinations.
- **Mobility Trace Generation:** To generate the trace of the mobile nodes in the system for the desired period.
- **Mobility Trace Analysis:** To analyse the trace visually and using statistical parameters to study the properties of the trace.
- **Mobility Trace Exportation:** To transform the trace in a format that can be used in the network simulator.

4.2 DGMGen- Implementation and Use

The DGMGen has been implemented in Java. With the help of NetBeans IDE 7.0.1, we used Java Swing package, the AWT package and the open source jFreeChart -1.0.13 package to build the graphical user interface (GUI) for the DGMGen. The GUI components of DGMGen have been implemented as hierarchical panels. The seven main GUI components are described here.

- **Parameter Setting Window:** The parameter setting window shown in Fig. 4.2 is used to configure the parameters for the simulation. It allows users to set simulation parameters and node parameters. The input for the simulation parameters are: simulation width, simulation height, duration of simulation, warm up period, node class, and mobility model. The input for the node parameters are: number of nodes (or number of groups and number of members in a group), speed range, pause time range, transmission range, and default probability distributions for choosing speed and pause time. The parameter *Boundary Action* is only used for the RWP model which has been implemented in this tool for comparative analysis purpose. After setting the node parameters, the user can

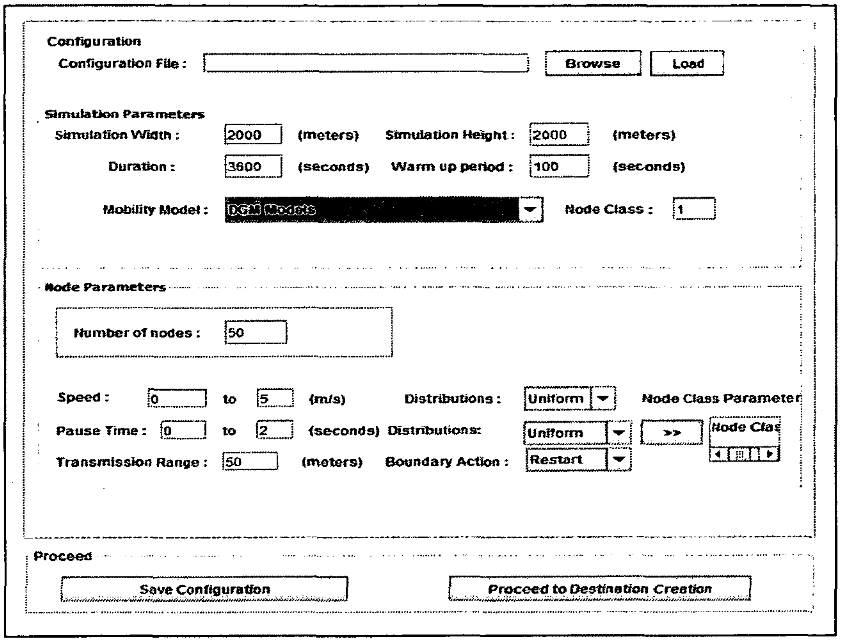


Figure 4.2: The Parameter Setting Window.

add the configured parameters into the *Node Class Parameter* list by pressing the *Double Right Arrow* button. Once the simulation parameters and the node parameters are entered, the user can save the configuration into a file by pressing the *Save Configuration* button. The *Browse* and *Load* buttons are used to retrieve the previously saved configuration file for simulation study. Once the simulation configuration is ready, the user can proceed to the *Destination Creation* phase by pressing the *Proceed to Destination Creation* button.

- **Mobility Generator and Animation Panel:** The mobility generator and animation panel depicted in Fig. 4.3 is used to create destinations (individual or cluster), set priority for transition matrix, generate mobility, see the generated traces, run animation, and save the created destination configuration into a file. This component has four parts: *Destination Draw and Animation*, *Individual*, *Cluster*, and *Mobility Generator* panels. First, the user can create destinations

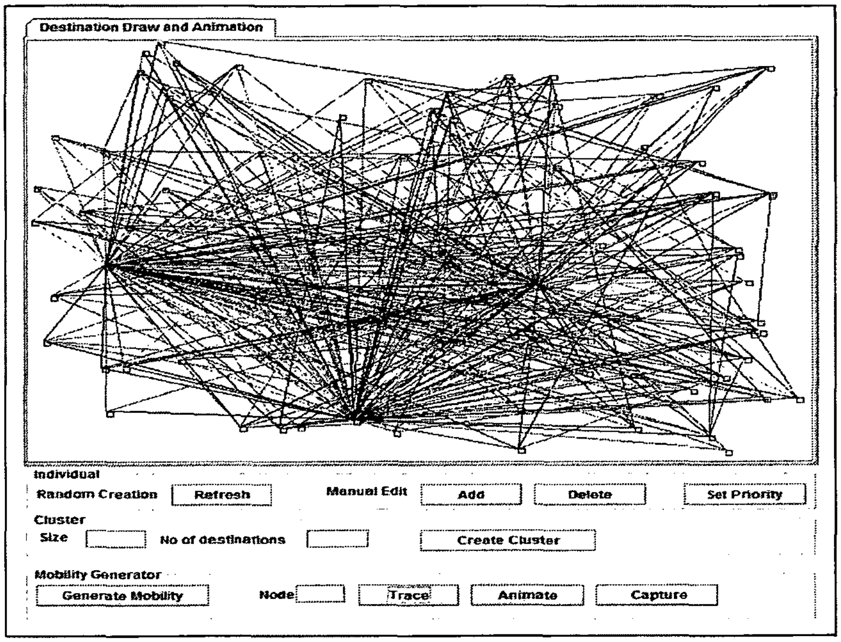


Figure 4.3: The Mobility Generator and Animation Panel.

in the animation window panel by pressing the *Refresh* button. The user can also manually add or delete destinations into/from the *Destination Draw and Animation* panel after pressing the *Add* and *Delete* buttons respectively. The *Set Priority* button is used to set priority to any designed destination individually. To design a cluster-based scenario, at first, a user needs to set the cluster size and the number of destinations in the cluster in the *Size* box and the *No. of destinations* box respectively. Thereafter, by pressing the *Create Cluster* button, one can create his/her desired cluster in the *Animation* panel by clicking the mouse. Once the destination creation is done, the user can generate mobility by pressing the *Generate Mobility* button, observe the trace graphically by pressing the *Trace* button (*Node* box is used if user wants to see the trace of one selected node), run the animation by pressing the *Animate* button, and save the destination configuration into a file by pressing the *Capture* button.

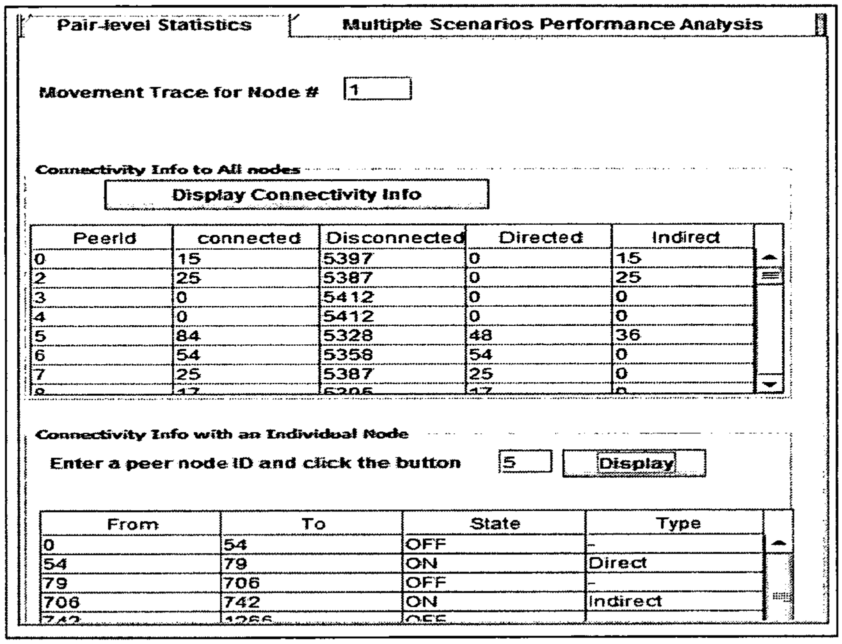


Figure 4.4: The Pair-level Statistics Panel.

- **Pair-level Statistics Panel:** This panel shown in Fig. 4.4 is used for observing the contact time and inter-contact time among node pairs. This component basically allows the user to observe the connectivity (e.g., connection by link or path, contact duration of each individual connection between each node pair, inter-contact time, and so on) among nodes. By putting one node number in the *Movement Trace for Node #* box and pressing the *Display Connectivity Info* button, one can observe the total connected time, disconnected time, directly connected time, or indirectly connected time of the given node with all other nodes in the upper table. Inserting a peer node ID in the box preceded the *Display* button and then pressing the button, the user can observe each contact duration (e.g.,*From, To, State, and Type*) and inter-contact time of the given node with the provided peer node.

- **Single Scenario Performance Analysis Panel:** Both the *Single Scenario*

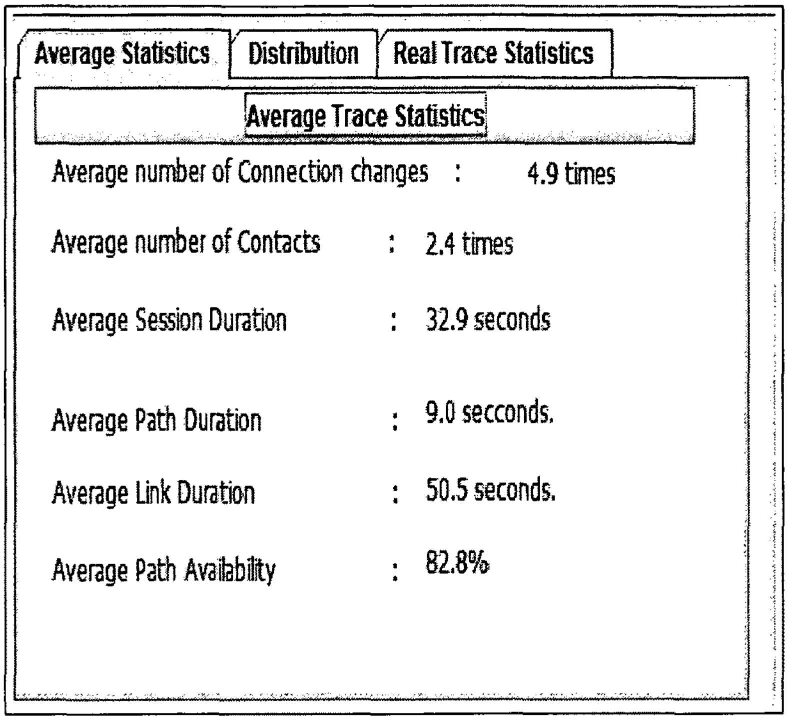


Figure 4.5: The Average Statistics Sub-panel.

Performance Analysis and the *Multiple Scenarios Performance Analysis* panels are used to measure the same set of performance metrics. But the *Single Scenario Performance Analysis Panel* is used to observe the performance metrics for an individual scenario whereas the *Multiple Scenarios Performance Analysis Panel* is designed to observe the performance metrics for multiple runs at the same time. This panel has three sub-panels: *Average Statistics*, *Distribution* and *Real Trace Statistics.* Figure 4.5 expands the *Average Statistics* sub-panel where the user can observe average number of connection changes, average number of contacts, average contact duration, link duration and path duration by pressing the *Average Trace Statistics* button. Figure 4.6 expands the *Distribution* sub-panel under the *Single Scenario Performance Analysis Panel* where the user can observe node degree distribution, node degree distribution at a particular

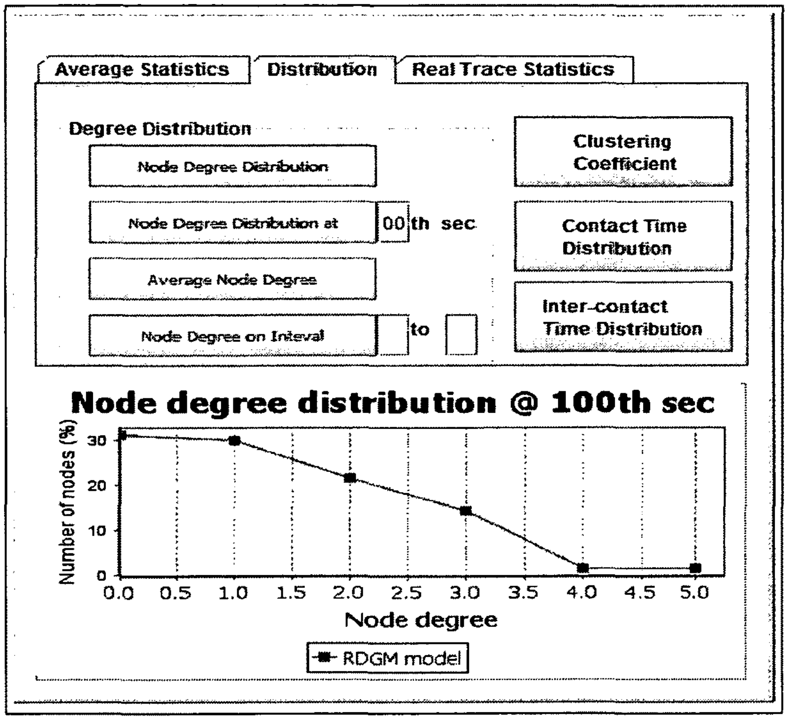


Figure 4.6: The Distribution Sub-panel.

time (e.g., node degree distribution at 100th second has been shown graphically for RDGM model by pressing the *Node Degree Distribution at* button), average node degree, node degree at interval, clustering coefficient, contact-time distribution and inter-contact time distribution by pressing the corresponding captioned buttons.

Figure 4.7 expands the *Real Trace Statistics* sub-panel. Using this component, the user can read a real trace file by selecting the trace name in the *Real Trace Analysis* combo-box and then pressing the *Read Trace* button. Thereafter, the user can observe contact-time and inter-contact time distribution graphically by pressing the *Inter-contact Time Distribution* and *Contact Time Distribution* buttons respectively.

- **Multiple Scenarios Performance Analysis Panel:** This component shown

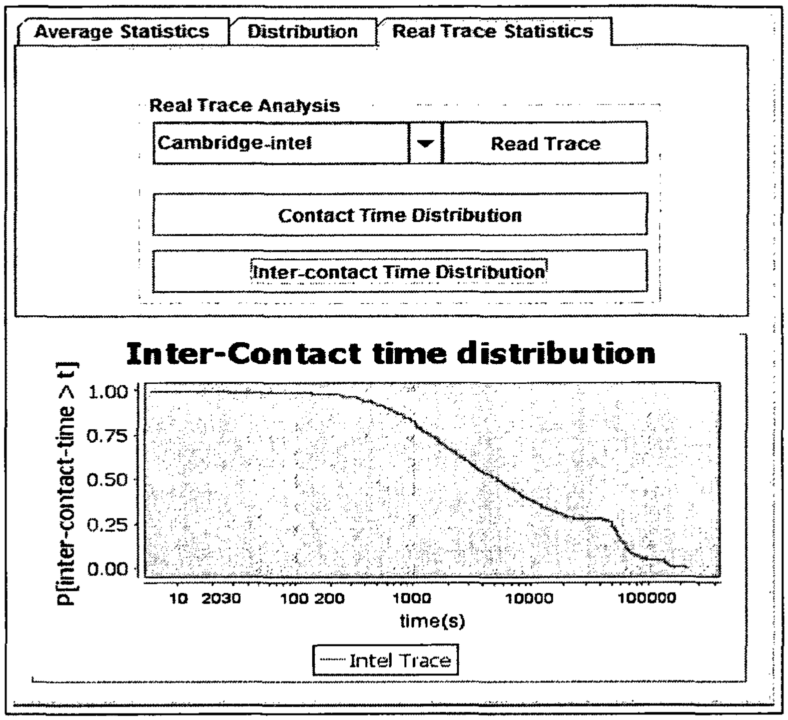


Figure 4.7: The Real Trace Statistics Sub-panel.

in Fig. 4.8 is designed for measuring the same set of performance metrics as the *Single Scenario Performance Analysis Panel.* But it is used to observe the performance metrics of multiple scenarios at the same time. The user can execute multiple runs (multiple models) at the same time in the DGMGen and analyse their comparative results using this panel. The panel has two sub-panels: *Computation* and *Result.* In the *Computation* sub-panel, pressing the *Average Trace Statistics* button, the user can analyse the average number of connection changes, the average number of contacts, the average contact duration, the link duration and the path duration for multiple runs simultaneously. Using the *K-hop Paths* button, the path of distinct lengths are calculated for the entire simulation time. Similarly, the *Clustering Coefficient*, the *Node Degree Distribution*, and the *Contact Time & Inter-contact Time Distribution* compo-

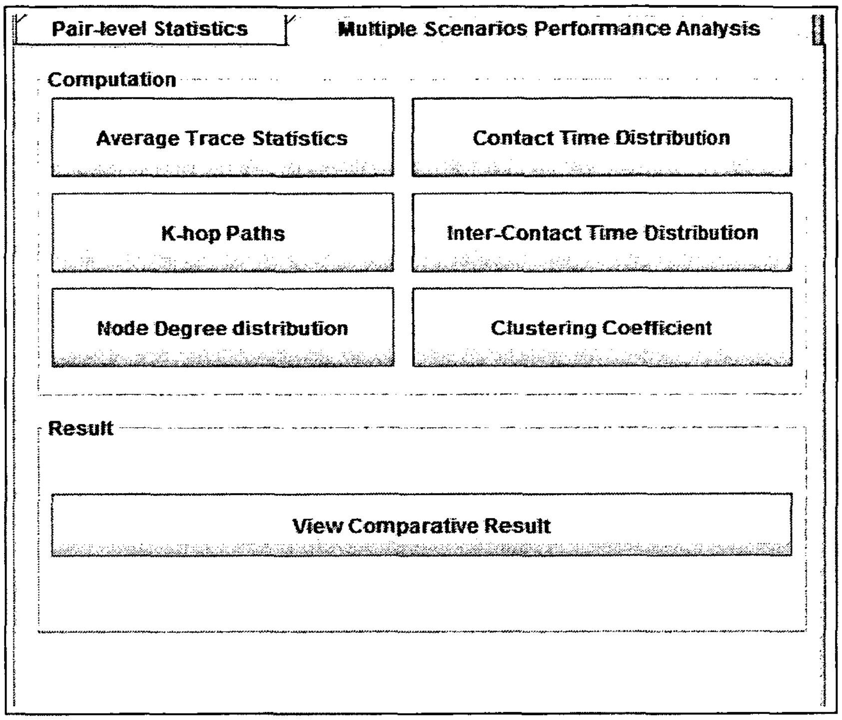


Figure 4.8: The Multiple Scenarios Performance Analysis Panel.

nents provide the facility to measure the clustering coefficient, the node degree distribution, the contact time distribution, and inter-contact time distribution respectively. All of these components allow multiple, simultaneous runs for analysing the respective metrics. The buttons in the *Computation* sub-panel are used to calculate the respective metrics and store the numerical results. The user can observe the calculated results by pressing the *View Comparative Result* button. The *View Comparative Result* button pops up the *Performance Observation Window* where the user can observe their calculated metrics one by one.

- **Performance Observation Window:** The performance observation window, shown in Fig. 4.9 allows the user to observe the result dynamically in graphical mode. The window has an option to choose the performance metrics to be

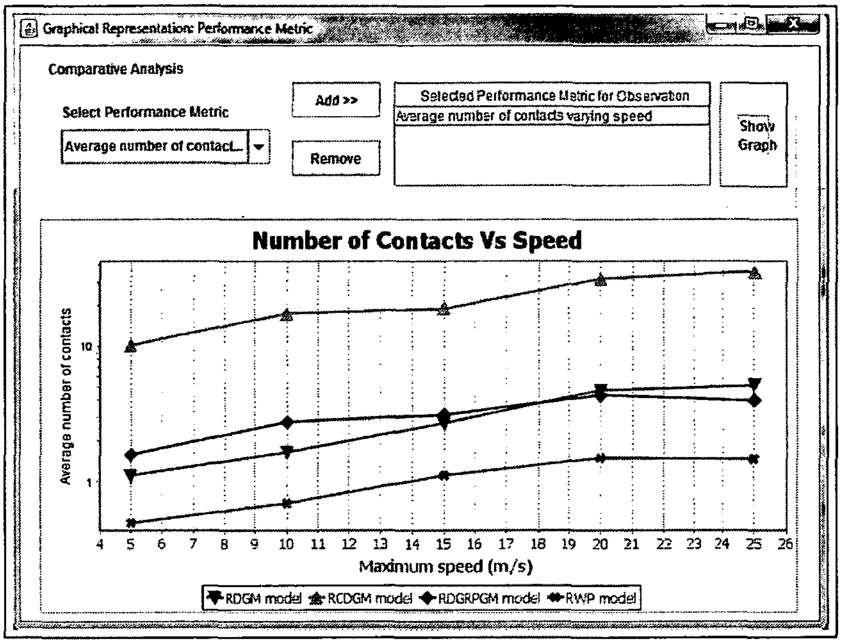


Figure 4.9: The Performance Observation Window in the DGMGen.

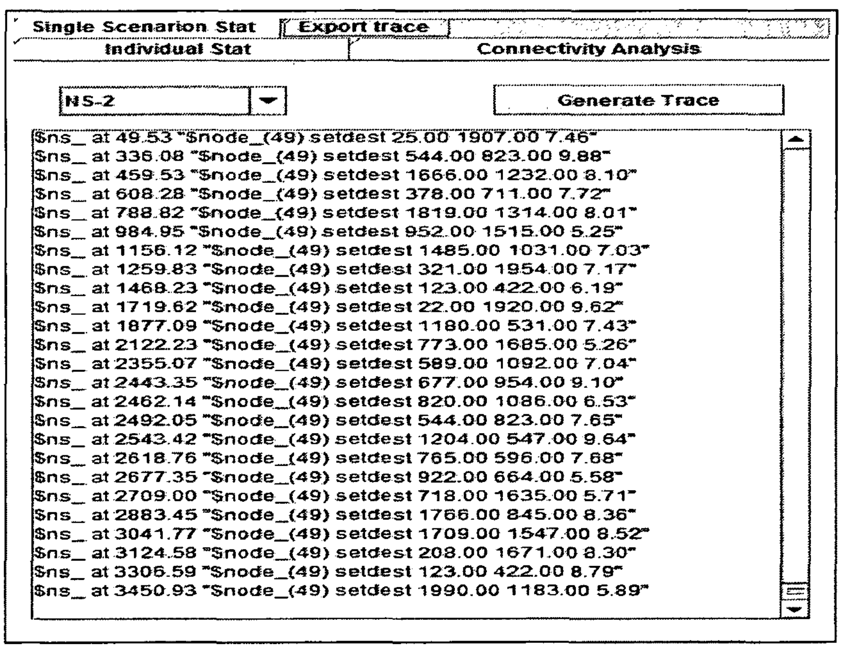


Figure 4.10: The Export Trace Panel of the DGMGen.

observed out of a list of performance metrics. Multiple simulation runs can be observed and the results can be compared at the same time. The user can analyse any metric choosing the desired metric from the given list of metrics.

- **Trace Exporter Panel:** The trace exporter panel shown in Fig. 4.10 is used to convert the generated mobility trace of a particular scenario into the desired network simulator format so that it can be used for analysing the different protocols. This component allows the user to convert the generated mobility trace into NS2, GlomoSim, and NAM format. The user can generate their desired trace by selecting the trace name from the given *Combobox* selector and then pressing the *Generate Trace* button. As an example, the NS2 trace shown in the box in the Fig. 4.10 is obtained by selecting the NS2 format in the drop down combo-box and then pressing the *Generate Trace* button.

4.3 Routing Protocol Performance Suite

The higher level architecture of the routing protocol performance suite is shown in Fig. 4.11. It has six components that are described next.

- **Mobility Trace in NS2 Format:** This component is a file containing a mobility trace generated by DGMGen. The trace is in NS2 format so that the performance of a routing protocol can be executed and tested in NS2.

- **TCL Script:** This component is the TCL (Tool Command Language) script for the routing protocol to be studied. To study the impact of the DGM models, we write the TCL scripts for simulating AODV routing protocol for various configurations and run these TCL scripts using the traces imported from DGMGen in NS2 simulation environment (shown in Fig 4.12). During the execution of

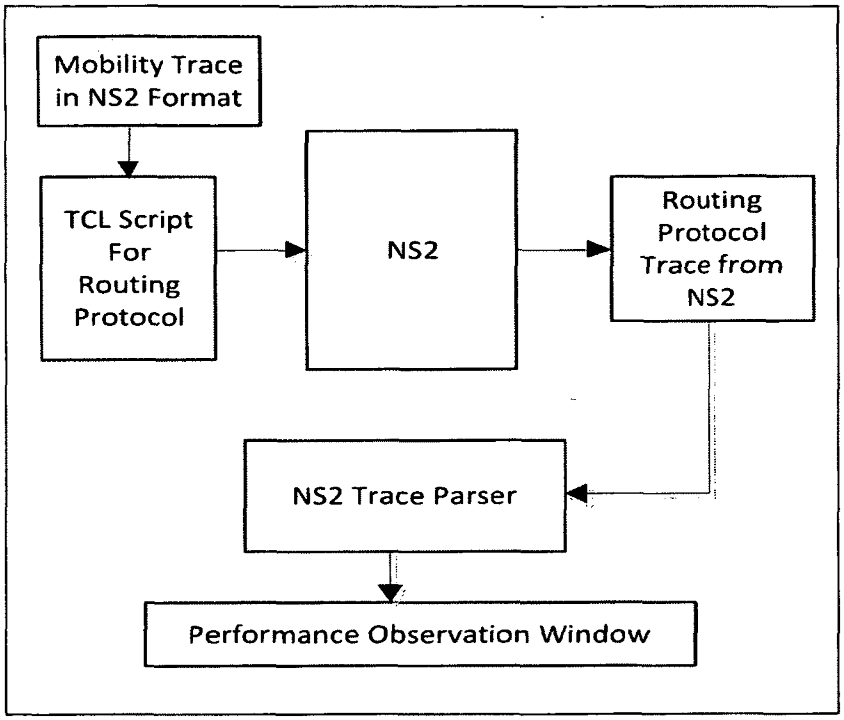


Figure 4.11: The Routing Protocol Performance Suite

those scripts, NS2 generates traces of the AODV routing protocol. The Traces are stored for further analysis.

- **NS2:** The network simulator (NS2) [47], developed by the VINT project supported by DARPA, is a discrete event simulator that provides substantial support for the simulation of the Transmission Control Protocol (TCP) and routing protocols over wired and wireless networks including satellite networks. This simulator provides an environment to simulate mobile nodes with wireless interface as well as multi-hop wireless ad hoc networks. By default, the NS2 supports random waypoint mobility model; however, any mobility model can be imported into NS2 to test the performance of the intended protocols. We used this tool to study the AODV routing protocol.

- **Routing Protocol Traces From NS2:** After running the TCL script written

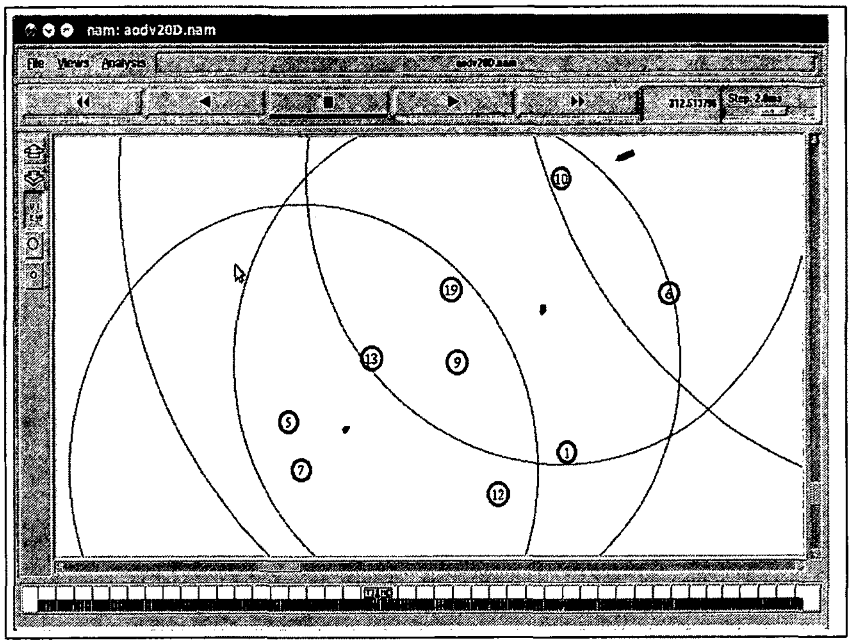


Figure 4.12: A GUI Snapshot of AODV Simulation in Ad Hoc Network in NS2.

```
s 7.915032539 _1_ AGT  --- 23 cbr 512 [0 0 0 0] ------- [1:0 2:0 32 0] [22] 0 0
r 7.915032539 _1_ RTR  --- 23 cbr 512 [0 0 0 0] ------- [1:0 2:0 32 0] [22] 0 0
s 7.915032539 _1_ RTR  --- 23 cbr 532 [0 0 0 0] ------- [1:0 2:0 30 2] [22] 0 0
s 7.915107539 _1_ MAC  --- 0 RTS 44 [14ee 2 1 0]
r 7.915459565 _2_ MAC  --- 0 RTS 44 [14ee 2 1 0]
s 7.915469565 _2_ MAC  --- 0 CTS 38 [13b4 1 0 0]
r 7.915773590 _1_ MAC  --- 0 CTS 38 [13b4 1 0 0]
s 7.915783590 _1_ MAC  --- 23 cbr 590 [13a 2 1 800] ------- [1:0 2:0 30 2] [22] 0 0
r 7.920503616 _2_ MAC  --- 23 cbr 532 [13a 2 1 800] ------- [1:0 2:0 30 2] [22] 1 0
s 7.920513616 _2_ MAC  --- 0 ACK 38 [0 1 0 0]
r 7.920528616 _2_ AGT  --- 23 cbr 532 [13a 2 1 800] ------- [1:0 2:0 30 2] [22] 1 0
r 7.920817641 _1_ MAC  --- 0 ACK 38 [0 1 0 0]
s 7.967622462 _7_ AGT  --- 24 cbr 512 [0 0 0 0] ------- [7:2 9:0 32 0] [1] 0 0
r 7.967622462 _7_ RTR  --- 24 cbr 512 [0 0 0 0] ------- [7:2 9:0 32 0] [1] 0 0
s 7.967622462 _7_ RTR  --- 24 cbr 532 [0 0 0 0] ------- [7:2 9:0 30 9] [1] 0 0
```

Figure 4.13: A Snapshot of AODV Routing Trace File in NS2

for the routing protocol which uses the synthetic mobility trace generated by any of the studied mobility models, the NS2 generates the traces called the routing protocol trace. As an example, a snapshot of a routing protocol trace from NS2 is shown in Fig. 4.13. For each run, one routing trace file is obtained. Those files are stored for further analysis in the *NS2 Trace Parser* module.

- **NS2 Trace Parser:** This is a Java-based parser which takes routing protocol trace file(s) as input, analyses them, and produces a numerical result. It basically parses the trace imported from NS2 and provides the information of how much data have been successfully transferred, what is the delivery ratio, and what is the end-to-end delay for sending the data packet. The numerical result is sent to the *Performance Observation Window* for observing the result graphically.

- **Performance Observation Window:** This module is used to visually observe the studied performance metrics of routing protocols. It takes the numerical result from the *NS2 Trace Parser* and displays the results graphically.

4.4 Summary

In this chapter, we presented the higher level architecture of the DGMGen with its background. We also described how the developed tool can be used to generate the mobility traces, import the real traces, visualize and analyse the connectivity characteristics of those traces, compare those trace characteristics dynamically, export the generated trace into different network simulator formats, and finally produce the result graphically. A higher level architecture of the routing protocol performance suite has also been discussed. In the next chapter, we will present the experiments we conducted for analysing the DGM models and evaluating the performance of one routing protocol using these tools.

Chapter 5

Exploration of DGM Models

The objective of this chapter is to present our study on DGM models. The study is conducted with two main objectives in mind: i) to illustrate the versatility of the DGM models, and ii) to analyse DGM models using connectivity metrics in comparison with RWP mobility model.

The chapter is organized as follows. After providing a brief discussion on DGM models in Section 5.1, we present some representative real-world scenarios in Section 5.2 and, in Section 5.3, show how the different real-world scenarios can be suitably modelled using DGM models. Section 5.4 presents a set of experiments we conducted for analysing the performance (connectivity) of the mobility traces generated by DGM models. A comparative analysis between the generated synthetic trace and the real trace has been shown in Section 5.5. Section 5.6 describes two sets of experiments for evaluating the impact of the studied mobility models on the performance of the AODV routing protocol. We conclude the chapter by providing a brief summary in Section 5.7.

5.1 DGM Models

We start with restating the definition of MANET provided in [1]:

> A MANET is a sextuple $< \mathfrak{N}, \mathfrak{R}_{\mathfrak{m}}, \mathfrak{D}, \mathfrak{F}_{\mathfrak{D}}, \mathfrak{F}_{\mathfrak{s}}, \mathfrak{F}_{\mathfrak{c}} >$, where
>
> > $\mathfrak{N}$ - a finite set of mobile nodes.
> >
> > $\mathfrak{R}_{\mathfrak{m}}$ - mobility space where the mobile nodes can move.
> >
> > $\mathfrak{D}$ - a finite set of destinations within $\mathfrak{R}_{\mathfrak{m}}$.
> >
> > $\mathfrak{F}_{\mathfrak{D}}$ - a function to choose a destination from $\mathfrak{D}$.
> >
> > $\mathfrak{F}_{\mathfrak{s}}$ - a function to choose travel speed.
> >
> > $\mathfrak{F}_{\mathfrak{c}}$ - a function from $\mathfrak{D} \times \mathfrak{D}$ to $\{0, 1\}$.
>
> $\mathfrak{F}_{\mathfrak{c}}(d_i, d_j) = 1$ means the destinations d_i and d_j are connected and therefore they communicate. With suitable implementation of $\mathfrak{F}_{\mathfrak{c}}$, various types of MANETs can be designed. If $\forall i \forall j [\mathfrak{F}_{\mathfrak{c}}(d_i, d_j) = 0]$ then the described MANET has no communication infrastructure.

The models generated using the above framework are called DGM models.

The most significant components in this definition of MANET are the destination selection function $\mathfrak{F}_{\mathfrak{D}}$ and the speed selection function $\mathfrak{F}_{\mathfrak{s}}$. They essentially model the transition probabilities and are highly abstract. These two functions $\mathfrak{F}_{\mathfrak{D}}$ and $\mathfrak{F}_{\mathfrak{s}}$, when implemented properly, can introduce realism in various levels. That is, using these two functions, we can model various scenarios by properly controlling both the probability for choosing the next destination to move and the probability for choosing the speed to travel.

The type of destination, the time, the role, and the speed of the mobile nodes can heavily influence these functions. As an example, let the destination be a bus stop, the time be a morning, and the mobile node be a college student. As individuals usually follow significant regularity in their travel pattern, the most likely destination of this college student is one of the local colleges and his/her speed will be a bus speed.

Moreover, the model deliberately avoids complex geometries; destinations are kept simply as locations. This abstraction keeps the DGM models simple and that will help the researchers to focus on developing and implementing the functions $\mathfrak{F}_{\mathfrak{D}}$ and $\mathfrak{F}_{\mathfrak{s}}$ systematically and gradually to capture more sophisticated mobility models, including group mobility and mobility of vehicular ad hoc networks.

In the next two sections, we present some representative real-world scenarios. We model some of these scenarios using the DGM framework and illustrate how those scenarios are modelled by just controlling the number of destinations and the destination selection function $\mathfrak{F}_{\mathfrak{D}}$.

5.2 Representative MANET Scenarios

To provide some real-world representative scenarios for MANETs, we look from three different perspectives: land, water, and air. We illustrate some interesting MANET scenarios under these topics next.

5.2.1 MANET Scenarios on Land

On land surface, there are many possible MANET scenarios. For example, human/vehicle movement in a city, student movement in a campus, participant movement in a conference, pedestrian mobility in different stations, user movement in a beach or any big recreation place, rescue worker mobility in disaster areas, soldier movement in a battle-field, and human/vehicle movement within and between cities are interesting MANET scenarios. Some of these representative scenarios are described below.

- **City scenarios:** A city generally has a set of popular places such as stores, shopping malls, institutions, parks or recreational places, and so on. People or vehicles in a city most frequently visit these popular places with the preference to the nearest places and less frequently some unpopular or far distant places.

- **Campus scenarios:** A university campus has a set of class rooms/labs, libraries, cafeteria(s), coffee-shop(s), sport centre(s), parking lot(s), and a few gathering places. Students, faculty and staff usually move among these mentioned places and spend their time based on the purpose of visit. For example, a student attending a class normally stays in the class 50 to 80 minutes but the same student usually spends 25 - 30 minutes in Cafeteria. The observation is that the mobility of the students in campus are normally guided mostly by those aforementioned destinations as well as by the time and type of the destinations.

- **Pedestrian mobility in stations:** The scenarios such as train stations, passenger ports or big bus stations have various types of mobile users. These scenarios are not occupied only by the restricted types of users like students in campus environment, participants in conference, and so on. In stations or passenger ports or big bus stations, passengers /pedestrians usually visit ticket counter(s), food court(s), arrival area(s), departure area(s), washroom(s), waiting room(s), and so on. Though the pedestrians have different speed based on the type of pedestrians, their mobility is generally influenced by the mentioned places.

- **Beach or any recreational place scenarios:** At a beach, there are some common places such as volleyball court(s), washroom(s), snack bar(s), and some predefined path through the landscape. Beach users such as sun-bather(s), walker(s), jogger(s), biker(s), and volleyball-player(s) are unevenly distributed over the landscape. Some of the beach users may be stationary while others may move with different characteristics and/or speeds. However, the actions that beach users take are not always random. Rather, some of their movements tend to be toward certain previously mentioned common places and others move in a predefined path through the landscape [77].

- **Inter-city scenarios:** Almost all cities have some popular locations that have already been mentioned in city scenarios. A person or a vehicle generally moves among these popular places within the city and rarely moves randomly in different locations. The same person or vehicle may travel from one city to another city, move within the destination city with a preferred set of destinations in mind, come back to the previous city and the process may be repeated. The observation regarding the mobility of the nodes (e.g., vehicles or peoples) in these scenarios is that their mobility is controlled by the different common places within the city that they most frequently visit and less frequently between cities.

- **Disaster area scenarios:** In the disaster area scenarios, the whole infrastructure for mobile communication may be partially or completely destroyed. In disaster areas, there may be injured people, animals, and so on who need help. To help them, civil protection services work as different groups such as medical teams, fire brigades, rescue teams, and so on. These groups in the disaster area scenario do not move randomly. They walk toward some specified regions in the disaster area and work under the leadership of different group leaders. The authors in [78] studied the two different real-life disasters that happened in

Germany, and divided the disaster area and its surrounding into five different zones: the *technical operation command*, the *incident site*, the *casualties treatment area*, the *transport zone*, and the *hospital zone*. Here, the mobility of the nodes such as medical teams, fire brigades, rescue teams is guided mostly by the regions and the group leader.

- **Battle-field scenarios:** Like the disaster area scenario, a battle-field scenario is a set of strategic locations where soldiers move as different groups. Instead of moving randomly from location to location in the entire battle field area, the soldiers move from one strategic location to another strategic location as a group. The mobility of the nodes (e.g., soldiers, vehicles, tanks) in these types of scenarios is also guided by the different strategic locations (destinations) as well as by the group leader.

5.2.2 MANET Scenarios on/under Water

Under water, some scenarios are single fish movement, the movement of schools of fish, pursuing one fish by the other, and so on. On the surface of the water, ship movements from port to port, and even boat movements between locations defined by different latitudes and longitudes are possible scenarios. Two representative scenarios are given below.

- **Fish movement scenarios:** Fish movement scenario is one of the under water scenarios. Fish generally swim in water randomly. They move or swim individually or as a group. Even the movement of fish sometimes is influenced by the places where foods sources are dense.

- **Ship movement scenarios:** Ship movement scenarios are heavily influenced by their infrastructure/destinations (e.g., ports). Ships travel from one selected port to another selected port.

5.2.3 MANET Scenarios in Air

An aircraft scenario (single or group in military scenario) is one example in this category. Two aircraft scenarios are explained below.

- **Single Aircraft scenarios:** Aircraft are heavily influenced by their destinations (e.g., airports). Single aircraft travel from one military airstrip to another military airstrip or to some predefined destinations; they generally never fly randomly from location to location. Here, the mobility of the nodes such as aircraft is primarily controlled by their airports (destinations).

- **Group aircraft scenarios:** In battle field, a group of aircraft flies together to achieve their strategic objectives. Even in such scenarios, their movements are controlled by different strategic locations in the air defined by the latitude and longitude as well as the land positions.

From a mobile nodes perspective, the nodes either move independently or as a group. Their mobility is typically influenced by their destinations. Both of these points can be closely modelled by suitably controlling the destinations in DGM models.

5.3 Versatility of the DGM Models

To model the scenarios and subsequently study the DGM models, we chose four DGM models that have the potential to represent several of the above described scenarios.

5.3.1 Representative DGM Models

- **RWP model** [1]: This model considers all the points in the simulation region as destinations. The transition probabilities for choosing the next destination, speed, and pause time from their respective given ranges are derived from a uniform distribution. This model can capture the fish movement (individual movement) scenario or the movements of birds flying in the air aimlessly.

- **RDGM (Random Destination Guided Mobility) model:** This model considers a finite set of uniformly distributed points in the simulation region as destinations. The transition probabilities for choosing next destination, speed, and pause-time are generally uniform. By suitably controlling the number of destinations, and the transition probability to choose destinations, we can model the mobility of people/vehicles in a city, in different stations and in beach scenarios.

- **RCDGM (Random Clustered Destination Guided Mobility) model:** This model considers a finite set of points in the simulation region as destinations but these destinations have to be organized into different clusters. Each cluster has its own session time which dictates how long a mobile node will stay inside that cluster once the node enters that cluster. The transition probabilities for choosing the next cluster and the next destination can be uniform or user-defined. By suitably controlling the number of clusters, the number of destinations within cluster, and the transition probabilities for choosing the next cluster and the next destination, we can model scenarios such as campus, beach, inter-city, etc.

[1]RWP modes is an extreme case of DGM models where all the points in the mobility region are considered as destinations. Therefore, we use RWP model as the base model to compare other proper DGM models.

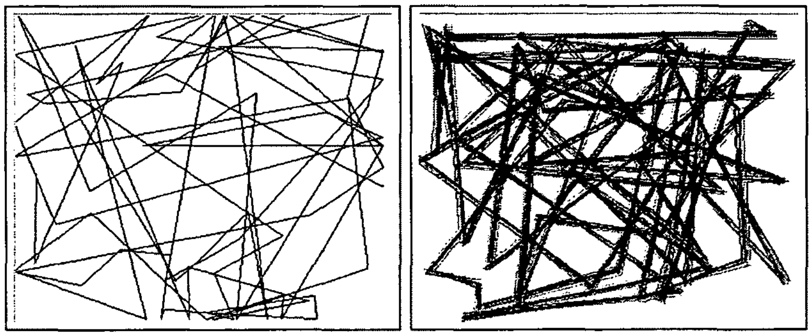
- **RDGRPGM (Random Destination Guided Reference Point Group Mobility) model:** This model considers a finite set of uniformly distributed points in the simulation region as destinations. The transition probabilities for choosing next destinations, speed, and pause time are also uniform. The nodes are divided into different groups; one node from each group is designated as a leader node and the remaining nodes are kept as the member nodes. Only leader nodes choose the next destination based on the transition probabilities but the member nodes follow their respective leader's mobility. This model can capture battle field scenarios, group aircraft scenarios, and, at least partially, disaster area scenarios.

The power of the DGM framework is that it can model various scenarios just by tuning its parameters suitably. We don't require an separate implementation for each scenario. To illustrate, next we model some of the real-world scenarios mentioned in the previous section just by controlling the destination and the destination selection functions of the DGM framework. As a case study, we have considered the following scenarios:

5.3.2 Scenario Modelling

- **Fish movement scenarios:** In these scenarios, the nodes are fish and all the points in the swimming space are the destinations. So the RWP mobility model can capture this scenario (single fish movement). If we consider all points in the simulation area as destinations, we can model the mobility of a group of fish movement using a RDGRPGM model.

  The trace generated by two DGM models (RWP model and its variant) using DGMGen for capturing the movement of a fish or a group of fish moving together



(a) Fish Movement Trace (single) (b) Fish Movement Trace (group)

Figure 5.1: Modelling Fish Movement

shown in Fig. 5.1. Fig. 5.1(a) shows the trace of a single fish movement and Fig. 5.1(b) shows the trace of a group of fish movement. Here, we set all the points in simulation region as destinations, the speed range as 0 - 10 meters/second, and the pause time as 0 - 5 seconds.

- **Ship or aircraft scenarios:** These scenarios can closely be captured by the RDGM model. In these scenarios, the nodes are ships or aircraft. To model these scenarios, each port or airport or landing station is assumed as a destination, the boarding time as the pause time and the travelling speed as the speed. Therefore, a user, based on the number of ports, can define the number of destinations as well as set extra priority to a destination which will represent a busy port.

  The trace of a ship or an aircraft modelled by the RDGM model is shown in Fig. 5.2. Here, we set the number of destinations as 25, speed range as 100 to 150 meters/second, and pause time as 1800 to 3600 seconds to model this scenario.

- **City scenarios:** In city scenarios, the nodes are the people or vehicles. All the common places such as shopping mall(s), different institutions, park(s), or recreational place(s) are preferred destinations and the places are ordinary

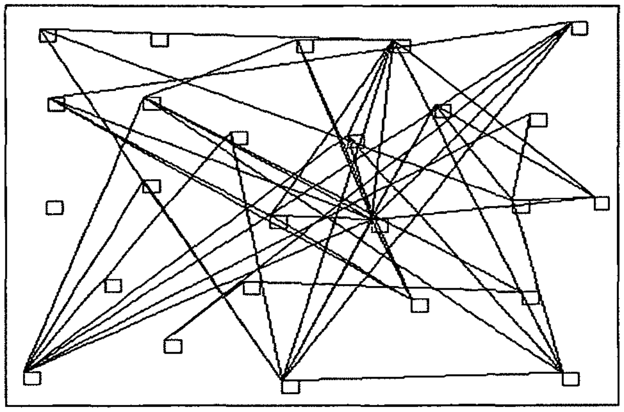
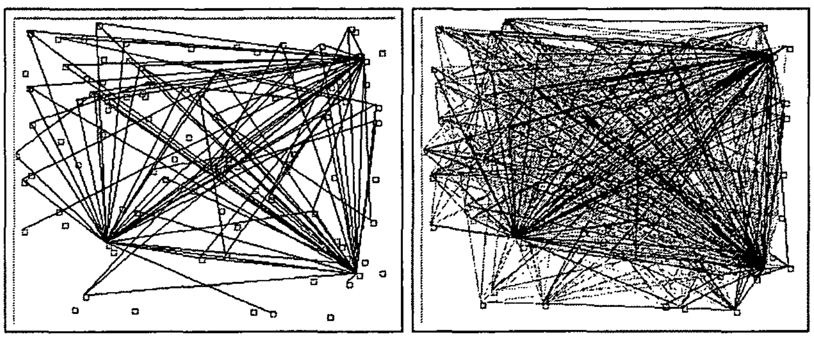


Figure 5.2: Ship or Aircraft Movement Trace

destinations. The RDGM model can closely capture these scenarios.



(a) Single Node Trace (b) Traces of All Nodes

Figure 5.3: Human or Vehicles' Movement Trace in a City

A sample trace for the city scenario modelled by the RDGM model is shown in Fig. 5.3 where few destinations have been assigned higher priority to be chosen by the mobile nodes. Fig. 5.3(a) shows the trace of a single node and Fig. 5.3(b) shows the trace of all the nodes in the simulation. Here, we set the number of destinations as 100 (3 destinations as higher priority destinations), the speed range as 0 - 5 meters/second, and the pause time as 600 - 900 seconds.

- **Campus scenarios:** In these scenarios, the nodes are the students and the common places such as classes, labs, sport centre(s), coffee-shop(s) and cafete-

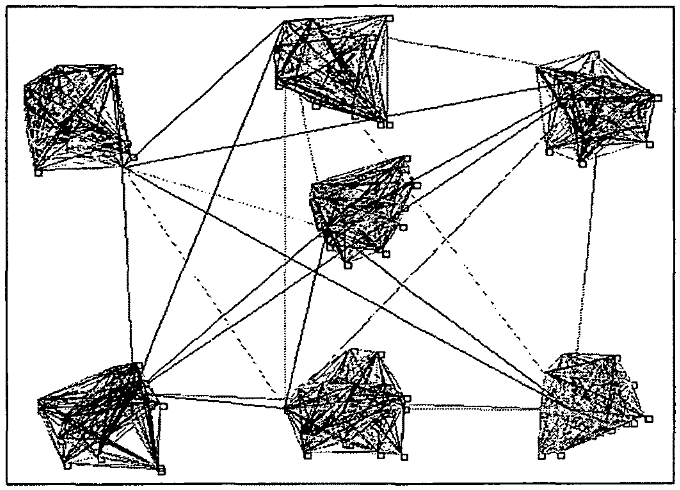


Figure 5.4: Students' Movement Traces in a Campus

ria(s) are considered as clustered destinations. These scenarios can closely be captured by the RCDGM model.

A sample trace of a university campus modelled by the RCDGM model is shown in Fig. 5.4. Here, the session time of each cluster is randomly chosen from 5 minutes to 60 minutes, the speed range as 0 to 2 meters/second, and the pause time varies based on the cluster. Similarly, one can model inter-city scenarios using the RCDGM model.

- **Battle-field scenarios:** In battle-field scenarios, the nodes are the soldiers and tanks (even helicopters). All the strategic locations are the destinations. These scenarios can be captured by the RDGRPGM model.

  A sample trace of group of soldiers' mobility in a battle-filed modelled by the RDGRPGM model is shown in Fig. 5.5. Here, we set the number of destinations as 50, the speed range as 5 - 10 meters/second, the pause time range 0 to 5 seconds, and the group size as 5 nodes.

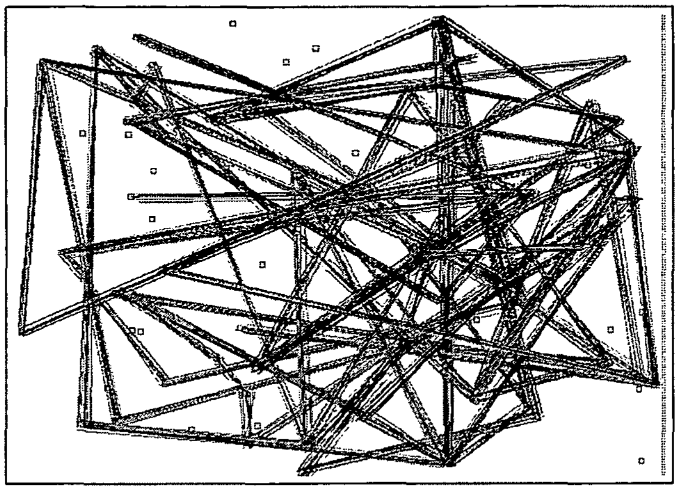


Figure 5.5: One Group Movement Trace in Battle-field Scenarios

Similarly, we can model various real world scenarios including the remaining scenarios mentioned in the previous section by the DGM framework. What the user needs is to set the right parameter after getting the intuition about the scenarios to be modelled.

With this understanding of the representative DGM models, we next analyse them for connectivity metrics. This, in a way, is a comparative study of three proper DGM models with its extreme case, RWP model - a widely used model in MANET simulation so far.

5.4 Connectivity Analysis of the DGM Models

The simulation study of connectivity analysis is conducted using a system with the following configuration:

- Operating System : Ubuntu 10.11
- Processor (CPU) : Intel(R) Core(TM)i7-2600 CPU 3.40GHz

- Installed Memory (RAM) : 12.0 GB
- Mobility Generator and Analysis Tool : DGMGen
- Network Simulator : NS2

5.4.1 Simulation Setup

In this study, we are interested in analysing the connectivity metrics on four mobility models: RWP, RDGM, RCDGM, and RDGRPGM models. The common simulation parameters such as the simulation area, the number of nodes, the transmission range, the speed range, the pause time, and the simulation time, and their values are summarized in Table 5.1.

Parameters	**Value(s)**
Nodes	50
Simulation area	2000m × 2000m
Transmission range	40-100
Speed range	0 m/s - 25 m/s
Pause time range	0s - 2s
Simulation time	1 hour

Table 5.1: Simulation Parameters for Mobility Modelling

For all four models, the pause time is chosen within the given range using uniform distribution. For the RWP model, the next destination within the simulation region is selected using a uniform distribution. The speed of the node is also chosen within the given range using a uniform distribution.

For the RDGM model, one hundred destinations are chosen within the simulation region using a uniform distribution. Each node chooses one of the remaining 99 destinations as its next destination to move and its travelling speed within the given range using a uniform distribution.

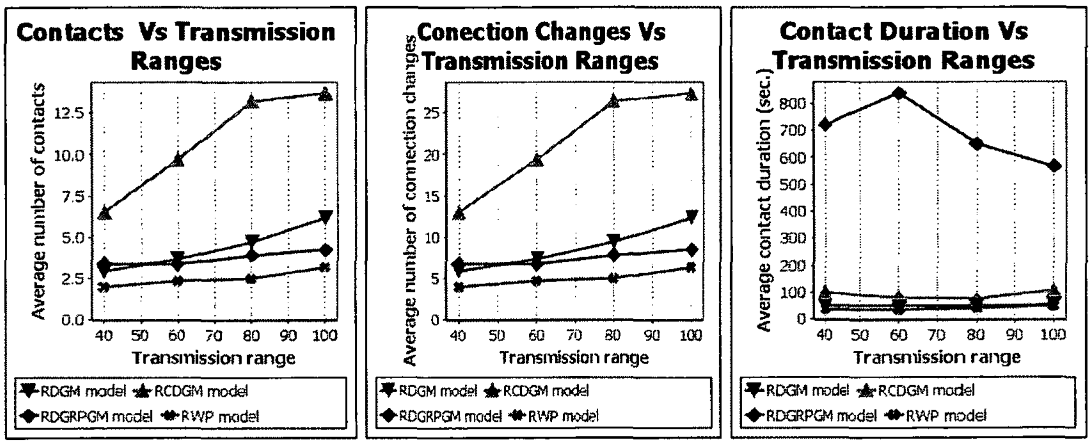
For the RCDGM model, four clusters within the area of 150m $\times$150m in the four corners of the simulation regions are chosen. Each cluster has 25 nodes chosen uniformly within their region. Each node has a home cluster where it is initiated. A node after entering a cluster moves within that cluster for a duration (referred to as a session) chosen uniformly randomly within the range of 0 to 6 minutes (one tenth of the simulation time). After a session expires, a node stays in the same cluster for another session with probability 0.2, may choose to move to another cluster with probability 0.3, or return to its home cluster with probability 0.5.

For the RDGRPGM model, the nodes move as a group where one acts as a group leader and the others act as members of the group. All nodes are organized into different groups. One hundred destinations are chosen within the simulation region using a uniform distribution. The group leader node chooses one of the remaining 99 destinations as its next destination to move to and chooses its travelling speed within the given range using a uniform distributions. The member nodes place themselves randomly around their group leader's current position and move with the same speed as their leader.

5.4.2 Simulation Experiments

The objective of our experiment is to study the connectivity in RDGM, RCDGM, and RDGRPGM models, in comparison with that of the RWP model. Connectivity is a complex metric and has several dimensions. We have conducted two sets each of 3 experiments, mainly observing the connection changes, number of contacts, and contact duration by varying the transmission range and the speed of the nodes.

Experiment 1 *In this experiment, we computed the average number of connection changes, the average number of contacts, and the average contact duration for four* *mobility models, RWP, RDGM, RCDGM, and RDGRPGM, by varying the transmission range as 40m, 60m, 80m, and 100m. The result is shown in Fig. 5.6.*



(a) Number of Contacts (b) Connection Changes (c) Contact Duration

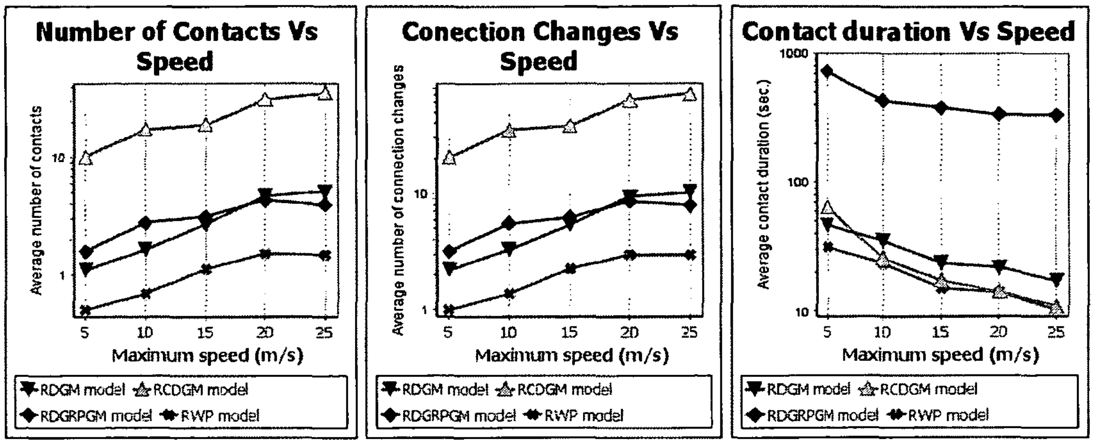
Figure 5.6: Variation of Contacts, Connection Changes, and Contact Duration vs. Transmission Range.

As the nodes in the RWP wander around randomly within the simulation area, a node meets another node rarely. Therefore, the average number of contacts is low for the RWP model, as shown in Fig. 5.6(a). Since the nodes rarely establish contacts with other nodes, the average number of connection changes is also low as shown in Fig. 5.6(b). Though the number of contacts and the connection change increases as the increment in transmission range, the trend is very low. The contact duration in all cases for the RWP model is also low as compared to the other models. As this model is very random, it provides the least number of contacts and the contact duration. As a result, any performance study of routing protocol on the RWP model will be biased by the random property of this model which may not be true in many real scenarios.

On the other hand in the RDGM, as mobile nodes choose destination from a fixed set of locations, more nodes will choose the common location. When they move toward the selected destination, they will have higher chance to have contact with one another. As a result, the average number of connection changes and the number of contacts are higher than that of the RWP model. The almost increases linearly as the transmission range increases. However, in the RCDGM, the average number of connection changes and contacts increases very sharply as the nodes' transmission range increases. This is because destinations are placed in compact way within a smaller region. Therefore, the nodes have a higher chance to meet. However, after certain ranges, the trend is flat and even goes down. This is because the connected nodes remain connected for long time for their high transmission range. The contact duration has the opposite effect as shown in Fig. 5.6(c). In the RDGRPGM model, the contact duration increases as the increment of the transmission range upto 60 meters but the duration decreases after that level. This is because the likelihood of one group of nodes meeting with another group of nodes for higher transmission range is high but contact time is low as they are different groups; however these contacts have greater impact on the average contact time.

Experiment 2 *In this experiment, we computed the average number of connection changes, the average number of contacts, and the average contact duration for four mobility models, RWP, RDGM, RCDGM, and RDGRPGM models, by varying the speed as 5 m/s, 10 m/s, 15 m/s, 20 m/s, and 25 m/s while keeping the number of nodes fixed at 50 and keeping other parameters constant. For the RDGRPGM, 50 nodes are divided into 10 groups; each group consists of 5 nodes. The result is shown in Fig. 5.7.*

Again, as explained with Experiment 3, the performance under the RWP model is not properly pronounced as compared to the DGM models and therefore, the RWP model may not be a suitable model to study protocols useful for practical MANETs.



(a) Number of Contacts (b) Connection Changes (c) Contact Duration

Figure 5.7: Variation of Contacts, Connection Changes, Contact Duration vs. Speed.

When the same study is repeated on the RDGM and the RCDGM models, the performance on the average number of contacts, connection changes, and contact duration are high. Furthermore, their variations with respect to change in the speed are sensitive, as they increase (or decrease) almost linearly, as shown in Fig. 5.7(a - c). The almost linear trend in performance is clear that the slower nodes can have fewer contacts overall, but each contact can last longer. The reason for the better performance of the RCDGM over RDGM model is intuitive in that in the RCDGM model the nodes have higher probability of staying longer time within the same cluster (smaller region), and hence have a higher chance of being connected longer.

For an experimental result to be useful and relevant, the performance results must be significant and sensitive to the changes of the critical parameters of MANETs such as nodes' speed and their transmission range. From these experiments, we observe that all the models are sensitive to the changes of nodes' transmission range and speed. We observed that DGM models always perform better. Therefore, we believe that the performance study of protocols must be conducted based on more realistic mobility models such as DGM models for the results to be more credible and useful.

Experiment 3 *In this experiment, we computed the clustering coefficient of the ad hoc networks generated by the studied mobility models while keeping the speed range at 5 -10 m/s, the number of nodes as 50, the transmission range as 50 meters, and all of the other parameters at the default shown in Table 5.1. The result for a selected duration (0 to 1000 second) is shown in Fig. 5.8.*

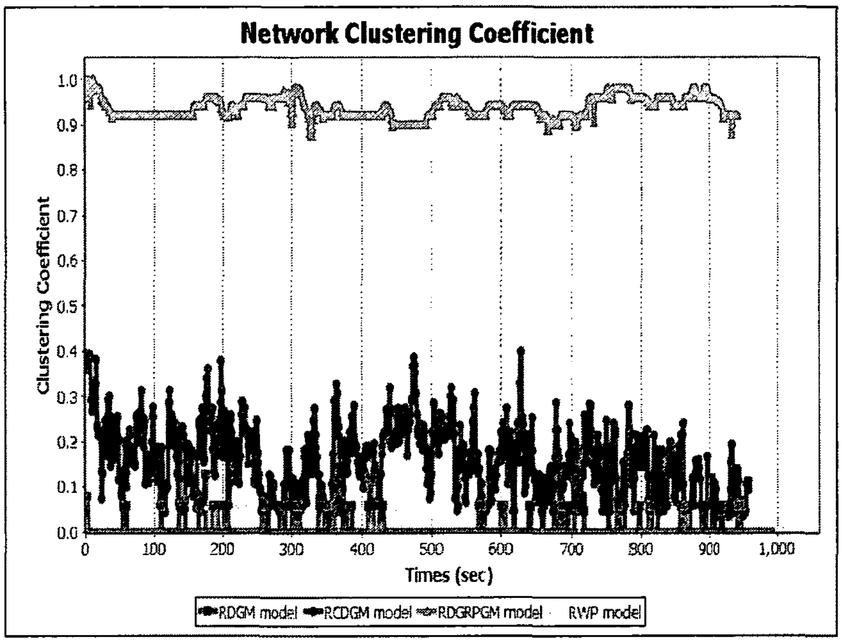


Figure 5.8: Clustering Coefficient of the Networks Generated by the Studied Models.

As the nodes wander around in the RWP model, the clustering coefficient of the ad-hoc network generated by the RWP model shows a very poor connection in the entire simulation time shown in Fig. 5.8. In contrast to the RWP model, the RDGM model represents a network that is better connected than that of the RWP model. The primary reason behind this is that the nodes move among the selected destinations only; they do not wander around randomly within the entire simulation area. The network generated by the RCDGM model is far more connected than even that of the RDGM model. This is because the nodes move most of the time within the cluster where the destinations are arranged very compactly within the different clusters and travel between the clusters less frequently. The other DGM model, the RDGRPGM model, which shows that the network is almost fully connected as the nodes move as a group from destination to destination. When the nodes move as a group, the nodes of one group maintain connection within the group most of the time. From the graph shown in 5.8, we can easily infer that DGM models provide better connectivity than that of RWP model. This, we believe, is the likely case for many real life MANETs.

Experiment 4 *In this experiment, we computed the node degree distribution at a particular time instant of the networks generated by the RDGM, the RCDGM, and the RWP models in the configuration where the number of nodes is 50, the speed range 5 -10 meters/second, the transmission range is 50 meters, and all other parameters remain the same as shown in Table 5.1. The result is shown in Fig. 5.9.*

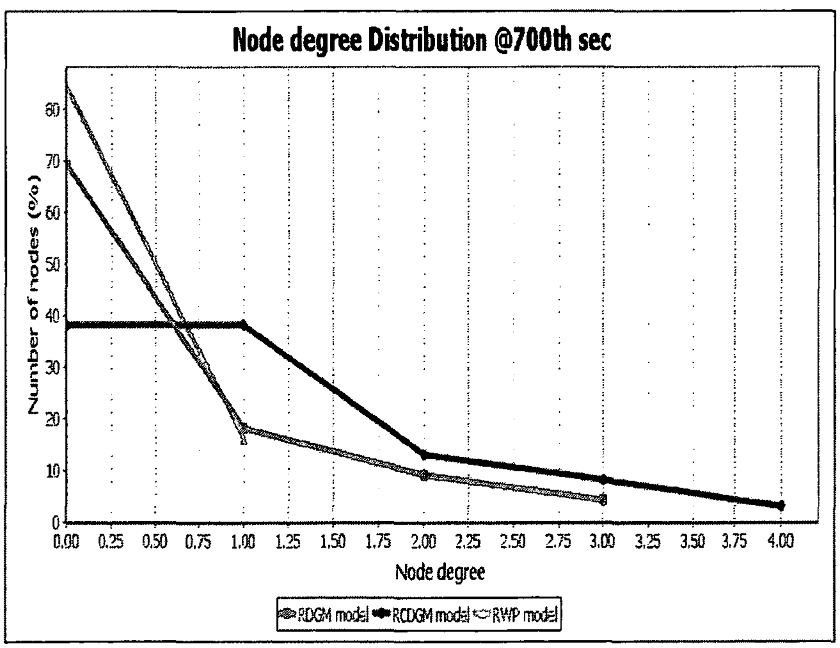


Figure 5.9: Degree Distribution of the Networks Generated by Three Studied Models.

The graph shown in Fig. 5.9 presents what percentages of the nodes have connected neighbours and how many neighbours are there for a particular node in the network. At a particular time, say at 700th second, almost 85% of nodes are isolated and even though the remaining 15% have connected neighbours, but they have only one neighbour in RWP model. In contrast to the RWP model, 69% of nodes are isolated and the remaining 31% have connection to other nodes. Of them, 19% have one neighbour, 9% have two connected neighbours and 3% even have three neighbours. In the RCDGM model, 39% of nodes are isolated at the observed time while the remaining 61% have 1 to 4 neighbours. Of the connected nodes, 37% have one neighbour, 15% have two neighbours, 6% have three neighbours and the remaining 3% have even four neighbours. Both the RDGM and the RCDGM models have the trends that reflect the power law distribution in terms of node degree distribution. This is because the nodes visit within the destinations arranged in different compact area for the RCDGM model and move only among the selected destinations. So, the nodes have higher chances to meet one another in the RDGM model and a far better chance to meet one another in the RCDGM model than that of the RWP model. This graph clearly shows that if the nodes move following the DGM models, then they will have higher chance to meet other peers. This happens in most of the real world scenarios.

Experiment 5 *In this experiment, we computed the number of different hop length paths seen during the entire simulation in the networks generated by the RDGM, the RCDGM, and the RWP models in the configuration where the number of nodes is 100, the speed range 5 -10 meters/second, the transmission range is 50 meters, and all of the other parameters remain the same as shown in Table 5.1. The result is shown in Fig. 5.10.*

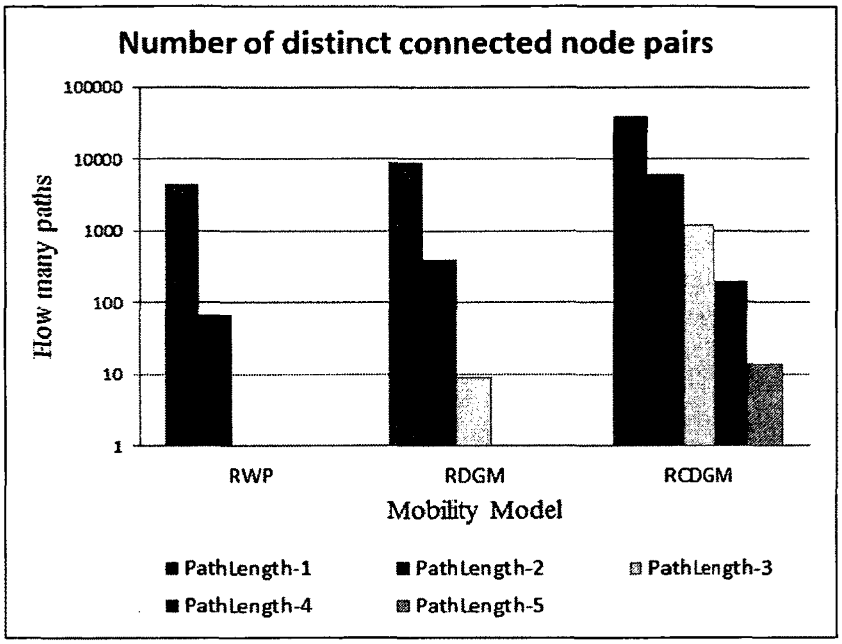


Figure 5.10: Number of Different Hop Length Paths During the Simulations

This Fig. 5.10 shows how many distinct length paths exist under different mobility models. The RCDGM model has 1-hop to 5-hop length paths, the RDGM has 1-hop to 3-hop length paths and the RWP has 1-hop to 2-hop length paths. Again, as the nodes wander around in the RWP model, one node meets another node rarely and if they meet, they are connected mostly by link and less frequently by 2-hop length paths. By contrast, the RDGM model has some 3-hop length paths. This is because the RDGM model uses a limited number of destinations; therefore, a set of nodes can build a larger length when entering/leaving into/from any common destination. The reason for having higher length paths in the RCDGM model is that the nodes are visiting the destinations that are arranged in a cluster. The presence of the long paths reflects that the respective model conforms better connectivity and captures clustering nature as well as series nature (e.g., a set of vehicles follows the same road) seen in real world scenarios.

5.5 Modelling and Analysis a Scenario Based on Real Trace

So far, we have seen how to model mobility of known scenarios using DGM models. Suppose we have a real trace of a mobility model collected from a scenario which is not explicitly known. The question is: can we model that scenario using DGM models? This section is an attempt to answer this question. We take a real trace collected from the Haggel project at Cambridge [46] and derive intuition to determine the number of destinations, the number of nodes, the pause time, the speed, and the transition probabilities to choose the next destination. A snapshot of the real trace is shown in Fig. 5.11.

ID1	ID2	BeginContactTime	EndContactTime	iThContactTime,	InterContactTime
1	8	121	121	1	0
1	3	236	347	1	0
1	4	236	347	1	0
1	5	121	464	1	0
1	**8**	**585**	**585**	**2**	**464**
1	10	589	589	1	0
1	5	700	816	2	236
1	3	589	940	2	242
1	4	589	940	2	242
1	9	940	940	1	0
1	2	1306	1306	1	0
1	11	121	1430	1	0
1	12	1430	1430	1	0
1	8	1662	1662	3	1077
1	13	121	1782	1	0
1	8	2025	2158	4	363
1	13	2275	2387	2	493

Figure 5.11: A Snapshot of Real Trace That Contains Contact Information Recorded by iMote Devices

In Fig. 5.11, the first and second columns represent the devices' IDs. First column gives ID of the devices which record the seen device ID represented in the second column. The third and fourth columns show the start time and the end time ID1 meets ID2. The fifth column enumerates the number of contacts happened between ID1 and ID2. The last column shows the time difference between the end of previous contact and the beginning of the current contact of ID1 and ID2. This real trace is about a group of users carrying small devices for six days in the *Intel Research Cambridge Corporate Laboratory*. The users are research students. The intuition behind this trace is that the probability of the users to stay a long time at the lab is high, the number of travelling places might be limited, they may visit a number of place in the university (that could be representative in cluster), and so on.

Based on this intuition that we get from the given real trace, we have considered the following simulation parameters for modelling this scenario using DGM models.

Parameters	**Value(s)**
Nodes	9
Number of destinations	15
Cluster size	100m × 100m
Destinations in a cluster	3
Cluster session time	0 - 8 hours
Simulation area	2000m × 2000m
Transmission range	50
Speed range	0 m/s - 5 m/s
Pause time range	0s - 1800s
Simulation time	3 days (259200s)

Table 5.2: Simulation Parameters for Modelling Scenario Derived from Real Trace

Using the above simulation configuration, we have conducted the following two experiments.

Experiment 6 *In this experiment, we computed and compared the inter-contact time distribution of the generated synthetic traces with that of the real trace collected from the Haggel project at Cambridge [46]. The result is shown in Fig. 5.12.*

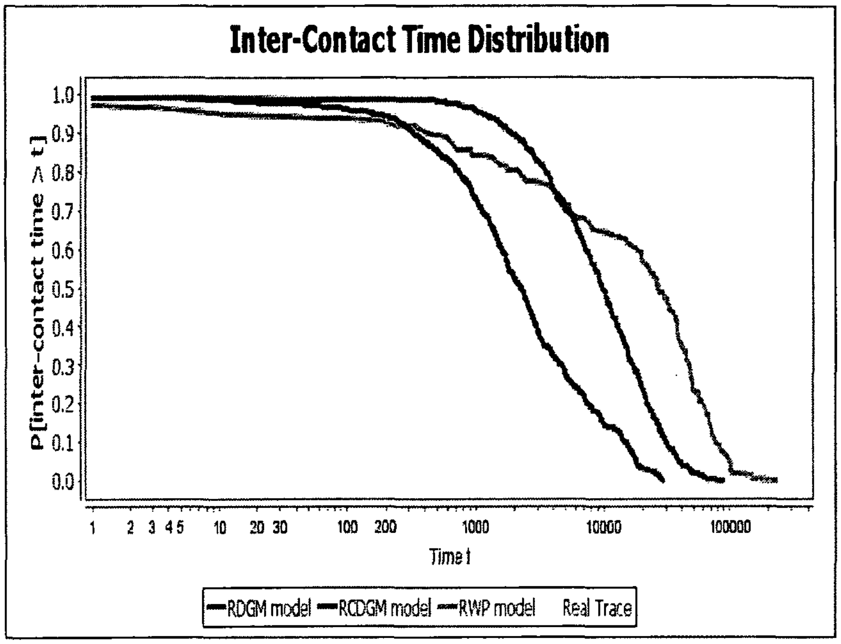


Figure 5.12: Inter-contact Time Distribution

The graph shown in Fig. 5.12 presents the inter-contact time distribution of the node pairs in the networks generated by the chosen DGM models and the real trace. In this test, as compared to the RWP model, the RDGM, and the RCDGM models show the closer proximity to that of the real trace. The trend of the inter-contact time distribution follows the power law distribution which is one of the important properties of many real world networks such as collaboration networks, Internet, WWW, protein-protein interaction network, social networks, and so on. The possible reason for showing the close proximity in the RDGM and the RCDGM models are the number of limited contact locations, the cluster size and its session time, and the transition probability. The trend is even closer in case of the RCDGM model. This is because the destinations are organized as cluster consisting of only a few destinations and the nodes frequently visit within a cluster, which is also true in the activity of research students.

Though it is difficult to model a scenario accurately based on intuition alone, our observation is that the DGM models can be the good choice as it has a set of parameters such as destinations, transitions probabilities to choose destination, and cluster size that can be tuned to fit the real world scenario to be studied. Although the inter-contact time is totally random for this experiment for all models, this can be tuned to represent the real-world scenario in the DGM models by properly choosing the destination as well as by incorporating the activity properties of the nodes.

Experiment 7 *In this experiment, we computed and compared the contact time distribution of our generated synthetic traces with that of the real trace collected from the Haggel project at Cambridge [46]. The comparative result is shown in Fig. 5.13.*

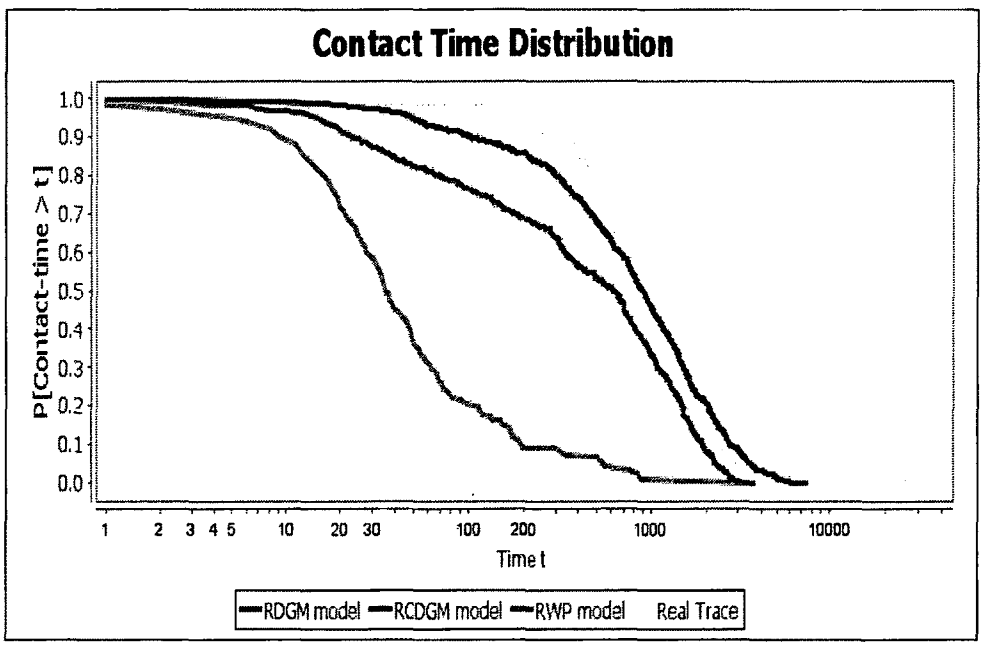


Figure 5.13: Contact Time Distribution

In Fig. 5.13, the trends of the contact time distribution of the studied traces clearly depict that the RDGM and the RCDGM models show similar trend as to the real trace. This is because the number of destinations are very limited (which might be also true in the real trace as research students rarely visit a large number of places). The trend is even very close in case of the RCDGM model. The reason behind this is that the destinations are organized into clusters consisting of only few destinations. The nodes move within the cluster frequently which is also true in the students' life. They may stay in lab, go to take class and spend time in cafeteria. During these times, they may remain connected. Similarly, the size of the clusters influences the contact time distribution.

From this observation, we believe that we can model a scenario based on real trace more accurately by tuning parameters like the number of destinations, the transition probability, the speed range, the pause time, the cluster size, and the session time of cluster. Though modelling a scenario based on real trace is a complex task, it is possible through trial and error process if we have a sufficient insight of the real trace. In this perspective, DGM models provide the better tuning mechanisms to model a real world scenario.

5.6 Performance Study on MANET Routing Protocol

In this section, we present the performance study on a MANET routing protocol, AODV, under DGM models in comparison with the RWP model. The performance is measured based on the protocol performance metrics mentioned in Chapter 3. Here we describe what was the simulation setup we followed, and then illustrate the experiments we did. Throughout the experiments, the behaviour of AODV is better pronounced in DGM models than that of the RWP mobility model.

5.6.1 Simulation Setup

In this study, we are interested in analyzing the performance of AODV based on the four mobility models. We use NS2 to conduct our simulation of routing. The common simulation parameters such as the number of nodes, the speed range, the simulation region, the data sources, the transmission range, the simulation time, and their values are summarized in Table 5.3.

Parameters Name	**Value(s)**
Number of nodes	40 - 80
Node speed range	5 - 10 m/s
Simulation region	2000m × 2000m
Data sources	30 - 50 CBR sources(4 pkt/sec, Packet size 512)
Transmission range	250m
Routing protocol	AODV
Simulation time	700 sec + 400 sec warmup

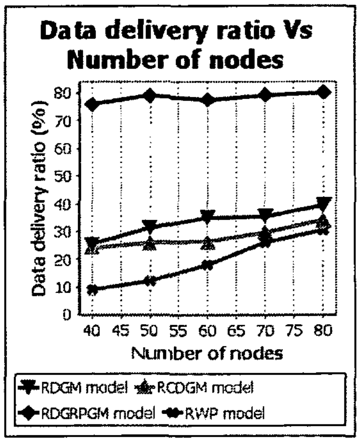
Table 5.3: NS2 Simulation Parameters

Mobility traces of the RWP, the RDGM, the RCDGM and the RDGRPGM models were generated using the DGMGen software tool. For all four models, the traces are generated by varying the number of nodes as 40, 50, 60, 70, and 80, and the speed range as 5 to 10 m/s. We used CMU generator embedded in NS2 to generate CBR traffics as data.

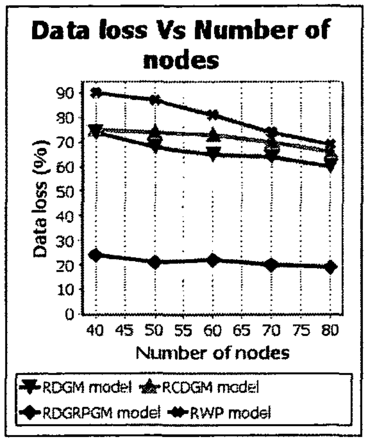
5.6.2 Simulation Experiments

We have conducted two sets each of 3 simulation experiments, primarily observing the data delivery ratio, the data loss, and the end-to-end delay, by varying the number of nodes and the number of data generating sources.

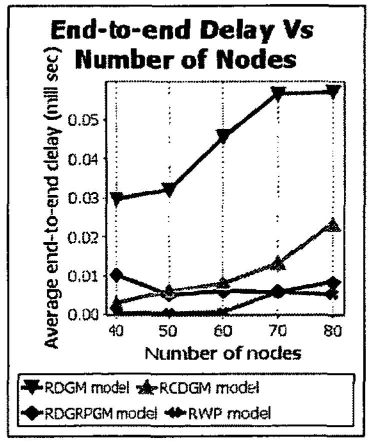
Experiment 8 *In this experiment, we computed the data delivery ratio, the data loss,* *and the average end-to-end delay of AODV for four models RWP, RDGM, RCDGM and RDGRPGM by varying the number of nodes as 40, 50, 60, 70, and 80, while keeping the number of data generating sources constant as 35 at each cases. The result is shown in Fig. 5.14.*



(a) Data Delivery Ratio



(b) Data Losses



(c) Average End-to-End Delay

Figure 5.14: Impact of Mobility Models on the Performance of AODV vs. Number of Nodes

As noted in the previous section, the poor connectivity in RWP model causes the data delivery ratio to be very low as shown in Fig. 5.14. The delivery gets better only when the region is highly populated with mobile nodes. Even then the decrease of data loss is very slow. The end-to-end delay is computed only for those delivered data. The true performance must include all the data, in which case the RWP model performs very poorly. Also, it is hard to explain the behaviour considering that the nodes move randomly.

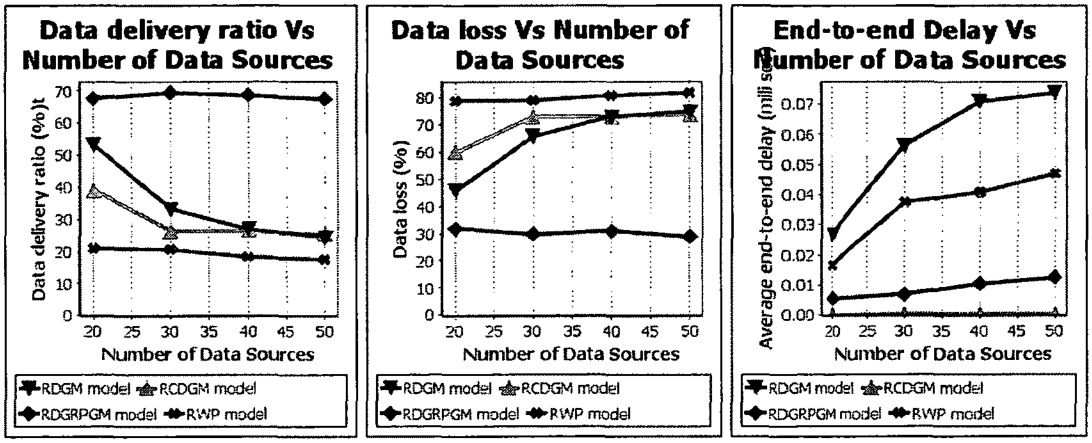
In RDGM and RCDGM models, the data delivery ratios are higher while the data loss is lower than the RWP model , but their trends are linearly increasing and decreasing respectively, as shown in Fig. 5.14(a & b). The increasing trend of the data delivery ratio in the RDGM and the RWP models is higher than that of the

RCDGM model. This is because the nodes in the RDGM move uniformly within the larger region, whereas the nodes in the RCDGM stay within the cluster of smaller regions longer than it moves between clusters. So, if a node moves with data to a new cluster, then it will have a lower chance of delivering the data to a location outside of that cluster during its session.

The end-to-end delay and delivery ratio in the RDGM increase as the number of nodes increases. This seems to suggest that more nodes facilitate more delivery and the increased portion is more likely the delayed deliveries. However, it is interesting to note that the end-to-end delay increases in the RCDGM model too, even though data delivery in the RCDGM increases very slowly as the number of nodes increases. This is because, although the number of sources is fixed, the number of possible receivers increases as the number of nodes increases. In addition, each receiver is confined within a cluster longer duration than it travels between clusters. In this experiment, AODV shows very high data delivery and very low data loss in the RDGRPGM model. This is because a set of nodes are almost always connected which greatly impacts on the overall the data delivery ratio, the data loss and the end-to-end factors.

Experiment 9 *In this experiment, we computed the data delivery ratio, the data loss, and the average end-to-end delay of AODV for four models, RWP, RDGM, RCDGM and RDGRPGM, by varying the number of data generating sources as 20, 30, 40, and 50, while keeping the total number of nodes constant as 70 at each cases. The result is shown in Fig. 5.15.*

Again, Fig. 5.15(a) shows that the data delivery ratio in RWP model is very low, and therefore makes the same impact that we already discussed. These experiments illustrate that increasing the number of source nodes decrease the data delivery ratio, and increase the data loss and the end-to-end delay. This is because, more data,



(a) Data Delivery Ratio (b) Data Losses (c) Average End-to-End Delay

Figure 5.15: Impact of Mobility Models on the Performance of AODV vs. Data Generating Sources

more loss, and more delayed delivery result in an increased average end-to-end delay increased. Overall, the performance of routing protocols using DGM models is more pronounced and has consistent explanation based upon the topology of the network.

5.7 Summary

In this chapter, first, we presented a set of real world representative scenarios and how different scenarios can closely be captured by the basic DGM models (RWP, RDGM, RCDGM and RDGRPGM models). Second, we explained the experiments conducted for analysing the performance metrics such as the average number of connection change, the average number of contacts and the average contact duration by varying the transmission range and the speed. In addition, we showed the trend of the node degree distribution,the clustering coefficient and the distinct $k - hop$ paths exhibited in the mobility traces generated by the DGM models. The trends of the node degree distribution and the k-hop paths of the DGM models' traces follow the power law distribution in some extent. The metrics such as the average number of connection changes, the average number of contacts, the average contact duration, and the clustering coefficients in the conducted experiments indicate that the DGM models better capture the connectivity patterns prevalent in real-world scenarios than that of the RWP model. Third, the experiments conducted incorporating real trace exhibited another strength of the DGM models. Though those two experiments are based on the intuition we obtained from the real trace, the close proximity trends of metrics such as the inter-contact time distribution and the contact time distribution explored the possibility that the larger social scenarios can be captured by the DGM models. Finally, we presented two sets of experiments for evaluating the performance of the AODV routing protocol using the DGM models. As per our expectation, the experiments showed that AODV performs better under the proper DGM models than under the RWP model.

Chapter 6

Conclusion and Future Directions

Mobile ad-hoc networks have received a great deal of interest in recent times, due to their potential applications and their technological advancements. The topology of MANETs is highly dynamic as the nodes are expected to move unpredictably. Due to their complexity, most research studies in MANETs are based on simulation. As the mobility of nodes is one of the fundamental characteristics of MANETs, mobility models have been proposed over the years with the objective of accurately capturing the mobility of the users in MANETs. Due to the possibility of numerous combinations and unknown factors, it is difficult to model mobility in a satisfactory way. Therefore, the credibility of simulations studies on MANET have been criticised heavily.

Recently, a generic framework to generate mobility models has been proposed to model mobility under several scenarios of MANET. DGM models are mainly based on the concept of destinations. The approach emphasizes that the destinations must be considered as an integral component of MANETs and that mobility can be modelled more accurately and easily based on destinations. In this thesis, we have implemented a mobility modelling and analysis software tool and have conducted a study on DGM models framework to test its versatility and suitability for modelling mobility in MANETs.

Through an analysis of representative scenarios (including real trace) and simulation studies using DGM models, we found that the DGM framework can be used to model mobility for a variety of MANET scenarios more accurately and easily than using the earlier mobility models of MANETs. That is, using DGM models framework mobility can be modelled more realistically with little effort than the earlier mobility models used in MANETs. Also, we conducted a simulation study of one of the dominantly used MANET routing protocols AODV. As we expected, the performance study of AODV shows that it performs better under more realistic DGM models than under RWP model.

Overall, the work we did for this thesis confirms our initial intuition that the DGM framework is simple and capable of modelling mobility for MANETs more accurately than the earlier models used in MANETs simulations. Therefore, we believe, if the DGM framework is used to model and analyse the mobility traces properly before using the trace to study MANETs, some of the scepticisms raised in the literature regarding MANET simulation studies can be dispelled. In that regard, we believe our work is interesting and useful.

Our thesis work is a first study on DGM models. It can be extended in several directions, and some of them are the following.

- More sophisticated or more specific MANET scenarios can be modelled and studied in detail using the DGM framework. For example, a specific real life scenario like a wild-life scenario or an office scenario can be modelled and studied in depth.

- An interesting research exercise would be examining the suitability of DGM models in modelling delay tolerant network scenario (e.g., a bus transit system, a message ferry in a remote village, etc.).
- The connectivity analysis can be done assuming that the destinations are connected to the Internet or connected to cellular networks.
- The performance analysis of other routing protocols such as DSR and DSDV can be conducted under DGM models and compared with their performance under RWP models.
- More experiments can be conducted importing traces of different real-world scenarios collected by different organizations, experimenting with DGM models to determine under what circumstance the DGM framework can simulate the collected real traces.
- Several analytical results have been reported in the literature for RWP and its variant models. It would be interesting to see how those metrics could be characterized and derived for DGM models.

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