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Abstract: Ad hoc networks can operate without fixed infrastructure and can survive rapid changes in the network topology. They can be studied formally as graphs in which the set of edges varies in time.

The main method for testing ad hoc networks is simulation. Choosing mobility model that describes the movements of the nodes in statistical terms is one of the most important choices of simulation parameters. This is because the location of nodes determines whether any pair of nodes has a direct communication link and the location of each node is determined by movement.

These links are used for creating routes between nodes that are not adjacent. When a link that is part of a route goes down, the route has to be rebuilt, which causes delays, packet loss and routing protocol overhead in the network. This report proposes that the route life time can be used as an indicator of the effects of mobility for reactive ad hoc routing. A method for estimating the route life time distribution for shortest routes between random nodes is also proposed.

The simulations do not correspond with the predictions of the model. This means that the model is lacking some critical aspect. Further research is required to understand the factors that affect reactive ad hoc routing protocol performance.

Keywords: ad hoc network, routing, mobility management, mobility model, simulation

Contents

List of Figures

1 INTRODUCTION

Ad hoc networks can operate without fixed infrastructure and survive rapid changes in the network topology. Usually nodes are mobile and use wireless communication links. In recent years many routing algorithms for ad hoc networks have been proposed. The algorithms are most often compared using simulation.

Mobility models play a key part when simulating ad hoc networks. A mobility model is used to describe the movements of the nodes in statistical terms. Several models have been proposed and used for ad hoc networks.

If one wishes to make meaningful comparisons between ad hoc routing protocols, the mobility models used in the simulations should either provide movement patterns that are similar to the real movement patterns of nodes, or at least provide patterns that are at least as challenging as the real life movements. There is currently little knowledge about how nodes actually move in ad hoc networks. This is because few ad hoc networks currently exist and because we do not know what kind of situations ad hoc networking will be used in.

Since currently it is very difficult to estimate how users will move when these ad hoc networks are deployed, it is a good idea to give the routing protocols as hard time as possible from the movement models.

Mobility creates the main characteristics of ad hoc networks. It is possible to identify characteristics of the networks that create most of the difficulties for ad hoc routing protocols. These characteristics can then be used for estimating the difficulty that a certain scenario provides for ad hoc routing. Among others the diameter of the network in hops, the density and the dynamicity and the diameter of the network are such characteristics.

If the network produced by the mobility model is dense, then on average there will be more route options than for a similar, but sparse network. This makes it possible to balance the load among nodes. It may also increase the probability that the communicating nodes are close to each other and thus make communications easier. On the other hand, a dense network increases the probability of collision and network congestion, since more nodes will be within transmitting range of each other.

When a link between two nodes that is in use disconnects, the routing protocol needs to adapt to the new situation. This creates a cost both in the amount of control traffic and in the message delay. Thus, the more durable links are probably better for data transmission than the less durable links. The larger a diameter a network has, the longer the routes between communicating parties will be on average. The cost of setting up routes increases with distance, as does the probability of individual link failures in a route. In other words, the lifetime of an individual link is independent of the diameter of the network, but the lifetime of a route is strongly dependent on the amount of links in the route.

This report presents a model that allows us to describe relative difficulty of different mobility models for ad hoc networking. The main focus is on creating such a model and then testing it with simulations.

The rest of this report is structured as follows: Chapter 2 introduces mobile ad hoc networking and defines the problem statement. Chapter 3 presents the criteria that the given model will be tested against. Most relevant previous work on this field is explained in Chapter 4. The proposed model is explained in Chapter 5. Chapter 6 explains the simulations done to test the model and Chapter 7 contains the simulation results. Chapter 8 contains the analysis of the proposed model. Chapter 9 concludes the report and gives ideas for future work on subject.

2 MOBILE AD HOC NETWORKING

Traditionally communication networks have been static, or nearly static. When computing devices became smaller and portable, need for solving mobility problems arouse. There are multiple different solutions that enable individual nodes to change their location in the network, but the main paradigm of static network infrastructure still remains.

However, there are many communication problems that prohibit the existence of static infrastructure. The most researched such areas have been military communications and disaster recovery. To solve these problems, a new dynamic network structure paradigm, ad hoc networks was created [29].

An *ad hoc network* consists of nodes that communicate with each other without the help of pre-existing infrastructure. The links between the nodes may change and the network adapts rapidly to the new situation. The changing network topology is usually due to mobile nodes using wireless links, but the techniques that solve the problems are not limited to such an arrangement.

The first problem in dynamic networks is delivering the information to its recipient. There are many different ad hoc routing protocols that tackle this problem (e.g. [7, 10, 12, 17, 20, 22, 25, 28, 30, 37, 39, 40, 41, 42, 46]).

2.1 Ad Hoc Routing Protocols

Ad hoc routing protocols can be divided into categories based on how they operate. Some protocols maintain topology information all the time [42] and some quickly find out the topology, information, or route to destination, only when that information is needed, i.e. on-demand [28, 41]. These are called proactive and reactive protocols, respectively. Some protocols consider all nodes equal and flat topology [28, 41, 42], where as some protocols use clusters or more complicated hierarchies to manage to dynamic network [10, 22, 25, 30, 40].

AODV

AODV [41] is the Ad-hoc On-Demand Distance Vector routing protocol. It is reactive by its nature and AODV nodes gather information relevant to routing from their surroundings only when it is needed.

When a node wishes to communicate to another, it broadcasts a route request (RREQ). This request is flooded throughout the network until a node with a valid route to the destination is found. Flooding means that the initiator and each node that receives it broadcasts the packet to all its neighbors, ensuring the message is received by all reachable nodes.
The node with valid route to the destination then sends a route reply (RREP) back to the original sender using the route through which it received the RREQ. Each node stores information about the RREQ into its routing table. This information is stored only for a short period of time, unless the node becomes part of the route between the source and the destination.

DSR

DSR [28] is a dynamic source routing protocol. As its name says, it uses source routing principle. That is, when a node sends a packet to another node, it attaches to the packet the exact route with which the packet must be forwarded.

If the sender does not know the exact route to the recipient, it will discover the route using a route discovery protocol. A packet requesting a route to the destination is flooded through out the network. The first receiver to know a route will send back a message with the full route to the destination.

2.2 Modeling Ad Hoc Networks

There are three different ways to model networks: formal analysis, real life measurements and simulation. The dynamic nature of ad hoc networks makes them hard to study by formal analysis.

Some formal techniques that have been used in static networks include Petri nets, stochastic processes, queuing theory, and graph theory. None of these is especially well suited to studying dynamic networks.

Since ad hoc networks are still mainly a research subject, most scenarios they will be used in are still unknown. For those scenarios that are known, e.g. military networks, extreme uncertainties and dynamicity are expected. Thus use of real life measurements is currently almost impossible and certainly costly. The commonly used alternative is study the behavior of the protocols in a simulated environment.

2.3 Simulation

The purpose of simulation is to create an artificial environment, usually a computer program, that captures the essential characteristics of the phenomena that is begin studied. Using simulations is cheap, which makes it economically viable possible to create a statistically significant amount of test runs. For these reasons simulation is a much used tool for comparing ad hoc routing protocols.

There are several network simulators that can be used for studying mobile ad hoc networks. [1, 2, 19, 38]

Ad hoc network researchers face the problem of not knowing how nodes will operate in real life situations, especially, how they will move. In order to create meaningful simulation results, good understanding of mobility and its effects on ad hoc routing is required.

2.4 Mobility Models

Mobility models are used to describe the movements of nodes statistically. Each model gives an algorithm that is used to randomize the movement of nodes. Mobility pattern is the actual set of movements that result from applying the mobility model to one, or more nodes. The models are divided into two categories, the entity mobility models and the group mobility models.

Entity mobility model gives a statistical movement description of a single node. This model can then be used to generate movements of several nodes by running the corresponding algorithm that generates the mobility pattern several times. Section 4.3 describes several models in more detail.

Group mobility model randomizes the movement of nodes such that the movement of nodes in the same group are correlated. One typical way of accomplishing this is to have a group center for each group, which moves and then allow the node positions to vary around that point.

2.5 Problem Statement

The main objective of this report is to design an experimental method for explaining the most significant impacts of mobility in wireless ad hoc networks that use reactive routing protocols.

This work evaluates existing entity mobility models, namely random walk, random direction and Gauss-Markov. Existing reactive ad hoc routing protocols, i.e. AODV and DSR are used to verify the results.

3 DESIGN CRITERIA

This section presents the criteria that the proposed method for explaining impact of mobility should meet. The proposed method must be in the form of parameters that can be easily measured from the simulations. These parameters should characterize the effects of mobility on reactive ad hoc routing.

3.1 Clarity

The proposed method will suggest a small number of mobility parameters that constitute the most significant impact on reactive routing. These must be such that a human can easily understand them and that a computer program can be used for ranking different scenarios according to their relative effect of reactive ad hoc routing.

This means that the number of significant parameters must be small and if multiple characteristics are suggested, a way to norm these into one single must be presented.

3.2 Predictivity

The proposed method must provide predictions on simulation results and simulation results done with actual reactive routing protocols must verify them. These predictions will take the form that mobility model A with certain mobility parameters will be harder, or easier for ad hoc routing than mobility model B with certain parameters.

Two measurements, average packet throughput and packet overhead will be used for measuring the hardness.

3.3 Consistence

The parameters that are found must have small variation from one simulation to another. This will be verified by comparing two sets of simulations with same mobility parameters.

4 PREVIOUS WORK

There are two main problems for comparing the efficiency of ad hoc network routing protocols via simulation. We do not know how actual users move and we do not know the communication patterns that users will effect on the network.

Much research has been done to understand mobility in structured networks, such as GSM networks. There are several different mobility models for GSM networks and the effects of mobility has been analyzed in detail [4, 21, 23, 35, 36, 43, 44]. Zonoozi et al [51] have a good survey of existing mobility models and their analysis for GSM networks.

Unfortunately these models and analysis are not suitable for ad hoc networks. GSM networks are based on cellular model, i.e. the physical geographical area is divided into cells and each cell is dominated by one base station. The problem in GSM networks is to understand how mobile nodes move between these cells. This makes it accurate enough to use flow models, i.e. merely model the movement of nodes from each cell to its neighbours.

On the other hand, in ad hoc networks the connectivity is based on mobile nodes connecting to each other. This means that the distance between each pair of nodes has to be known. Thus, the locations and movements of nodes have to be modeled more precisely than those in GSM networks, for example.

The rest of this chapter is organized as follows. First part will introduce the graph theoretic definitions required for the rest of the report. The next part explains how the effects of mobility on ad hoc networking have been measured and quantified in earlier research. After that the most relevant mobility models and network simulators for ad hoc network simulation studies are described.

4.1 Graph Theory

This report models ad hoc networks as graphs, where each link between any pair of nodes either exists or does not exist at any given moment of time. The basic definitions for graphs come from Diestel [15].

Graph is a pair of finite sets $G = (V, E)$ that satisfies $E \subseteq V \times V$.

A pair $(A, B) \in E$ is called a *link*.

Path from A to B is a non-empty graph $P = (V, E)$ such that $V = \{x_1, \ldots, x_k\}$ and $E = \{(x_1, x_2); (x_2, x_3); \ldots; (x_{k-1}, x_k)\}$ and $x_1 = A$ and $x_k = B$. The length of the path is $k - 1$ and is denoted by $|P_{A,B}|$.

The *distance* D between two nodes $A \in V$ and $B \in V$ for graph G is:

(1) $D = \infty$ if no path exists between the nodes.

(2) $D = \min(|P_{A,B}|$, for all paths from A to B)

There are many algorithms for finding the shortest path between two nodes in a graph [11, 16].

4.2 Suggested Models for Effects of Mobility on Ad Hoc Routing

Interest in the effects of mobility on ad hoc networks has grown in the past few years. This section presents previous attempts to characterize the effects of mobility on ad hoc routing.

Early Models on the Effects of Mobility

Until late 90s little effort was put into understanding the effects of mobility on ad hoc networking. The focus was clearly on creating new kinds of routing protocols and comparing them. Less thought was put into understanding how mobility affects routing. This is quite understandable, since it was more important to be able to propose protocols with new qualities and better performance for different scenarios.

Broch et al [7] suggested that mobility could be characterized using the length of time that nodes stay stationary between periods of movement. This approach works quite well, when nodes spend most of their time still and move only rarely. Unfortunately most models and scenarios do not consist of nodes sitting around doing nothing most of the time. Thus this characterization fails to depict the true nature of mobility.

Camp [8] proposes average speed of the nodes for representing their mobility.

These models do not show an accurate picture, because they consider the speeds of the nodes relative to the surroundings and not relative to other nodes. Thus the model fails to depict correctly the amount of dynamicity caused by moving nodes.

Effects of Mobility Come to Focus

As ad hoc networks research has started to mature, interest in the effects of mobility has risen. Some researchers started analyzing and creating better models to study effects of mobility. Several papers which had emphasis on analysis of mobility were written.

Larsson et. al [33] proposed a model of mobility for characterizing movement in ad hoc networks. The idea is to calculate a mobility metric called *mobility* to characterize the difficulties that mobility creates for ad hoc routing. Mobility measures the change in average distance (A_x) from one node to all other nodes between successive simulation time steps (Δt). This is then averaged over the whole simulation time (T) and all nodes. Equation 1 shows the average mobility for one node through the simulation. The mobility metric they propose is the average of this over all nodes.

$$M_x = \frac{\sum_{t=0}^{T-\Delta t} |(A_x(t) - A_x(t+\Delta t))}{T - \Delta t} \tag{1}$$

Johansson et. al [27] refined the model developed in [33]. Their model calculates the following metric. For each moment the relative velocity between two nodes x and y is $v(x, y, t)$. The mobility metric for the pair of nodes is the absolute relative speed ($v(x, y, t)$) averaged over the simulation time (T) as shown in Equation 2. The mobility metric over the whole simulation is the average of this over all node pairs.

$$M_{xy} = \frac{1}{T} \int_0^T |v(x, y, t)| \, dt \tag{2}$$

Their purpose was to show that this metric, which describes the velocity of the nodes relative to each other, is linearly correlated with amount of link changes. Kwak has proposed another model, which describes the amount of link changes in terms of relative movement velocity [31, 32].

These proposals still suggest a single mobility metric, which should be able to quantify the effects of mobility on all different ad hoc routing protocols. For example reactive ad hoc routing is dependent on the life time of the used route, whereas proactive routing protocols are dependent on the life time of each individual link. This is because in reactive ad hoc routing, even a single failed link in a route causes packets to be dropped, or delayed and much extra overhead to restore the route. Similarly each link changes causes packet overhead in the network that is trying to adjust to the new situation.

Turgut et al [50] proposed that the expected lifetime of the route is the important metric. He also proposed that the lifetime of a route can be estimated with the minimum of the expected lifetimes for all the hops. The latter claim doesn't hold as shown in Chapter 5.

Mobility Analysis Matures

Currently, mobility research on ad hoc networks focuses in understanding different parts of ad hoc routing protocols and the way these parts are affected by mobility. For example one can define a flooding building block. Flooding means that a packet is propagated from the sender to all receivers that are within the radius of flooding. This method is commonly used in reactive routing protocols for finding a route to destination.

This enables one to study the behavior of each generic building block in different mobility schemes and find out how and why mobility affects the performance of the building block in question. For example one can study the building block, e.g. flooding protocol in different mobility schemes and then conclude that the analysis is valid for any protocol that uses flooding. This method was suggested by Bai et al [18]

Bai et al [3] also suggested several metrics for analyzing how mobility affects routing protocol performance. The studied metrics were divided into two different groups: Mobility metrics and connectivity graph metrics. Among others, *average degree of spatial dependence* and *average relative speed*, and *average number of link changes* and *average link duration* and *average path availability* were defined.

Degree of spatial dependence for two nodes is defined as the cosine of the angle between their velocities multiplied by their speed ratio. Average spatial dependence is the average of the pairwise spatial dependence over all nodes that are within a certain predetermined range. The relative speed RS of two nodes i and j at time t is $RS(i, j, t) = |\vec{V_i}(t) - \vec{V_j}(t)|$

In the study they measured spatial dependence and average relative speed with different range values to find out which range values could differentiate different mobility scenarios they studied. In both the range value of twice the transmission range could differentiate the scenarios clearly. The research group also found indication that average relative speed metric is correlated with maximum velocity of the nodes.

The average number of link changes did not seem to have an effect on simulation results [3]. This is easy to explain, since high number of link changes

can either come from the scenario having a high amount of relatively stable links, or a relatively low amount of links with low lifetime. Since the metric cannot distinguish between those two situations, it does not provide useful information.
Bai et al [3] also notice that average link duration has a strong correlation with routing protocol performance, which has been shown in previous studies.
They did not find average path availability to be a good metric. Average path availability describes the portion of time that a path is available from a certain node to another averaged over all node pairs. This may be because they used simulations in which it was rare for a node to be disconnected from a network.

Sadagopan et al [47] studied the probability density functions of link and path lifetime. They define link lifetime to be the time that a link is continuously up from the point of time when it becomes into existence to the point of time, when it dies. Their definition of path lifetime for path $P = n_1, n_2, \ldots, n_k$ at time t is the longest continuous time interval during which all $k-1$ links exists. Thus path lifetime is constrained by the life time of the link with shortest lifetime in the path.

In the same paper, the authors also suggest that the throughput of DSR [28] is dependent only on the portion of time used to transfer data and the time used to repair broken paths. The overhead is dependent only on the average path duration, fraction of requests replied by first hop neighbors and number of nodes. The study proposed following equations:
throughput $= (1 - \frac{t_{repair}}{D_P})r$
overhead $= \frac{T}{D_P}(p \cdot 1 + (1-p)N)$, where

- N is the total number of nodes
- T is the total simulation time
- t_{repair} is the time spent to repair a broken path each time
- D_P is the average path duration
- r is the data rate, which is assumed to be constant
- p is the fraction of requests answered by first hop neighbors

In other words, the maximum throughput of the network cannnot be higher than a certain percentage of the data rate in which the percentage is the fraction of time a valid route between two communicating parties exists. However, this only applies to real time traffic. For non-real time traffic, the data rate r needs to be replaced with maximum bandwidth of the network.
The overhead metric calculates the expected amount of control messages required to keep one connection up for the duration of the simulation. The fraction $\frac{T}{D_P}$ expresses the expected amount of path breakages and the latter portion of the equation the expected amount of control messages required to repair the path. The simulation results show high correlation for the average path duration and throughput and overhead (> 0.9) for Random Waypoint, Freeway and Manhattan mobility models, but not for Reference Point Group

Mobility model. These models are described in Section 4.3.

Summary
In past few years, several different metrics have been proposed in order to quantify the effects of mobility on ad hoc networking. This is an ongoing work just getting started. The metrics that currently seem most profitable are link life time and route life time distributions.

It also seems clear that no one metric that can accurately describe the effect of mobility on all ad hoc networks.

The building block approach [3, 18, 47] is the best framework that currently exists to understand the effects of mobility on ad hoc networking.

4.3 Mobility Models

Ad hoc mobility models are used to describe the movements of nodes statistically. Each model gives an algorithm that is used to randomize the movement of nodes. The models are divided into two categories, entity mobility models and group mobility models [13]. The entity mobility models randomize the movements of each individual node. The group mobility models have groups of nodes that stay close to each other and then randomize the movement of the group. The node positions also vary randomly around the group reference point.

This report examines only entity models, mainly because currently they are most often used in simulations for ad hoc routing protocol comparisons. They are also chosen, because the mobility patterns they produce are simpler to analyze and thus provide a better starting point for the research.

This section presents the entity mobility models used in this report.

Random Walk *Random walk* is a simple mobility model. Each node moves in a straight line for a predetermined time t. The direction is picked at random from uniform distribution between 0 and 2π and the speed is randomly chosen from uniform distribution between $\text{Speed}_{\text{min}}$ and $\text{Speed}_{\text{max}}$. The node then moves for a time t and then picks another direction and speed at random. The simulation parameters for random walk mobility models are shown in Table 1.

Table 1: Simulation Parameters for random walk

$\text{Speed}_{\text{min}}$	Minimum Speed
$\text{Speed}_{\text{max}}$	Maximum Speed
t	Duration between changes of speed and direction

Random walk is a memoryless mobility model. It assumes that the behavior of the node does not depend in any way from its past history. Random walk is often referred to as brownian motion.

Figure 1 shows an example of one node moving in a 300 m × 300 m area using random walk mobility model. As can be seen from the picture the node tends to randomly poke around one particular area for a long while. This is due to the fact that after each period of movement the future direction and speed do not depend on the current direction and speed.

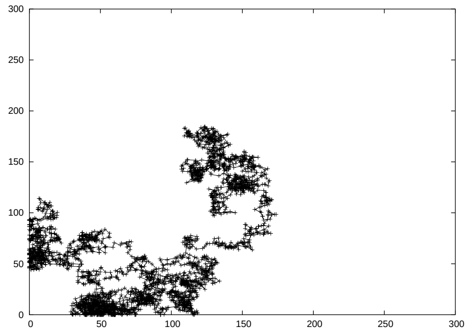

Figure 1: Random walk mobility pattern

Random Direction In *random direction* [45] mobility model, a node chooses a direction and speed from uniform distributions of $(0, 2\pi)$ and $(Speed_{Min}, Speed_{Max})$ respectively. The node then continues with constant velocity to the chosen direction until it hits the edge of the simulated area. It then pauses for a random period of time (from uniform distribution) and then chooses a new direction and velocity.

The simulation parameters for Gauss-Markov mobility models are shown in Table 2.

Table 2: Simulation Parameters for random direction

$\text{Speed}_{\text{min}}$	Minimum Speed
$\text{Speed}_{\text{max}}$	Maximum Speed
$p_{\min}$	Minimum pause time at the edge
$p_{\max}$	Maximum pause time at the edge

Figure 2 shows a mobility pattern caused by one node moving in a 300 m$\times$ 300 m area.

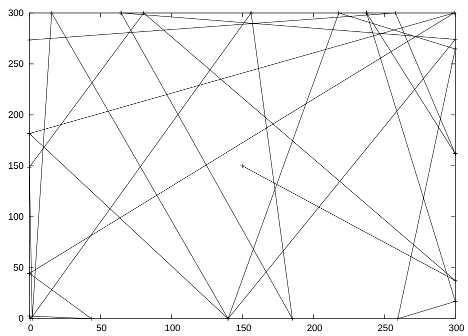

Figure 2: Random direction mobility pattern

Gauss-Markov *Gauss-Markov* mobility model creates random movement changes that are dependent on node's current speed and direction. At fixed intervals the simulator generates a new speed and direction based on their current values and standard deviations. In addition the model keeps nodes away from the edges by changing their direction away from them should they get too close.

Originally Gauss-Markov mobility model was proposed for simulating mobility in personal communication systems such as GSM [34]. There are many mobility models that use the same basic principle, but differ in the details. This report uses the one implemented in [6]. It uses following equations to calculate new values for speed and direction at fixed intervals.

$$s_n = s_{n-1} + \alpha \cdot r_g \cdot s \tag{3}$$

$$d_n = d_{n-1} + \alpha \cdot r_g \cdot \alpha \tag{4}$$

Here s_n is new speed and s_{n-1} the current speed. d_n is new direction, d_{n-1} the current direction, and r_g a random number taken from standard Gaussian distribution. s and α are the standard deviation of speed and angle for the gaussian distribution.

The simulation parameters for Gauss-Markov mobility models are shown in Table 3

Table 3: Simulation Parameters for Gauss-Markov

$\text{Speed}_{\text{max}}$	Maximum speed
s	Speed standard deviation
α	Angle standard deviation
t	Speed & angle update frequency

As can be seen from Figure 3, the Gauss-Markov mobility model produces movements with smooth curves and the mobile node tends to stay away from the edges of the simulation area.

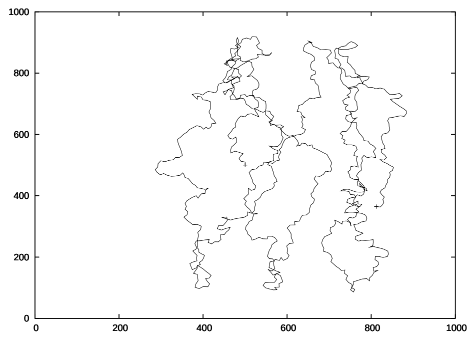

Figure 3: Gauss-Markov mobility pattern

4.4 Other Mobility Models

This section presents mobility models that have been proposed for and used in simulating ad hoc networks.

Entity Models
This section presents several other entity models proposed in literature. These models are random waypoint, boundless simulation area, probabilistic version of random walk, city section, obstacle and enhanced random mobility model.

Random Waypoint *Random waypoint* [28] describes nodes as entities that have certain randomly chosen locations in the map that they wish to visit in given order. First the node decides a random location in the simulation area. It chooses a speed S from uniform distribution between $\text{Speed}_{\text{min}}$ and $\text{Speed}_{\text{max}}$. Then it travels straight to X using speed S.

When the node arrives at place X, it waits there for a period of time chosen from uniform distribution between p_{min} and p_{max}. After waiting, it chooses a new point it wants to visit and decides the speed it uses to get there.

Table 4: Simulation Parameters for random waypoint

$\text{Speed}_{\text{min}}$	Minimum speed
$\text{Speed}_{\text{max}}$	Maximum speed
p_{min}	Minimum pause time
p_{max}	Maximum pause time

Figure 4 shows an example of mobility pattern caused by one node moving in 300 m $\times$ 300 m area using random waypoint mobility model.

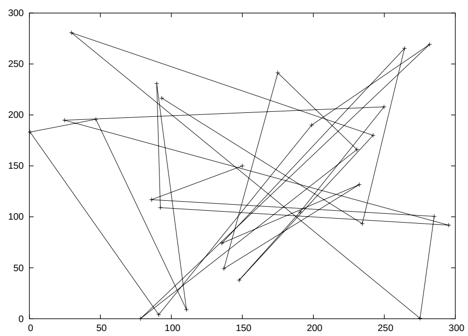

Figure 4: Random waypoint mobility pattern

A Boundless Simulation Area In *Boundless Simulation Area* model [22] the nodes change speed and direction randomly and continuously. Every Δt time steps the node adjusts its speed and direction, using current speed and direction as a basis for the new values. The equations used for calculating new coordinates and values for speed are shown below.

$$v(t + \Delta t) = \min[\max(v(t) + \Delta v, 0), V_{\max}]; \quad (5)$$

$$\theta(t + \Delta t) = \theta(t) + \Delta\theta \quad (6)$$

$$x(t + \Delta t) = x(t) + v(t) \cdot \cos\theta(t) \quad (7)$$

$$y(t + \Delta t) = y(t) + v(t) \cdot \sin\theta(t) \quad (8)$$

Here $v(t)$ is the current velocity and $\theta(t)$ current direction. The change in speed and direction is denoted by Δv and $\Delta\theta$ respectively. The change in speed is uniformly distributed between Δv $[-A_{\max} \cdot \Delta t, A_{\max} \cdot \Delta t]$, where $A_{\max}$ is maximum acceleration for the node in question; The change in angle is uniformly distributed between $[-\alpha \cdot \Delta t, \alpha \cdot \Delta t]$, where α is the maximal angular direction change. The time that passes between two successives checks on nodes speed and direction is Δt and node's position in xy-plane at moment t is described by $x(t)$ and $y(t)$.

As the nodes move randomly, they may come to the edge of the simulation area. To solve the discontinuity problem arising from this, boundless simulation area converts the simulation area into a toroid shape. Thus when a node goes over the right most edge of the simulation area, it instantly appears at the same position in the left most edge of the simulation area.

The necessary simulation parameters for Boundless Simulation Area model are shown in Table 5.

Table 5: Simulation parameters for boundless simulation area

V_{Max}	Maximum speed
δt	update interval
A_{Max}	Maximum acceleration
α	Maximum angle change

As seen in Figure 5, the boundless simulation area mobility model produces movements with few sudden turns and smooth curves.

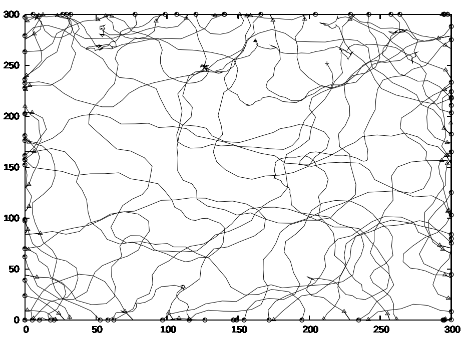

Figure 5: Boundless simulation area mobility pattern

A Probabilistic Version of Random Walk *Probabilistic random walk* model by Chiang [9] is based on Markov Chains. The movement of each node is determined by 3×3 probability matrix. The nodes current movement is represented as three states for x-dimension and as three states for y-dimension. These states represent node's current movement, i.e. whether node stays still (state 0), moves backward (state 1), or moves forward (state 2).

The probability matrix represents the probabilities that the node switches from one state to another and is shown below.

$$P = \begin{bmatrix} P(0,0) & P(0,1) & P(0,2) \\ P(1,0) & P(1,1) & P(1,2) \\ P(2,0) & P(2,1) & P(2,2) \end{bmatrix}$$

For a specific simulation, the matrix is given values that correspond to desired node movements. It is difficult to find the right values for the matrix. One possibility is to use real world traces of node movements. The matrix below is an example of a possible probability matrix. It was used by Chiang [9].

$$P_1 = \begin{bmatrix} 0 & 0.5 & 0.5 \\ 0.3 & 0.7 & 0 \\ 0.3 & 0 & 0.7 \end{bmatrix}$$

Figure 6 shows an example of a node movement using the probabilistic version of random walk.

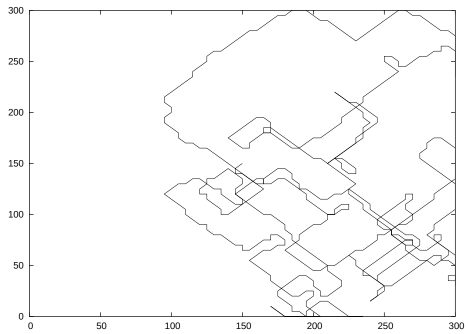

Figure 6: Probabilistic version of random walk mobility pattern

City Section Mobility Model *City section mobility model* places mobile nodes in a real or imagined city map [36]. The nodes can move only using the streets of the city. As in random waypoint mobility model, the nodes always choose a point as a goal. They then go there using the fastest path and then pause for a certain time. The city model may place restrictions on the use of streets, such as limiting speeds or by making them one directional.

Obstacle Mobility Model In *Obstacle mobility model* [26] the simulation area may contain polygon shaped obstacles, e.g. buildings. They block both radio signals and movement totally, except for the doors, which allow movemen. The doors can be placed on the sides of the buildings. The nodes use pathways for moving from one place to another and choose their destinations from a predetermined set of sites. These pathways are the edges of the

Voronoi-diagram [14] over the simulation area using the corners of obstacles as dividing points.

Voronoi-diagram partitions a plane into cells using a set of dividing points on the plane. The partition is such that each cell contains exactly one of these dividing points. In addition at each point on the plane, the closest dividing point is in the same cell as the point itself. In other words, the edges between cells consist of those points in which the distance to the closest location points is the same.

When a node chooses a destination, it first travels directly to an edge on the Voronoid graph, and then uses the shortest proute to the destination such that it stays on the edges of the graph.

Table 6 shows the simulation parameters for the obstacle mobility model.

Table 6: Simulation parameters for obstacle model

V	Speed distribution
d_i	The destination sites
p	Pause time distribution

Smooth Mobility Model In *smooth mobility model* [5] a node chooses a direction and then starts accelerating to change its velocity to the chosen direction. The node also chooses a certain amount of time that it will travel to that direction before it chooses a new direction. Both of these decisions are controlled by stochastic processes.

This creates movements that is smooth and more realistic, because real life acceleration capabilities are taken into account.

Group Mobility Models

This section presents group models proposed in literature. These models are pursue, nomadic community, column and reference point group mobility model (RPGM).

Pursue Mobility Model *Pursue mobility model* [48] describes a group of nodes that are trying to catch a runaway node. Each node tries to move as close to the runaway nodes current position as possible. The position updates are done using the following equation, where $P(x, y, t)$ describes the nodes position at time t. R is a random vector, which controls how well the nodes are capable of following their prey and D is a vector toward the runaway node. The vector D is between $D_{\min}$ and $D_{\max}$ specified as simulation parameters and such that without the random vector, the node would end up as close to the runaway nodes location as possible.

$$P(x, y, t + \Delta t) = P(x, y, t) + D + R$$

Nomadic Community Mobility Model *Nomadic community model* [48] represents a group of people moving from one location to another. This is simulated so that each group has a reference point that moves toward the group destination. Each member of the group roams around the group reference point using an entity mobility model (e.g. random walk). When the reference point is updated, all nodes start travel to the area defined by the new reference point and then start wandering again.

Column Mobility Model In *column mobility model* [48], each node has a certain place in a column just as one might have in a search/rescue operation. The column moves forward at a constant speed. The new reference point for a node can be calculated using newReferencePoint = oldReferencePoint+ advanceVector equation. Each node is allowed to move randomly around its reference point. This node movement is accomplished using some entity mobility model, such as random walk.

Reference Point Group Mobility Model *Reference point group mobility model* (*RPGM*) [24] separates the motion of the group and the motion of each node in the group. Each group has a motion vector V_{g_i}. Each node is assigned a reference point with relation to the group reference point. A movement of a node is done so that first the reference point of the node is transferred using the group motion vector and then the node's position is randomly varied around the reference point. The random vector that is used for varying the position is uniformly distributed between 0 and 360 degree and between 0 and certain predefined length.

Individually Simulated Mobility Model
The individually simulated mobility model cannot be categorized as entity mobility model, nor as group mobility model.

In *individually simulated mobility model* [49] each node has a decision system that makes decisions about movements. This system consists of three components: the perception component, the behavioral component and the movement component. The perception component provides information about the immediate surroundings of the node. The behavioral model chooses what actions the node should make based on the perception information and the movement component executes these actions.

The behavioral model is built with four rules: Group centering, collision avoidance, velocity matching and inertia. Each of these rules takes its priority (between 0 and 1) as simulation parameter. Group centering means that nodes want to be at the center of the group that they can percept; collision avoidance means that nodes want to avoid getting too close to other nodes; velocity matching means that nodes wish to match their velocity with those in their immediate surroundings and inertia tells how fast they can change their velocity vector.

These potentially conflicting desires are combined by using a weighted sum over acceleration requests provided by each rule.

4.5 Simulators

Network Simulator 2 (NS2) [38] is a discrete event simulator targeted at networking research. It includes support for both wireless networking and wired networking. It is implemented combining C++ and TCL, so that scripting different networking scenarios with TCL is easy while adding new protocols and features to the underlying simulator is efficient using compiled C++ code. In addition to this, NS2 is widely used in ad hoc networks research. Thus using NS2 makes the results more comparable to other work done in the field. These factors made NS2 an ideal choice for this work.

The code providing Random Walk and Random Direction mobility was provided by Camp et al [8]. The code providing Gauss-Markov mobility was provided by BonnMotion group [6].

There are other network simulators that support ad hoc networking to some degree, e.g. PARSEC [1] and Glomosim [19].

5 MEASURING MOBILITY

Routing in ad hoc networks is harder than in traditional networks. This is mainly due to the fact that in traditional networks links between nodes do not change, or change very slowly in time. Thus key difference between these types of networks is the dynamicity of links and the lack of specific infrastructure designed to handle network control.

Route life time distribution is an important metric for understanding the effects of mobility on reactive ad hoc routing [47, 50]. This Chapter proposes an experimental method for measuring the route lifetime distribution.

5.1 Dynamic Networks

A dynamic network can be considered as a set of graphs that is ordered by time. This discussion considers a discrete time in which Δt is the smallest time step. From here on, the this set of graphs is referred just as a graph. If there is a possibility of a confusion between this and ordinary graphs, they will be referred as a dynamic and an ordinary graphs.

A graph can be expressed as

$$G[t] = (V, E[t])$$

Let $(A, B)[t] = 1$ denote that a link between A and B exists in $G[t]$, i.e. a link exists at time t. Similarly let $(A, B)[t] = 0$ denote that no link between A and B exists in $G[t]$. If $\forall t,\ t_0 \leq t \leq t_1\ \ (A, B)[t] = 1$ and $(A, B)[t_1 + \Delta t] = 0$, then the *remaining life link time* (*llt*) of the link between A and B at time t_0 is *llt* $= t_1 - t_0$.

llt is thus the time that link is continuously up from a given moment to its destruction. This concept is used, because when ad hoc routes are formed, the links that are used for it are those that are available at the particular time of forming the link.

5.2 Distance Distribution

The distance distribution for an ordinary graph describes the discrete probability distribution for the distance of randomly chosen pair of nodes. The distance of a pair of nodes is defined in Section 4.1.

The distance distribution can be calculated by calculating the number of node pairs $N(i)$ within distance $i, i = 1, 2, 3, \ldots$. The probability distribution $P(i)$ is then $P(i) = \frac{N(i)}{\frac{n \cdot (n-1)}{2}}$, where n is the number of nodes. The distance distribution of a set of k graphs is the average of their respective distance distributions.

The distance distribution of an ad hoc network for a given mobility model with certain parameters can be measured with simulation. The formula is following:

Run n simulations with given mobility model and parameters.

Choose a moment between (t, t_{max}) and measure the distance distribution at that point. The initial spatial distribution of nodes does not necessarily resemble the distribution that the mobility model produces. Because of this $t \gg 0$ is required in order to let the spatial distribution resemble that produced by the model rather than the initial distribution.

Calculate the distribution using these samples and scale it to have the probabilities sum to 1.

5.3 Measuring Remaining Link Life Time Distribution

The llt distribution describes the probability distribution of the remaining life time of a randomly chosen link at given time t.

To find the llt probability distribution, n simulations are run. A certain moment is chosen from uniform distribution between (t_1, t_2), where $t_1 \gg 0$ and $t_2 \ll t_{max}$. The former is a requirement, because the initial spatial distribution may not resemble one created by the mobility model and the latter, because the chosen time should be such that no link lasts until the end of the simulation. If some links last from the chosen time point till the end of the simulation, then the estimate of llt will be too small.
llt will then be calculated for each link that exists.

The distribution that we get is the distribution of remaining link lifetimes for those links that exist at certain moment. It is not the life time distribution for randomly chosen link at the time of its birth. This is chosen, because all links in a route are chosen at a particular moment.

5.4 Route Life Time Distribution (*rlt*)

This report proposes that the life time distribution of the shortest route (*route life time distribution rlt*) between two random nodes is a good metrics for the impact of mobility for ad hoc routing. The model assumes that the *llt* distributions of links in this route are independent of each other and that the distribution is the same as the llt distribution produced by the mobility model. This assumption is not valid, since the two links that a node participates in within a route are dependent on each other. Still, it should be a good enough approximation.

The life time distribution of a route between two random nodes can be calculated, if the distance distribution of nodes and life time distribution of links is known. These can be measured from simulation samples. The route life time distribution is calculated as follows.

Measure the distance distribution and link life time distribution from the samples.

1. Let $P(p_1, \ldots, p_n)$ be a discrete distance distribution, where p_i denotes the probability that the distance between two random nodes in a graph is i. This can be measured from simulation samples.

2. Let f be a continuous density such that $\int_a^b f = P(a \leq X \leq b)$ denotes the probability that the remaining link life time is between a and b. Then $F(t) = \int_t -\infty^t f$ is the cumulative link life time distribution.

3. The remaining life time distribution of a given route can be calculated in following manner. It is assumed that the lifetime of each link in a route is randomly selected from the given density function.

4. Let

$$G(t) = 1 - F(t) \tag{9}$$

be the probability that at time t the link has not yet broken. Then the probability that none of i random links has yet broken is $G(t)^i$.

Thus the cumulative random distribution that the route is still valid t seconds after creation is thus

$$\mathcal{F}(t) = \Sigma_{i=1}^{n} P_i G(t)^i \tag{10}$$

The *rlt* distribution $\mathcal{F}$ describes how long communications between two nodes will continue before the route has to be renewed.

Eventually we will want to compare *rlt* distributions from different mobility models and judge their relative difficulty for reactive ad hoc routing for each other.

The ranking system has to meet the following criterion:

If $\forall t$ $\mathcal{F}_A(t) \leq \mathcal{F}_B t$ then A must be ranked more difficult mobility than B.

There are three obvious ways of ranking the distributions and each has its problems. These are average route life time; median, or any given percentile of route life time; and measuring what percentage of routes are still valid after t seconds.

Average Route Life Time

Under ordinary circumstances average route life time measurement gives a good understanding of how long on average a route will last. However, if the mobility model produces some links that live forever, as some group mobility models do, then the *rlt* distribution will contain a non-zero portion of routes with infinite lifetime.

Non-zero portion of routes with infinite lifetime automatically raise the expected route life time to infinity. Thus average route life time measurement fails to convey important information about relative hardness of different *rlt* distributions.

Percentile of Route Life Time

Choosing a certain percentile to represent the difficulties posed by the mobility is another possibility. The question is, which percentile would be representative for ranking different *rlt* distributions.

The problem of using any pre-determined percentile is that it lumps together many different scenarios in which *rlt* of the given percentile is zero. This is possible, because the *rlt* distribution includes in itself those communication attempts that happen between nodes that are disconnected from each other.

Percentage of Routes Valid After t Seconds

Another possibility is to measure what portion of routes is still valid after a predetermined time. This means that meaningful comparisons cannot be made based on this criteria, if a very small, or big portion of the routes survive to the given time limit.

Proposed Variant

I propose that median of *rlt* should be used, when that median is greater than zero. If the median is zero, then the percentage of routes with a lifetime at least one seconds should be used.

This approach has the good qualities of median of *rlt* and still gives a meaningful basis for comparison on those cases, where more than 50% of routes last less than 1 second.

6 SIMULATIONS

This Chapter presents the simulations that were done to test the proposed model for measuring effect of mobility on reactive ad hoc routing. The simulation results can be found in Chapter 7. The results are analyzed in Chapter 8.

Three scenarios and three mobility models and two routing protocols were chosen for further study. The mobility models chosen for study are random walk, random direction and Gauss-Markov. The scenarios were chosen in such a manner that in each the average speed of the nodes stays the same. The routing protocols, AODV and DSR are the most commonly known reactive routing protocols.

Scenario 1 describes a 300 m × 300 m area, in which nodes move exactly $4m/s$. Scenario 2 was constructed in order to study how increasing variance to the node speeds affects the network. Scenario 3 has exactly the same parameters as Scenario 1, except the area of movement is only 200 m × 200 m. The purpose of Scenario 3 was to measure how the density of the network affects ad hoc -routing performance. The simulation parameters for the scenarios are summarized in Table 6.

Table 7: Summary of the simulation parameters for all scenarios. (*) The real area used for Gauss-Markov scenarios is slightly bigger, because of the way the model handles boundary effects.

Mobility model	Scenario	Parameter	Value
All	All	Number of nodes	50
		Radius of connectivity	50 m
		Simulation time	1000 s
		Initialization time	1000 s
	1 & 2	Area	300 m · 300 m(*)
	3	Area	200 m · 200 m(*)
Randwalk	All	Move Time	3 s
	1 & 3	Speed	4 m/s
	2	Min Speed	1 m/s
		Max Speed	7 m/s
Randdir	All	Pause Time	0 s
	1 & 3	Speed	4 m/s
	2	Min Speed	1 m/s
		Max Speed	7 m/s
Gauss-Markov	All	Angle Std. Deviation	0.4
	1 & 3	Speed	4 m/s
	2	Max Speed	7 m/s
		Speed Std. Deviation	1 m/s

The purpose of the simulations was two-fold. They were designed to show that the average speed and the link life time, the mobility measures proposed earlier, are not capable of describing the effects that mobility has on ad hoc routing. They were also used to test the new mobility measure proposed in this report.

The simulations were done in two phases.

The first part of the simulations measured the route life time (*rlt*) for each mobility model for each scenario. Using these measurements these 9 different scenarios will be ranked by the relative difficulty they pose for reactive ad hoc routing.

The second part of the simulations used the same scenarios and same mobility models. The purpose of these simulations was to measure the performance of two routing protocols, AODV and DSR. The basis of performance measurements is from Broch et al. [7] and Johansson et al. [27]. If the model proposed in this report is correct, then the performance results should reflect the ranking from the first set of simulations.

6.1 Finding Route Life Time Distribution

Three mobility models, random walk, random direction and Gauss-Markov, were sampled to find their route life time (*rlt*) distribution for different parameter values. Each model was simulated 1000 times for each scenario. The *rlt* distribution is used to predict the difficulty each scenario presents to ad hoc routing. The method for estimating *rlt* is described in Chapter 5.

Table 9 shows the distance distribution created by Random Walk in Scenarios 1 and 2 and 3. The results are organized such that each column shows the whole distance distribution for one scenario and each row shows the probability that two nodes are at a certain distance. For example value 1.1% in row 10 and column 2 indicates the probability that the distance between two nodes is 10 in Scenario 2.

Similarly, tables 10 and 11 show the distance distribution results for Scenarios 1 and 2 and 3 with Random Direction and Gauss-Markov.

The *llt* distributions were measured as defined in Section 5.3. Figure 7 shows the *llt* distribution for random walk in Scenarios 1, 2 and 3. A point (t, p) in the graph expresses the probability that a randomly selected link survives at least t seconds from the moment the observation is started.
Similarly 8 and 9 show the *llt* distribution for random direction and Gauss-Markov mobility models for each scenario.

The *rlt* distributions were calculated from these measurements. Figure 10 shows the *rlt* results for random walk in Scenarios 1, 2 and 3. The distribution shown is the $\mathcal{F}$ distribution defined in Equation 10. A point (t, p) in the graph expresses the probability that the shortest path between randomly selected pair of nodes survives at least t seconds from the moment the observation is started.

Similarly 11 and 12 show the *rlt* distribution for random direction and Gauss-Markov mobility models for each scenario.

6.2 Simulation Results for Testing Hypothesis

This section provides the description and results of the simulations for testing the hypothesis. The hypothesis is that those mobility models with certain parameters that were rated more difficult in previous chapter will produce more problems for communication. Thus simulations are set up to test this in this chapter.

This report uses communication patterns and traffic analysis as in Johansson et al. [27]. They compare different ad hoc routing protocols in their work. The following sections describe the simulation setup.

Mobility Pattern

The mobility scenarios in these simulations are exactly the same as in the simulations in Chapter 6.1. The simulations used a simple communication schemes, in which 15 randomly nodes were randomly selected and each communicates to a randomly selected node. Table 8 summarizes the communication parameters.

Table 8: Summary of the communication parameter values for simulation scenarios

Transmitter range	50 m
Bandwidth	2Mbps
Simulation time	2000 s
Number of nodes	50
Traffic type	Constant Bit Rate
Packet rate	5 packets/s
Packet size	64 byte
Number of flows	15

The actual patterns used for measurements in Section 6.1 will not be used in these simulations. Instead new mobility patterns were created with exactly the same simulation parameters. The distance and life time distributions of these patterns are shown in Appendices A and B and C with the patterns taken from the simulations in previous section.

This was done to see how big the deviation from the estimated distribution is seen, when another set of simulations was run. In addition to this, the computation power in use for this project did not permit such a large number of simulations for the testing phase of the simulations.

The measured variables were throughput and packet overhead. The throughput results are summarized in Table 12. In the table the first two columns indicate the mobility model, used scenario and the used routing protocol. Packet loss column indicates the average percentage of lost packets from all the payload packets sent in the simulation. The Max and Min columns indicate the maximum (and minimum) percentage of lost packets in the repeated simulations.

Table 13 summarizes the packet throughput results. The first two columns indicate the mobility model, scenario and routing protocol. Packets/delivered column indicates how many packets were sent, on average, in the network for each payload packet that was delivered to the destination and packets/sent indicates how many were sent for each payload packet that was sent in the simulations.

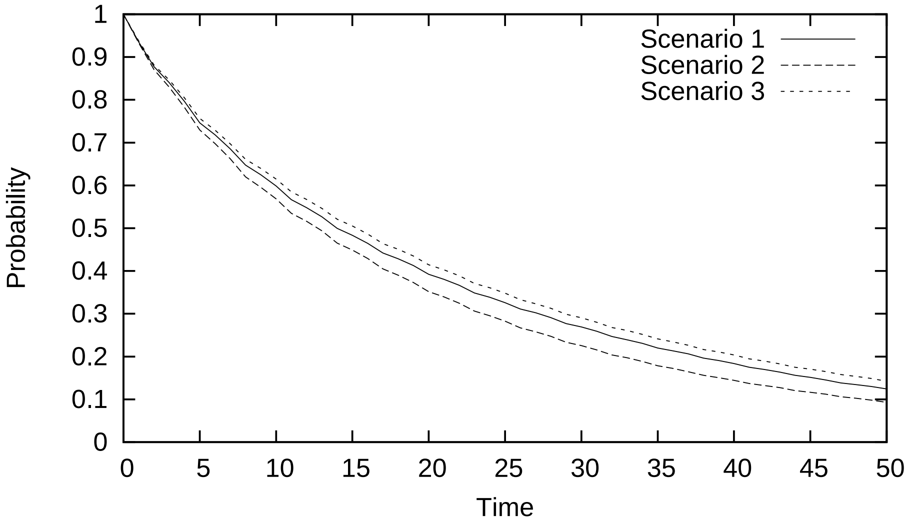

Figure 7: The link lifetime distribution for Random Walk in Scenarios 1, 2,3 and 3

7 SIMULATION RESULTS

This chapter shows the simulation results. Tables 9, 10, and 11 show the measured distance distribution. The tables are organized so that each row shows the probability for a certain distance and the columns indicate the scenario. The scenario parameters are summarized in Table 6.

Figures 7, 8 and 9 show the measured *llt* distribution. Similarly Figures 10, 11 and 12 show the measured *llt* distribution. Each Figure shows the life time distribution for all three scenarios. The figures show the remaining life time distribution, i.e. the percentage at y-axis shows the probability that a link/route is still alive after so many seconds.

Tables 12, and 13 summarize the routing protocol performance results. They show the overhead and throughput information for all scenarios and mobility models for AODV and DSR. The throughput results show the average, minimum and maximum packet loss percentage over the 30 simulation runs. The overhead results show the average of packets required to deliver one payload packet and the average of packets required for each payload packet sent.

Table 9: The distance distribution for Random Walk model in Scenarios 1, 2, and 3

Distance \ Scenario	1	2	3
1	7.3%	7.3%	15%
2	6.9%	6.9%	20%
3	6.6%	6.6%	21%
4	5.9%	5.9%	19%
5	5.0%	5.1%	13%
6	4.1%	4.1%	6.0%
7	3.2%	3.2%	2.0%
8	2.4%	2.4%	0.67%
9	1.7%	1.7%	0.24%
10	1.1%	1.1%	0.095%
11	0.68%	0.70%	0.036%
12	0.40%	0.44%	0.011%
13	0.23%	0.26%	0.0029%
14	0.13%	0.16%	0.00082%
15	0.072%	0.084%	0%
16	0.038%	0.048%	0%
17	0.019%	0.027%	0%
18	0.0095%	0.017%	0%
19	0.0041%	0.0098%	0%
20	0.0013%	0.0069%	0%
21	0.00049%	0.0038%	0%
22	0.000082%	0.0016%	0%
23	0%	0.00057%	0%
24	0%	0.00025%	0%
∞	54%	54%	3.0%

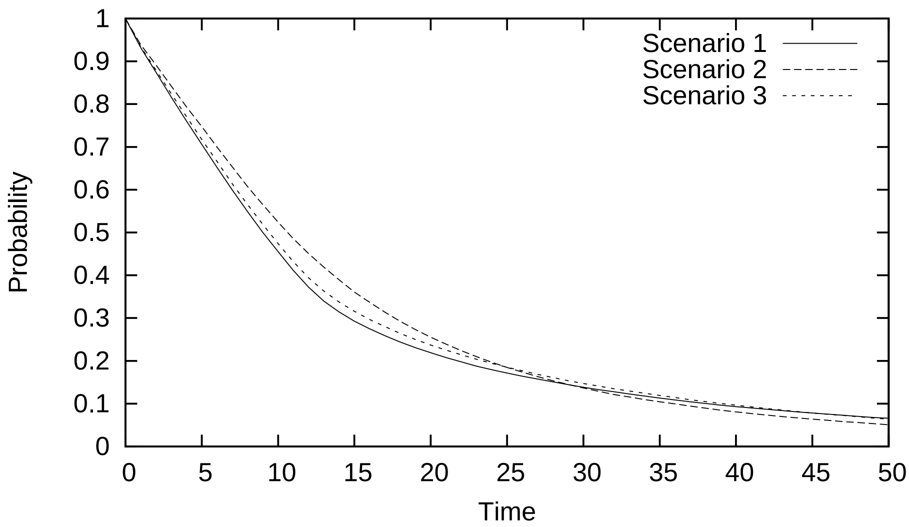

Figure 8: The link lifetime distribution for Random Direction in Scenarios 1, 2, and 3

Table 10: The distance distribution for Random Direction model in Scenarios 1, 2, and 3

Distance	1	2	3
1	6.9%	6.9%	14%
2	5.9%	5.9%	17%
3	5.2%	5.2%	18%
4	4.3%	4.3%	18%
5	3.5%	3.5%	14%
6	2.8%	2.8%	8.6%
7	2.2%	2.2%	3.8%
8	1.6%	1.6%	1.5&
9	1.1%	1.1%	0.62%
10	0.76%	0.77%	0.28%
11	0.51%	0.50%	0.13
12	0.33%	0.31%	0.061%
13	0.20%	0.19%	0.016%
14	0.12%	0.11%	0.0044%
15	0.072%	0.064%	0.00090%
16	0.040%	0.037%	0.00016%
17	0.020%	0.020%	0%
18	0.0084%	0.010%	0%
19	0.0055%	0.0043%	0%
20	0.0015%	0.0011%	0%
21	0.00049%	0.000082%	0%
∞	65%	64%	3.8%

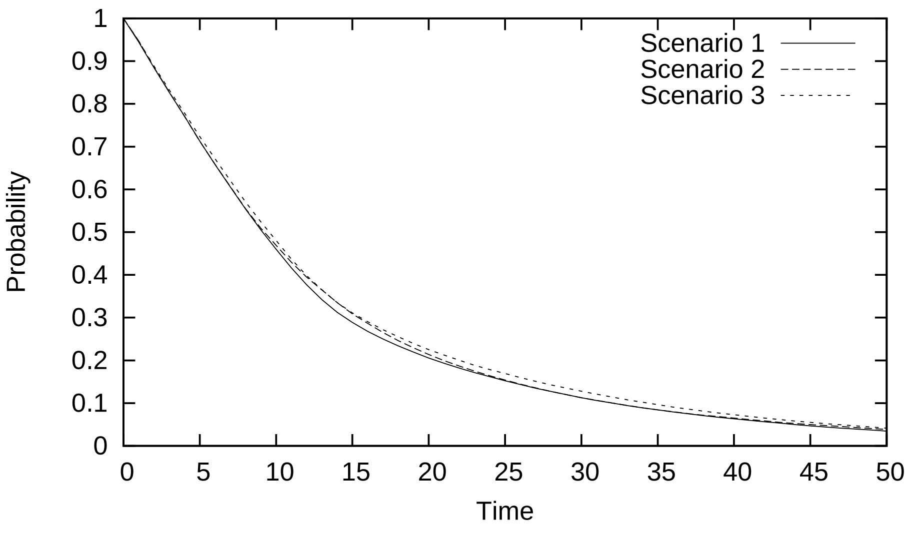

Figure 9: The link lifetime distribution for Gauss-Markov in Scenarios 1, 2, and 3

Table 11: The distance distribution for Gauss-Markov model in Scenarios 1, 2, and 3

Distance	1	2	3
1	7.2%	7.2%	15%
2	6.8%	6.8%	19%
3	6.5%	6.5%	21%
4	5.8%	5.8%	18%
5	4.9%	5.0%	13%
6	4.0%	4.1%	5.9%
7	3.1%	3.2%	2.1%
8	2.3%	2.4%	0.69%
9	1.6%	1.6%	0.24%
10	1.0%	1.1%	0.089%
11	0.65%	0.68%	0.029%
12	0.38%	0.41%	0.0066%
13	0.21%	0.24%	0.0016%
14	0.11%	0.13%	0.00049%
15	0.060%	0.074%	0%
16	0.034%	0.038%	0%
17	0.018%	0.020%	0%
18	0.0087%	0.0074%	0%
19	0.0034%	0.0028%	0%
20	0.0012%	0.00065%	0%
21	0.00033%	0.000082%	0%
∞	55%	55%	5.05%

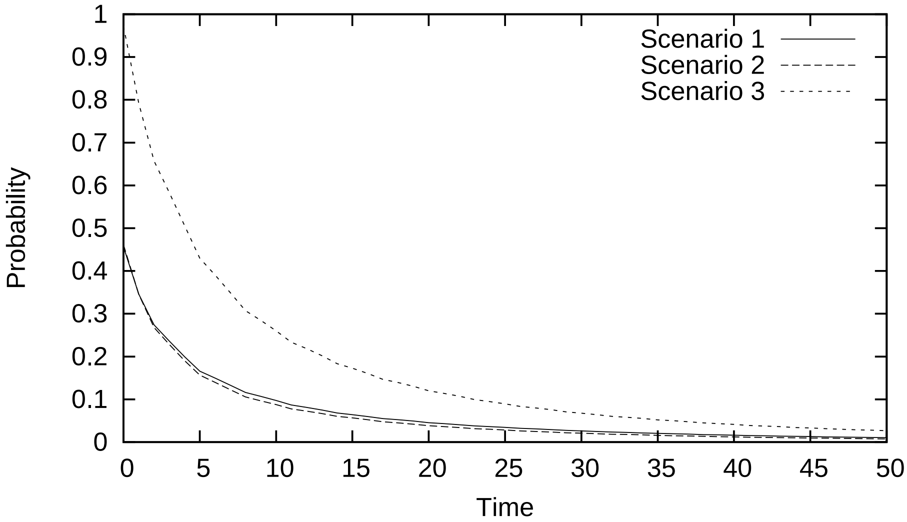

Figure 10: The route lifetime distribution for Random Walk in Scenarios 1, 2, and 3

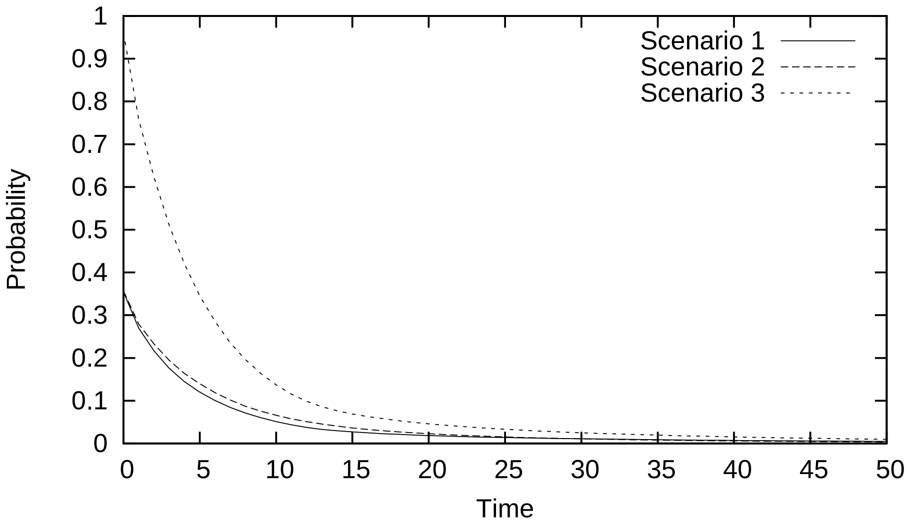

Figure 11: The route lifetime distribution for Random Direction in Scenarios 1, 2, and 3

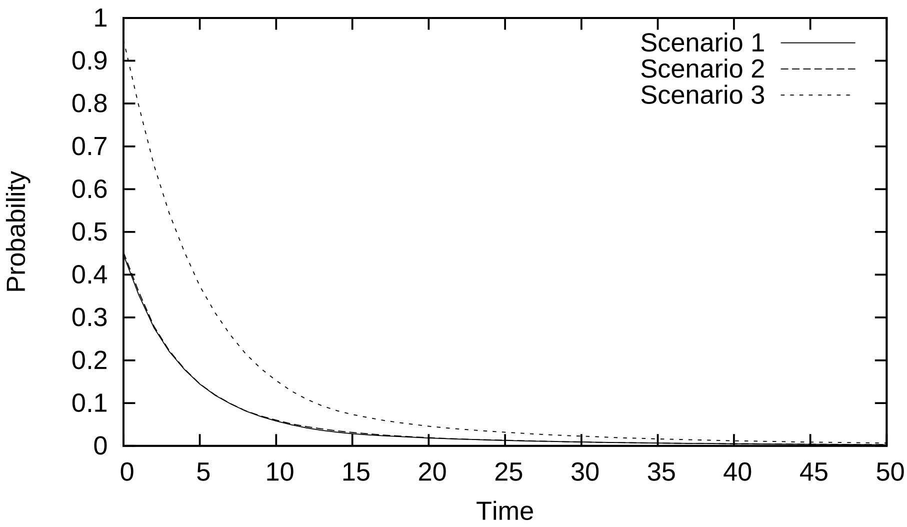

Figure 12: The route lifetime distribution for Gauss-Markov in Scenarios 1, 2, and 3

Table 12: Packet throughput results

Scenario	Routing Protocol	Packet loss	Min	Max
Random Walk 1	DSR	66,1%	57,8%	75,2%
Random Walk 2	DSR	69,3%	55,6%	81,9%
Random Walk 3	DSR	63,3%	51,1%	74,9%
Random Walk 1	AODV	59,8%	51,6%	73,1%
Random Walk 2	AODV	60,2%	49,1%	71,2%
Random Walk 3	AODV	27,0%	17,2%	50,6%
Random Direction 1	DSR	77.8%	73.5%	80.9%
Random Direction 2	DSR	75.2%	71.3%	78.7
Random Direction 3	DSR	86.9%	83.6	88.8%
Random Direction 1	AODV	66.7%	62.5%	71.4%
Random Direction 2	AODV	66.4%	62.1%	72.2%
Random Direction 3	AODV	32.6	28.6%	37.2%
Gauss-Markov 1	DSR	81.4%	78.1%	84.1%
Gauss-Markov 2	DSR	80,0%	75.7%	84.6%
Gauss-Markov 3	DSR	84.7%	82,0	88.2%
Gauss-Markov 1	AODV	58.1%	53.5%	65.3%
Gauss-Markov 2	AODV	58.1%	52.6%	68.5%
Gauss-Markov 3	AODV	28.0%	22.6%	37.7%

Table 13: Packet overhead results

Scenario	Routing Protocol	Packets/delivered	Packets/sent
Random Walk 1	DSR	18.0	6.1
Random Walk 2	DSR	21.6	6.6
Random Walk 3	DSR	21.4	7.8
Random Walk 1	AODV	8.7	3.5
Random Walk 2	AODV	9.3	3.7
Random Walk 3	AODV	10.0	7.3
Random Direction 1	DSR	32.8	7.3
Random Direction 2	DSR	27.5	6.8
Random Direction 3	DSR	71.7	9.4
Random Direction 1	AODV	8.2	2.7
Random Direction 2	AODV	8.1	2.7
Random Direction 3	AODV	11.5	7.7
Gauss-Markov 1	DSR	42.8	8.0
Gauss-Markov 2	DSR	38.9	7.8
Gauss-Markov 3	DSR	60.7	9.3
Gauss-Markov 1	AODV	8.5	3.6
Gauss-Markov 2	AODV	8.5	3.6
Gauss-Markov 3	AODV	10.1	7.3

8 ANALYSIS

This chapter presents the analysis of the proposed model on effects of mobility on reactive routing in ad hoc networks.

Reactive routing protocols consist of two major phases [47]:

Route Setup Phase: This phase is responsible for setting up a path between the source and the destination. The basic mechanisms for doing this are flooding, possibly using widening circles from the source and caching of known routes.

Route Maintenance Phase: This phase is responsible for maintaining the validity of a route. The basic mechanisms for this are Error Detection, Error Notification, and Error Recovery.

Route life time distribution is a good measure of effects of mobility on ad hoc networks. First of all, many proposed reactive routing protocols [17, 28, 41] use flooding as the basic way of creating and recreating routes. Each flooded route search creates a major cost to the network in terms of taking up bandwidth and consuming energy from the nodes. Thus short route life times produce major costs to most reactive ad hoc routing protocols.

The proposed model is to use the median of route life time distribution, or if median is zero, then the percentile of route life time distribution that has duration greater than zero.

8.1 Simulation Analysis

This section analyses the simulation results. The scenario parameters can be found in Tables 6 and 8. The main differences between Scenarios 1, 2, and 3 were following:

- In Scenarios 1, and 3 nodes move at constant speed $4m/s$
- In Scenario 2 node speed is uniformly distributed $1 \ldots 7m/s$
- In Scenarios 1, and 2 the simulation area is $300m \times 300m$
- In Scenario 3 the simulation area is $200m \times 200m$

Distance Distribution

Table 9 shows the random walk distance distribution in Scenarios 1, 2, and 3. Each row in this distribution indicates the probability that two randomly selected nodes are at certain distance from each other.

As can be seen from the table, there is practically no difference in distance distribution between Scenarios 1, and 2. The distance distributions of random direction (Table 10 and Gauss-Markov (Table 11 show the same situation. Thus we can conclude that variance in speed has at most little effect to distance distribution with these mobility models.

The Scenarios 1, and 2 show another significant detail. The percentage of node pairs that cannot reach each other is high, above 54% in random walk, 65% in random direction and 55% in Gauss-Markov. Note, that the figures indicate the probability that two randomly chosen nodes are not connected to each other. Thus one disconnected node causes the probability of disconnect to be $\frac{n-1}{\frac{n \cdot (n-1)}{2}} \approx 4.1\%$.

The probabilities in the distance distribution table for infinite distance mean that around 16 (Random Walk and Random Direction) to 21 (Gauss-Markov) nodes are unreachable from the biggest connected network. On the other hand, in Scenario 3 the percentage of node pairs that cannot reach each other is between 3% (random walk and random direction) and 5% (Gauss-Markov). These percentages mean that on average in the Scenario 3 one disconnected node existed.

The difference in distance distribution differs greatly in the Scenario 3, because in it the nodes are packet inside a much smaller area. The size difference was exaggerated a little to make the difference in this respect clear. The reason for this is that many proposed models of how mobility affects reactive routing performance concentrate on metrics that do not take this into account. The purpose of these scenarios was to clearly show the difference that the density of the network presents.

Link Life Time Distribution

The *llt* distributions for random walk, random direction, and Gauss-Markov are shown in Figures 7, 8, and 9. The figures show the probability (in y-axis) that a randomly chosen link survives at least a certain time (in x-axis) for Scenarios 1, 2, and 3. Thus, the distribution is an inverted cumulative probability distribution of the probability that the link breaks before a given moment read from the x-axis.

The llt distribution is estimated using Equation 9.

The results show that in random walk the link lifetimes are longest in Scenario 3 and shortest in Scenario 2.

For the random direction the results are mixed, i.e. Scenario 1 has the lowest probability of links with life time at least in the middle range (10+ seconds). It also has a tie with Scenario 3 of the probability over links with long lifetimes (40+ seconds). On the other hand, Scenario 2 has the largest probability of links with lifetime between 5 and 25 seconds.

The Gauss-Markov results show little difference, if any, between the three scenarios. It would seem that Scenario 1 produces slightly shorter link lifetimes than the other two scenarios.

Route Life Time Distribution

The *rlt* distributions for random walk, random direction, and Gauss-Markov are shown in Figures 10, 11, and 12. The figures show the probability (in y-axis) that the shortest route between two randomly chosen nodes survives at least a certain time (in x-axis) for Scenarios 1, 2, and 3. Thus, the distribution is an inverted cumulative probability distribution of the probability that the rout breaks before a given moment read from the x-axis.

The *rlt* distribution is estimated using Equation 10.

The *rlt* distribution results for all three mobility models show that the Scenario 3 has significantly larger route lifetimes than Scenarios 1, and 2 and that Scenarios 1, and 2 are virtually indistinguishable. The reason for the Scenario 3 producing the best route lifetimes is due to the fact that nodes tend to be closer to each other in Scenario 3 than in Scenarios 1 and 2. We can conclude that in these scenarios the distance distribution dominates the results.

8.2 Criterion Analysis

The purpose of this section is to examine how the model compares with the proposed criteria, i.e. clarity, predictivity and consistency.

Clarity

Intuitively, the lifetime of a route has a great effect to the reactive routing protocols, because re-establishing a route takes time and also because it consumes resources such as network bandwidth and node energy.

Global flooding mechanism is such that every node broadcasts a given packet once, so that all connected nodes are certain to receive it. It is easy to understand that route breakages have a tremendous effect on network performance for a routing protocol using a basic flooding mechanism to repair routes.

Since this is the case, most routing protocols also try to limit the amount of global flooding they do. AODV first searches the node from a distance of 1, 3, 5, and 7 in that order and only after these have failed uses global flooding. DSR has a mechanism for repairing routes locally. Still, both do resort to flooding protocol to discover and repair routes.

This means that the effects caused by the proposed metric are both intuitive and easy to understand.

The model consists of two different parts, which are distance distribution and link life time distribution. They are combined to get the route life time distribution. A human observer can look at *rlt* distributions (see Figures 10, 11 and 12) and get a basic understanding of how mobility will affect routing protocol performance. If more detailed analysis of the reasons for performance differences is needed, the observer may study the *llt* and distance distributions (see Tables 9, 10 and 11 and Figures 7, 7, 9).

Different scenarios can also be compared using the median value of the *rlt* distribution. This allows comparisons of different scenarios to be done automatically.

Predictivity

The given model gives predictions about how different mobility scenarios will affect reactive routing protocol performance. Table 14 shows the rankings and *rlt* values for the studied scenarios. The scenario parameters are summarized in Table 6.

The average packet loss and overhead results are reported in Tables 12 and 13. The relative predicted and actual rankings are summarized in Table 15 and 16. As can be seen from the tables, the throughput rankings of AODV are in line with the predictions, but the overhead rankings of AODV and the rankings for DSR show no similarity between the predicted rankings and the results from actual simulations.

One should especially note that with each mobility model, the Scenario 3 should produce the best performance. But instead in DSR Gauss-Markov and random direction produce worst results in both throughput and overhead.

This means that the model does not predict results accurately. The analysis of the factors that affect the results in these unanticipated ways is left out

Table 14: The *rlt* values for each Scenario. The Median column indicates the median route lifetime and the $P(rlt > 0)$ column indicates the percentage of routes with lifetime greater than 0

Scenario	Ranking	Median	P(rlt>0)
Random Walk 1	4.	0	46%
Random Walk 2	4.	0	46%
Random Walk 3	1.	$4s$	97%
Random Direction 1	9.	0	35%
Random Direction 2	8.	0	36%
Random Direction 3	2.	$3s$	96%
Gauss-Markov 1	6.	0	45%
Gauss-Markov 2	6.	0	45%
Gauss-Markov 3	2.	$3s$	95%

as further work to be studied.

It is also worth noting that Scenario 2 has approximately the same performance as Scenario 1 for all three mobility models. It would seem that adding variance to the speed as was done in Scenario 2, adds variance to the results, but does not change the average results.

Table 15: Summary of the rankings of different scenarios for AODV. Overhead rankings are per packet delivered.

Scenario	Predicted Rnk	Throughput Rnk	Overhead Rnk
Random Walk 3	1.	1.	7.
Gauss-Markov 3	2.	2.	8.
Random Direction 3	2.	3.	9.
Random Walk 1	4.	6.	5.
Random Walk 2	4.	7.	6.
Gauss-Markov 1	6.	4.	3.
Gauss-Markov 2	6.	4.	3.
Random Direction 2	8.	8.	1.
Random Direction 1	9.	9.	2.

Consistency

For each scenario/mobility model combination two sets of simulations were done. The first was done to measure the *rlt* distribution and the second to measure actual performance of routing protocols with those scenarios. In order to measure whether the mobility models produce similar mobility with different runs, these two simulation sets have been compared against each other. The first simulation set was run 1000 times and the second 30 times.

Appendix A shows the comparison of distance distribution between the first and second set of simulation runs. The results are quite similar in the

Table 16: Summary of the rankings of different scenarios for DSR. Overhead rankings are per packet delivered payload data packet.

Scenario	Predicted Rnk	Throughput Rnk	Overhead Rnk
Random Walk 3	1.	1.	2.
Gauss-Markov 3	2.	8.	8.
Random Direction 3	2.	9.	9.
Random Walk 1	4.	2.	1.
Random Walk 2	4.	3.	3.
Gauss-Markov 1	6.	7.	7.
Gauss-Markov 2	6.	6.	6.
Random Direction 2	8.	4.	4.
Random Direction 1	9.	5.	5.

first and second set, except for the percentage of disconnected nodes, which varies rather much.

To study the distributions a bit further, Table 18 shows the average, standard deviation, skew and kurtosis for both runs. The figures are calculated without the disconnected portions, since their involvement would rise the average to infinity. Table 17 shows how close average, standard deviation, skew and kurtosis were in the first and second set of simulations.

Average measures the center of the distribution. Standard deviation measures how much a typical sample deviates from the center. Skew measures whether the distribution is symmetric (skew = 0) right tailed (skew > 0), or left tailed (skew < 0). Kurtosis measures the density of the distribution such that values greater than 0 denote distributions that are more dense than the normal distribution.

As can be seen from the table, all the distributions (average, std, skew and kurtosis) are almost identical in each case except for the amount of disconnected nodes. The amount of node pairs that cannot reach each other varies more than 5%, which means that on average more than one node more is disconnected from the rest of the network. (See Section 8.1. Thus we conclude that the studied mobility models produce consistent distance distributions with the exception that the amount of disconnected nodes varies much from one measurement to another.

Appendix B shows the comparison of link lifetime distribution between the first and second set of simulation runs. The results from first and second set are almost indistinguishable from the graphs.

Further analysis (see Tables 20 and 21 shows that the average link lifetime change is negligible, less than 5% for all scenarios except random direction 1. The standard deviations in each scenario are also within 10% of each other. On the other hand, the random walk Scenario 1 shows a great difference in skew (35/42) and kurtosis (48/65) and otherwise the skew and kurtosis are very close to each other in both scenario runs.

This is caused by two outliers in the latter simulations done with random

Table 17: Closeness of runs 1 and 2 for distance distribution

Model	Average	Std	Skew	Kurtosis
RW2	94,6%	94,9%	86,7%	88,9%
RW3	98,2%	97,6%	95,6%	96,8%
RD1	93,5%	97,9%	98,4%	100%
RD2	98,6%	98,4%	99,7%	99,8%
RD3	98,9%	98,9%	98,8%	99,6%
GM1	92,4%	94,4%	98,9%	97,5%
GM2	96,3%	98,6%	94,6%	93,0%
GM3	99,7%	98,8%	97,8%	98,7%

walk Scenario 1. The most lasting five links in the latter set (30 runs) are $212s$, $225s$, $238s$ and twice $381s$. These two outliers have a tremendous effect on the moments of the series, even though the probability of their existance is so low that in the first set of 1000 runs the longest lasting link lasted merely $350s$. Table 19 shows the results for the random walk Scenario 1 without taking these outliers into account. As can be seen, if these outliers are not accounted, there is almost an exact match between these two test runs of random walk Scenario 1.

Appendix C shows the comparison of route lifetime distribution between the first and second set of simulation runs. The results from first and second set are almost indistinguishable from the graphs, which is to be expected since their components, the distance distribution and link lifetime distributions have been shown to be very close to each other.

8.3 Summary

The proposed model of route lifetime was studied in this chapter. The simulation studies showed that the model does not predict routing results accurately. Since there are good reasons to assume that route lifetime has effect on reactive ad hoc routing, and no reasons to assume otherwise, it is probable that the model is missing some other factor that contributes greatly to the performance of reactive ad hoc routing protocols.

Table 18: The average, variance, skew and kurtosis for distance distributions

Test run	Model	Average	Standard Deviation	Skew	Kurtosis
1	RW1	4,39	2,86	2,80	3,97
2	RW1	4,33	2,80	2,63	3,72
1	RW2	4,44	2,92	2,93	4,15
2	RW2	4,2	2,77	2,54	3,69
1	RW3	3,28	1,65	1,37	2,21
2	RW3	3,22	1.61	1.31	2.14
1	RD1	4,16	2,91	3,02	4,16
2	RD1	3,89	2,85	3,07	4,16
1	RD2	4,14	2,89	2,99	4,11
2	RD2	4,08	2,84	3,00	4,12
1	RD3	3,60	1,89	1,61	2,55
2	RD3	3,56	1,87	1,63	2,56
1	GM1	4,37	2,84	2,80	3,96
2	GM1	4,73	3,01	2,83	4,06
1	GM2	4,41	2,86	2,80	3,96
2	GM2	4,58	2,90	2,96	4,26
1	GM3	3,28	1,65	1,37	2,20
2	GM3	3,29	1,67	1,40	2,23

Table 19: Random walk Scenario 1 without outliers

1	RW1	22,5	26,0	34,7	48,4
2	RW1	22,2	25,4	33,9	47,2
		98,7%	97,7%	97,7%	97,5%

Table 20: Closeness of runs 1 and 2 for link lifetime distribution

Model	Average	Std	Skew	Kurtosis
RW1	100%	95,2%	83,0%	75,0%
RW2	97,0%	99,5%	97%	93,9%
RW3	99,6%	98,5%	96,8%	95,2%
RD1	94,4%	91,1%	91,5%	94,2%
RD2	98,7%	95,8%	88,3%	82,0%
RD3	99,4%	98,9%	98,9%	97,9%
GM1	100%	93,5%	92,9%	89,6%
GM2	96,5%	98,1%	96,1%	94,5%
GM3	98,6%	98,1%	100%	98,3%

Table 21: The average, variance, skew and kurtosis for link life time distributrion

Test run	Model	Average	Std.	Skew	Kurtosis
1	RW1	22,5	26,0	34,7	48,4
2	RW1	22,5	27,3	41,8	64,5
1	RW2	19,6	22,5	29,8	41,3
2	RW2	20,2	22,7	28,9	38,9
1	RW3	24,2	27,5	37,6	52,2
2	RW3	24,1	27,7	36,2	49,8
1	RD1	15,2	20,8	31,1	43,9
2	RD1	16,1	22,8	34,0	46,6
1	RD2	15,8	19,5	30,8	46,1
2	RD2	15,6	18,7	27,2	37,8
1	RD3	15,4	19,4	27,4	37,7
2	RD3	15,3	19,2	27,7	38,5
1	GM1	13,2	14,7	20,1	27,7
2	GM1	13,2	15,7	22,3	31,0
1	GM2	13,6	15,6	22,0	30,9
2	GM2	14,1	15,9	22,9	32,7
1	GM3	14,1	15,8	21,4	29,4
2	GM3	14,2	16,0	21,4	28,9

9 CONCLUSIONS

This report proposed a method for measuring the effects of mobility on reactive ad hoc routing protocols. The proposed method is to measure the expected route life time distribution a given scenario produces.

The simulation results show that route life time distribution alone is not a good measure for problems that mobility causes to reactive ad hoc routing (See Tables 14, 15 and 16). However, intuitively it should be a major contributor to the performance of reactive routing. This means that there are probably other, yet unknown, variables that have a major effect on the performance of reactive routing protocols.

The effect that is especially of notice is that DSR performed worse when the network was more dense, which is directly against the predictions of the proposed model. Some possible explanations for this are that collisions become more common, especially if no good collision prevention algorithm is in use, and network congestion caused by the large size of radio radius compared to simulation area. Further work on this is required to fully understand the effects that affect protocol performance.

From these results we can predict that routing in networks with large diameter and dynamic links is very difficult - the route life time goes down exponentially to the number of links.

If the route lifetime distribution does have a major effect on reactive ad hoc routing, it also means bad news for those who wish to use as short links as possible to conserve energy. This is because one of the key methods for conserving node energy is to use less energy for transmissions. This, however, has two effects. First it raises the diameter of the network, and secondly makes it more likely for the existing links to have short lifetimes.

Further work is required to study the effects in more detail and to get better idea of how much differences in velocity and graph diameter affect the routing protocol performance.

One should also note that link life time distribution seems like a good metric for the effects of mobility to proactive ad hoc routing. This is because each link failure creates a surge of network activity, since proactive protocols spread the information about changed topology throughout the network.

It also suggests that for large networks with relatively stable links, proactive routing gives better performance. Especially if link changes are mostly local.

This analysis also suggests another possibility for routing in ad hoc networks. When distances between nodes are long, it may be a better idea to anchor the route only for certain points, or areas in the network between source and destination - such as clusters. This might enable the routing protocol to abstract away part of the mobility that is merely local in scope.

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A DISTANCE DISTRIBUTION

These tables show the distance distribution estimates from the first phase simulations of 1000 runs and from the second phase simulations of 30 runs. The first phase simulations were used to measure the route life time distributions and the second phase simulations to measure the actual effect of the scenario on reactive ad hoc routing. The Initial columns show the distribution for the first phase simulations and the test columns for the second phase simulations.

Table 22: The distance distribution for Random Walk model

D	1 Initial	1 Test	2 Initial	2 Test	3 Initial	3 Test
1	7.3%	7.2%	7.3%	7.5%	15%	16%
2	6.9%	6.6%	6.9%	6.9%	20%	20%
3	6.6%	6.4%	6.6%	6.6%	21%	22%
4	5.9%	5.5%	5.9%	6.3%	19%	19%
5	5.0%	4.6%	5.1%	5.5%	13%	13%
6	4.1%	3.7%	4.1%	4.5%	6.0%	5.7%
7	3.2%	2.9%	3.2%	3.5%	2.0%	1.7%
8	2.4%	2.3%	2.4%	2.7%	0.67%	0.44%
9	1.7%	1.7%	1.7%	1.9%	0.24%	0.16%
10	1.1%	1.1%	1.1%	1.1%	0.095%	0.068%
11	0.68%	0.64%	0.70%	0.70%	0.036%	0.057%
12	0.40%	0.36%	0.44%	0.36%	0.011%	0.0054%
13	0.23%	0.20%	0.26%	0.21%	0.0029%	0%
14	0.13%	0.082%	0.16%	0.10%	0.00082%	0%
15	0.072%	0.014%	0.084%	0.033%	0%	0%
16	0.038%	0.0027%	0.048%	0.0054%	0%	0%
17	0.019%	0%	0.027%	0%	0%	0%
18	0.0095%	0%	0.017%	0%	0%	0%
19	0.0041%	0%	0.0098%	0%	0%	0%
20	0.0013%	0%	0.0069%	0%	0%	0%
21	0.00049%	0%	0.0038%	0%	0%	0%
22	0.000082%	0%	0.0016%	0%	0%	0%
23	0	0%	0.00057%	0%	0%	0%
24	0	0%	0.00025%	0%	0%	0%
∞	54%	57%	54%	52%	3.0%	2.9%

Table 23: The distance distribution for Random Direction model

D	1 Initial	1 Test	2 Initial	2 Test	3 Initial	3 Test
1	6.9%	6.7%	6.9%	6.8%	14%	14%
2	5.9%	5.3%	5.9%	6.2%	17%	17%
3	5.2%	4.3%	5.2%	5.4%	18%	19%
4	4.3%	3.4%	4.3%	4.6%	18%	18%
5	3.5%	2.7%	3.5%	3.6%	14%	14%
6	2.8%	2.1%	2.8%	2.8%	8.6%	8.2%
7	2.2%	1.5%	2.2%	2.1%	3.8%	3.1%
8	1.6%	1.1%	1.6%	1.6%	1.5&	1.4%
9	1.1%	0.90%	1.1%	1.1%	0.62%	0.72%
10	0.76%	0.58%	0.77%	0.70%	0.28%	0.26%
11	0.51%	0.36%	0.50%	0.40%	0.13	0.16%
12	0.33%	0.16%	0.31%	0.24%	0.061%	0.079%
13	0.20%	0.13%	0.19%	0.17%	0.016%	0.011%
14	0.12%	0.11%	0.11%	0.13%	0.0044%	0%
15	0.072%	0.065%	0.064%	0.082%	0.00090%	0%
16	0.040%	0.038%	0.037%	0.057%	0.00016%	0%
17	0.020%	0.016%	0.020%	0.027%	0%	0%
18	0.0084%	0.0054%	0.010%	0.0082%	0%	0%
19	0.0055%	0.0027%	0.0043%	0%	0%	0%
20	0.0015%	0%	0.0011%	0%	0%	0%
21	0.00049%	0%	0.000082%	0%	0%	0%
22	0%	0%	0%	0%	0%	0%
∞	65%	70%	64%	64%	3.8%	4.7%

Table 24: The distance distribution for Gauss-Markov model

D	1 Initial	1 Test	2 Initial	2 Test	3 Initial	3 Test
1	7.2%	7.3%	7.2%	6.9%	15%	15%
2	6.8%	7.0%	6.8%	6.8%	19%	20%
3	6.5%	7.3%	6.5%	7.0%	21%	21%
4	5.8%	6.6%	5.8%	6.5%	18%	18%
5	4.9%	5.5%	5.0%	5.9%	13%	12.7%
6	4.0%	4.7%	4.1%	4.9%	5.9%	6.2%
7	3.1%	3.9%	3.2%	3.9%	2.1%	2.1%
8	2.3%	3.2%	2.4%	2.8%	0.69%	0.78%
9	1.6%	2.4%	1.65%	1.8%	0.24%	0.30%
10	1.0%	1.6%	1.1%	1.0%	0.089%	0.11%
11	0.65%	1.0%	0.68%	0.67%	0.029%	0.027%
12	0.38%	0.63%	0.41%	0.36%	0.0066%	0.0054%
13	0.21%	0.39%	0.24%	0.27%	0.0016%	0%
14	0.11%	0.18%	0.13%	0.17%	0.00049%	0%
15	0.060%	0.090%	0.074%	0.12%	0%	0%
16	0.034%	0.044%	0.038%	0.073%	0%	0%
17	0.018%	0.033%	0.020%	0.046%	0%	0%
18	0.0087%	0.019%	0.0074%	0.033%	0%	0%
19	0.0034%	0.0054%	0.0028%	0.030%	0%	0%
20	0.0012%	0%	0.00065%	0.022%	0%	0%
21	0.00033%	0%	0.000082%	0.0054%	0%	0%
∞	55%	48%	55%	51%	5.05%	4.2%

B LINK LIFE TIME DISTRIBUTION

These figures show the link life time distribution estimates from the first phase simulations of 1000 runs and from the second phase simulations of 30 runs. The first phase simulations were used to measure the link life time distributions and the second phase simulations to measure the actual effect of the scenario on reactive ad hoc routing. The "run 1" graph depicts the link life time distribution measured in the first phase simulations and the "run 2" graph the link life time distribution measured in the second phase simulations.

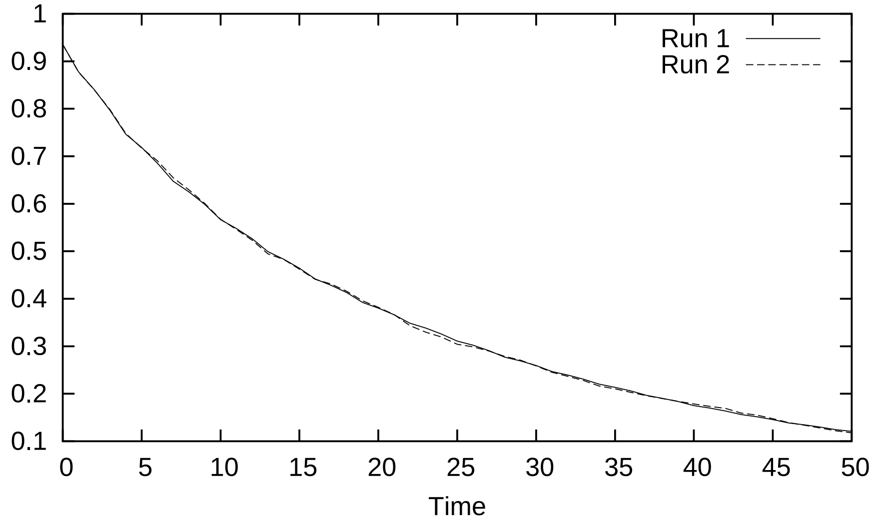

Figure 13: The link lifetime distribution for Random Walk in Scenario 1

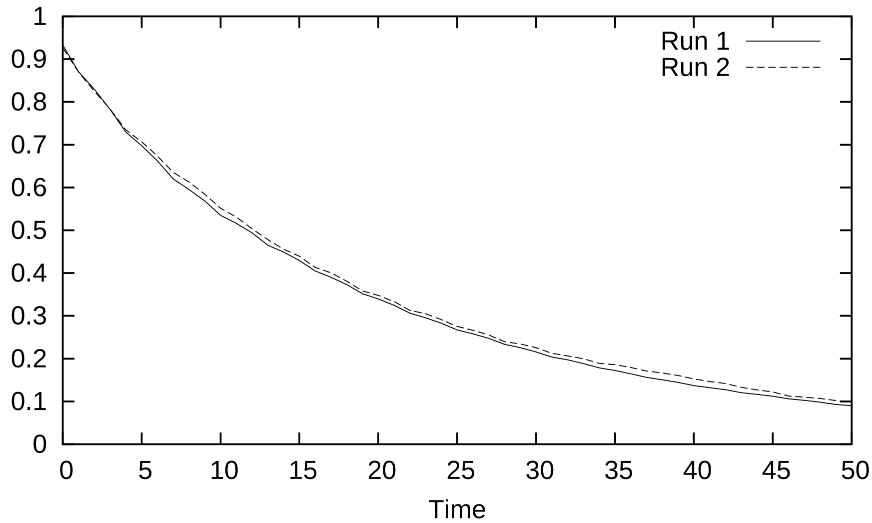

Figure 14: The link lifetime distribution for Random Walk in Scenario 2

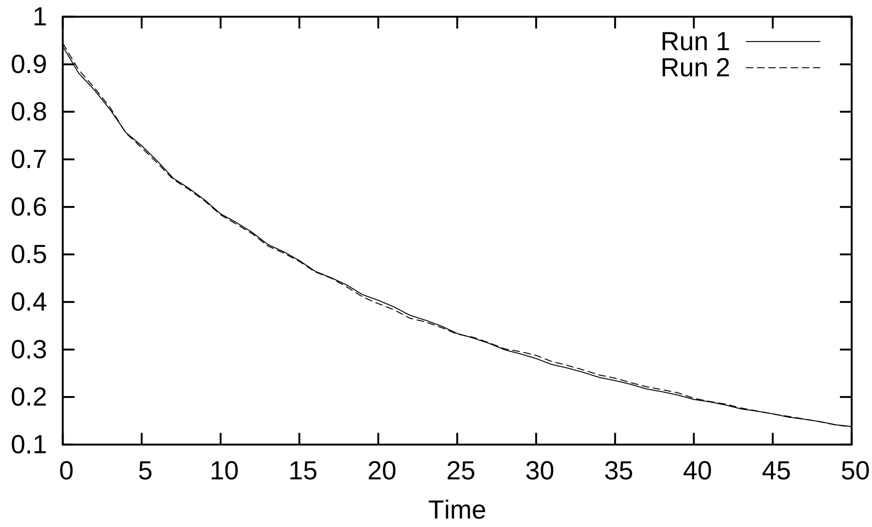

Figure 15: The link lifetime distribution for Random Walk in Scenario 3

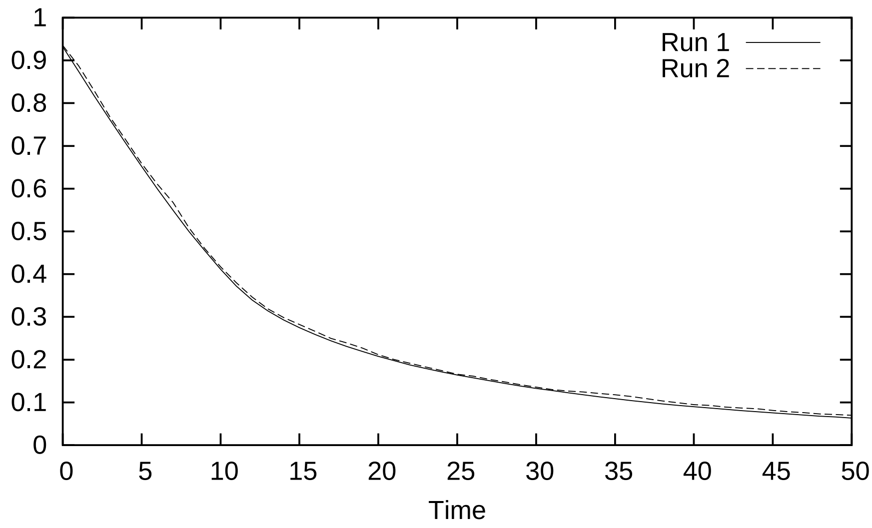

Figure 16: The link lifetime distribution for Random Direction in Scenario 1

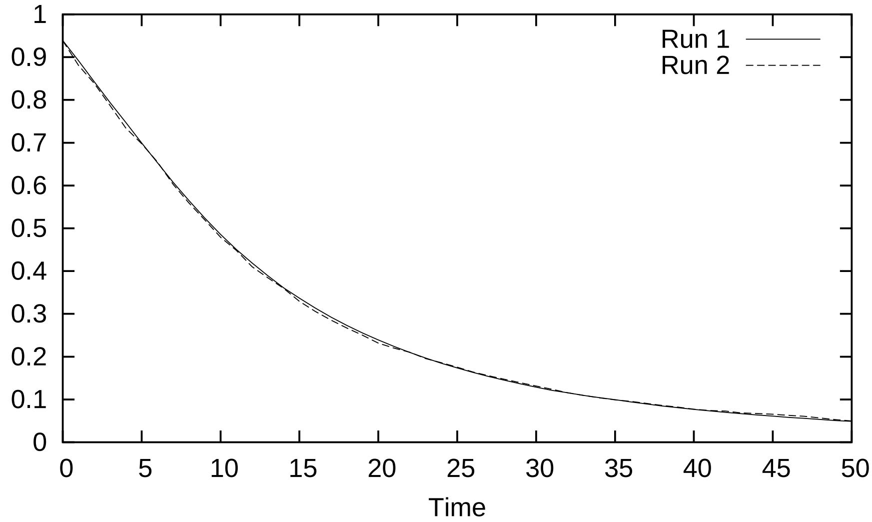

Figure 17: The link lifetime distribution for Random Direction in Scenario 2

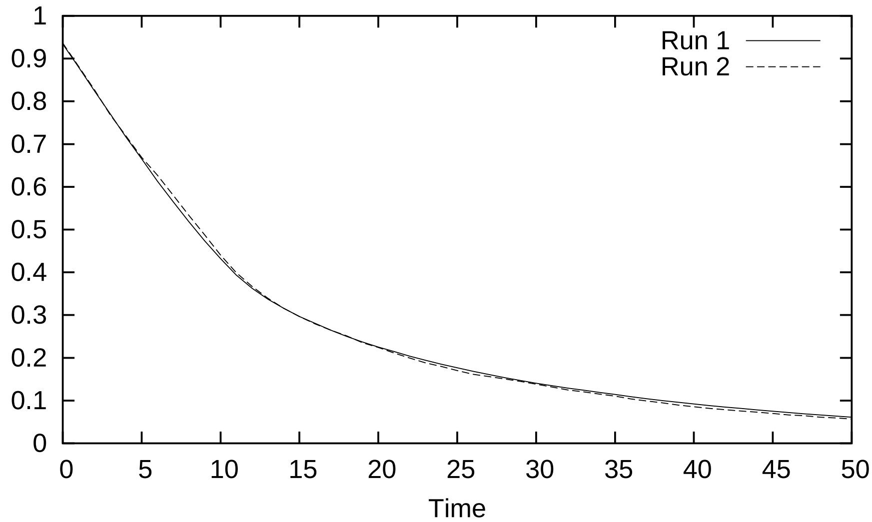

Figure 18: The link lifetime distribution for Random Direction in Scenario 3

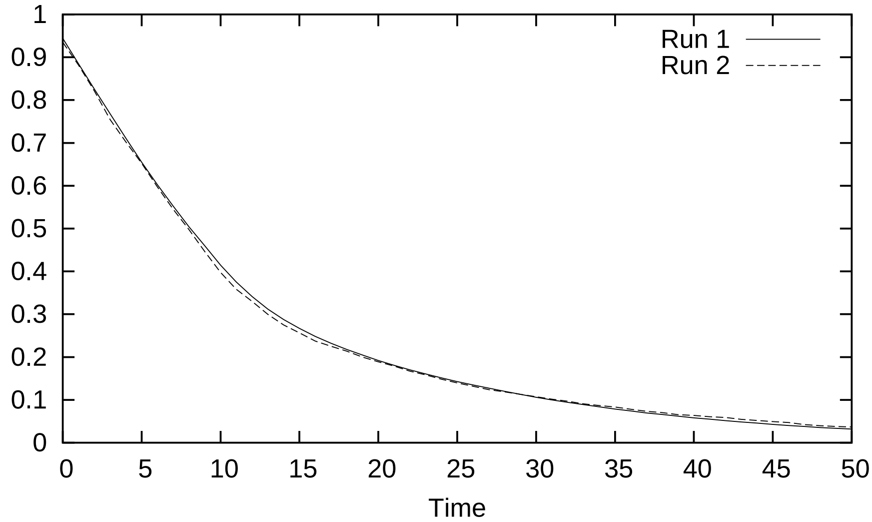

Figure 19: The link lifetime distribution for Gauss-Markov in Scenario 1

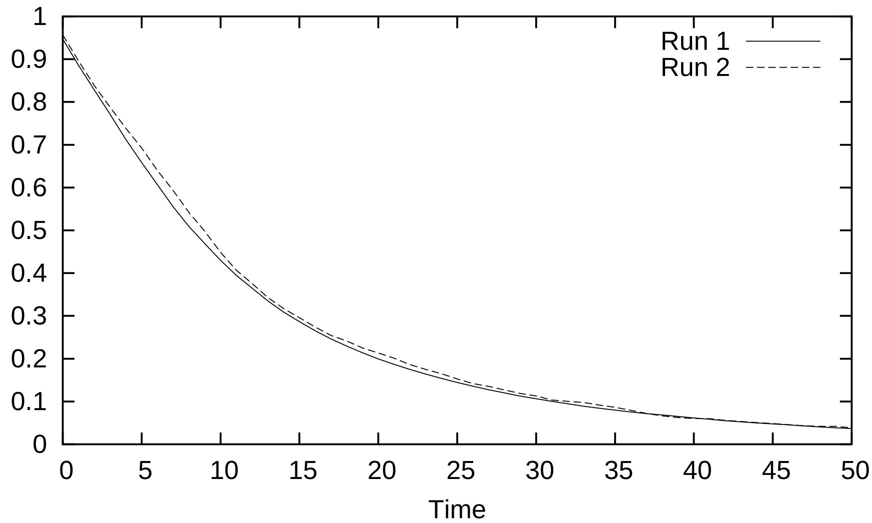

Figure 20: The link lifetime distribution for Gauss-Markov in Scenario 2

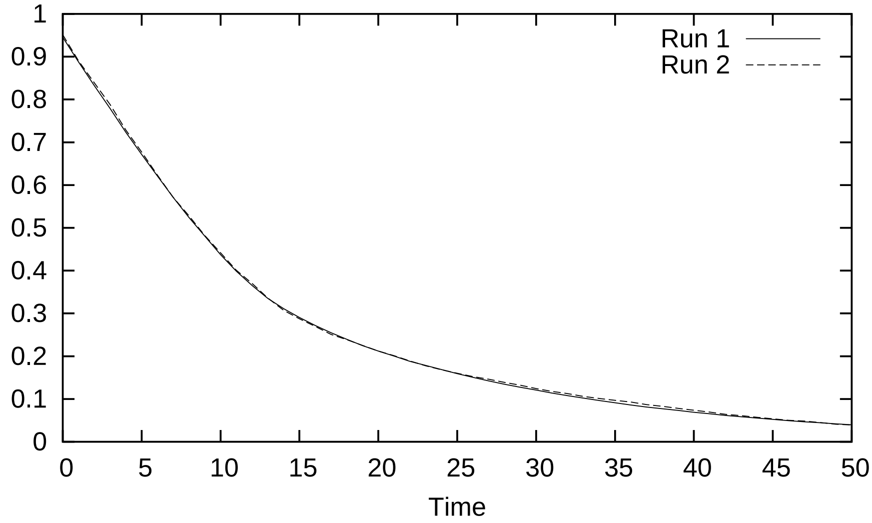

Figure 21: The link lifetime distribution for Gauss-Markov in Scenario 3

C ROUTE LIFE TIME DISTRIBUTION DISTRIBUTION

These figures show the route life time distribution estimates from the first phase simulations of 1000 runs and from the second phase simulations of 30 runs. The first phase simulations were used to measure the route life time distributions and the second phase simulations to measure the actual effect of the scenario on reactive ad hoc routing. The "run 1" graph depicts the route life time distribution measured in the first phase simulations and the "run 2" graph the route life time distribution measured in the second phase simulations.

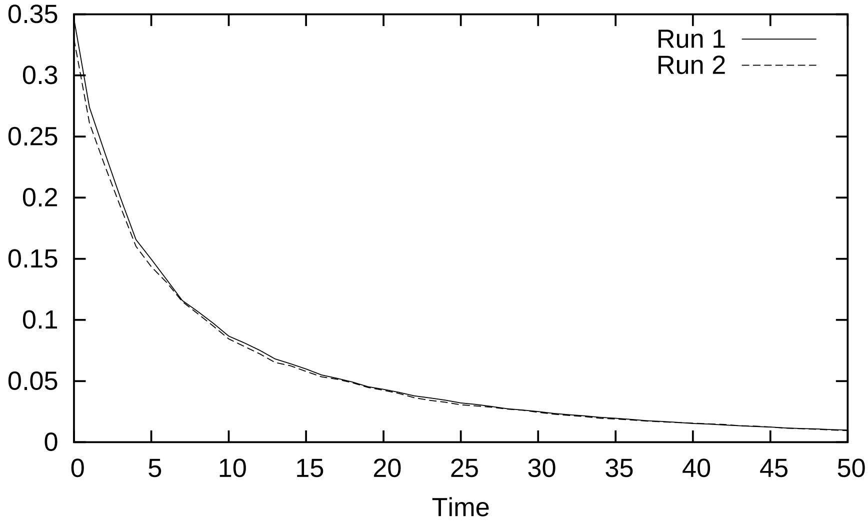

Figure 22: The route lifetime distribution for Random Walk in Scenario 1

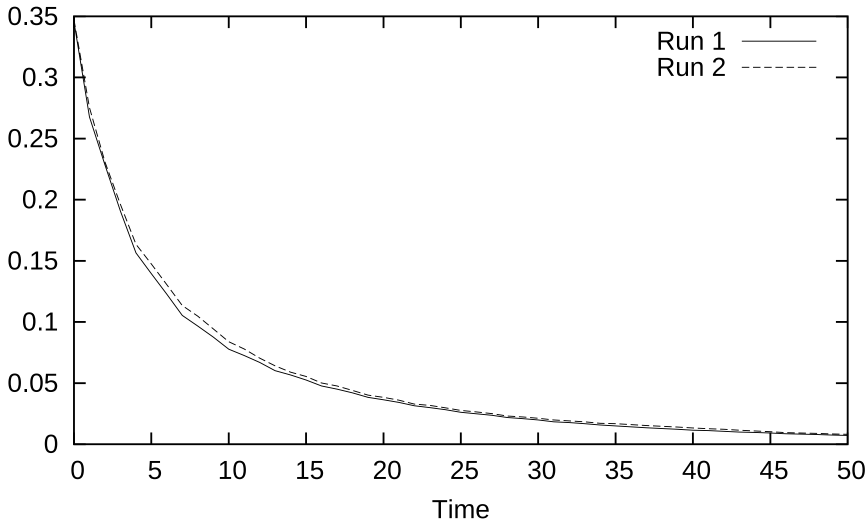

Figure 23: The route lifetime distribution for Random Walk in Scenario 2

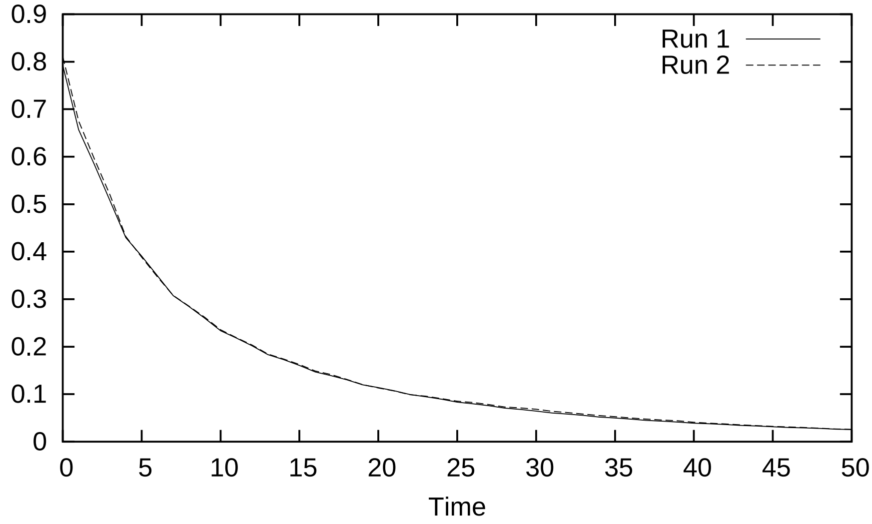

Figure 24: The route lifetime distribution for Random Walk in Scenario 3

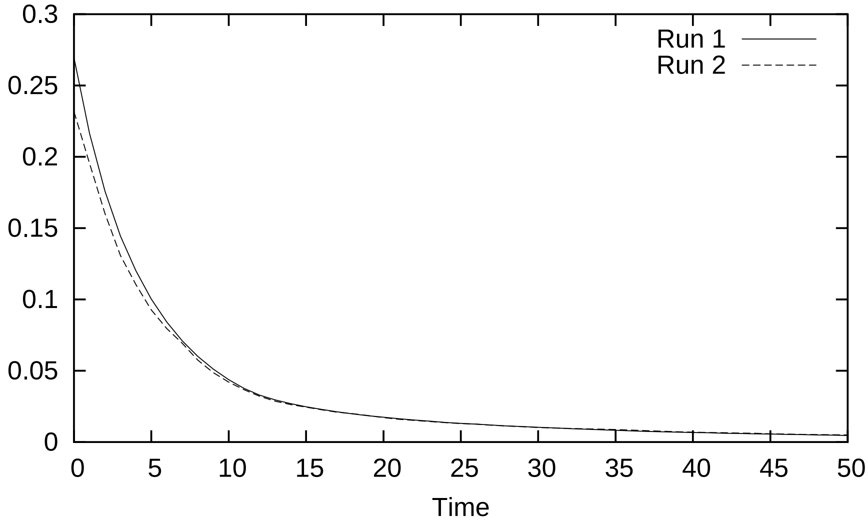

Figure 25: The route lifetime distribution for Random Direction in Scenario 1

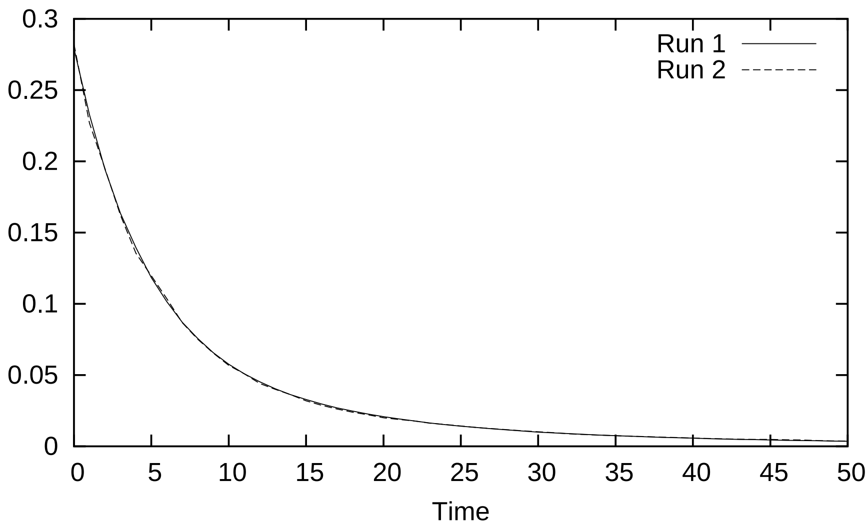

Figure 26: The route lifetime distribution for Random Direction in Scenario 2

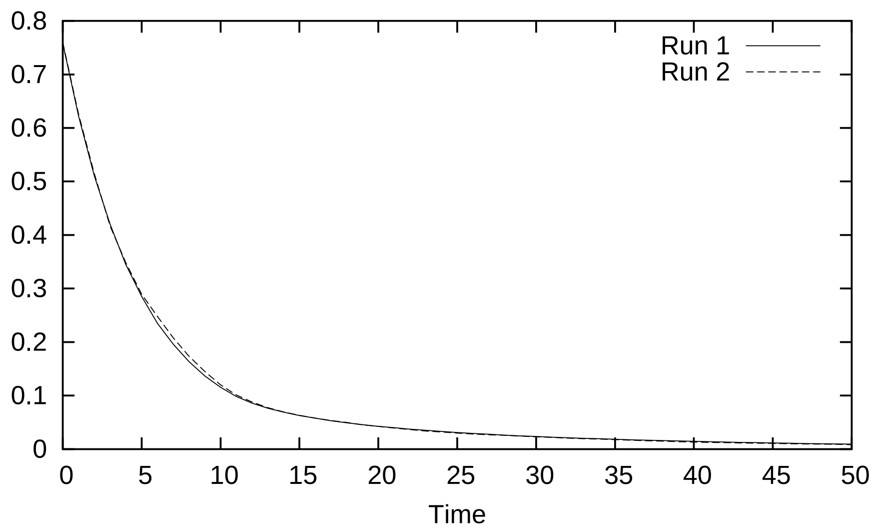

Figure 27: The route lifetime distribution for Random Direction in Scenario 3

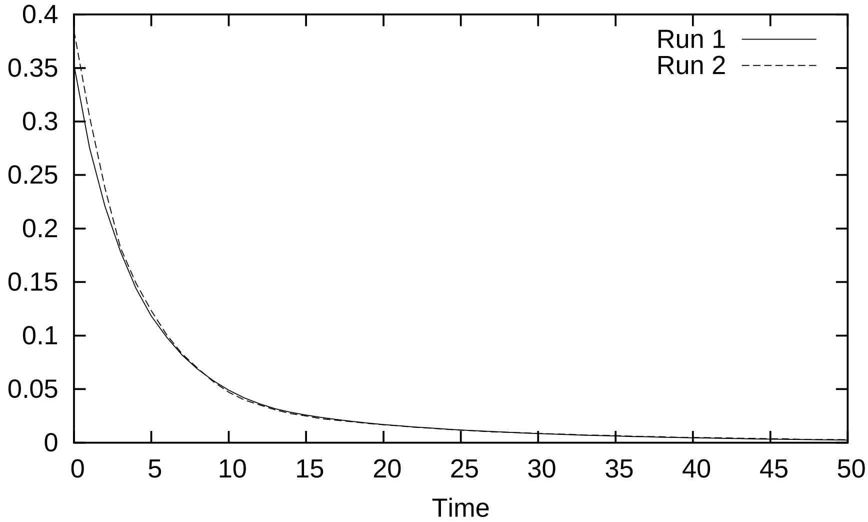

Figure 28: The route lifetime distribution for Gauss-Markov in Scenario 1

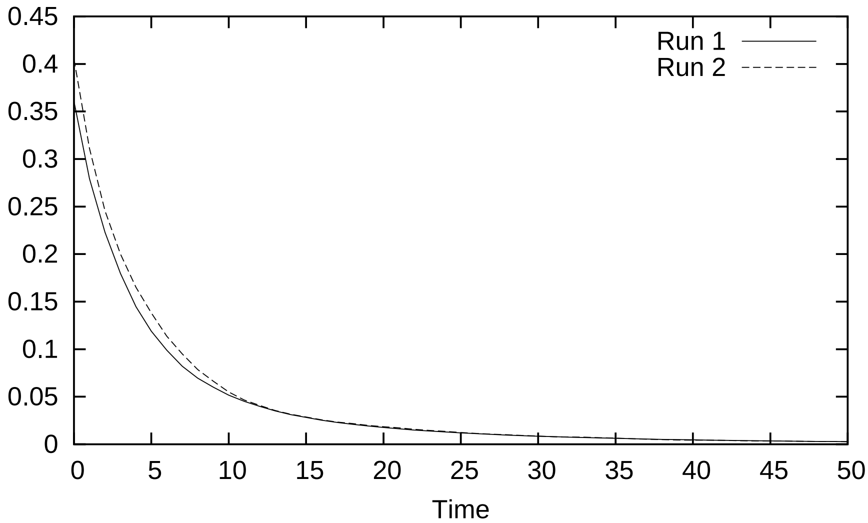

Figure 29: The route lifetime distribution for Gauss-Markov in Scenario 2

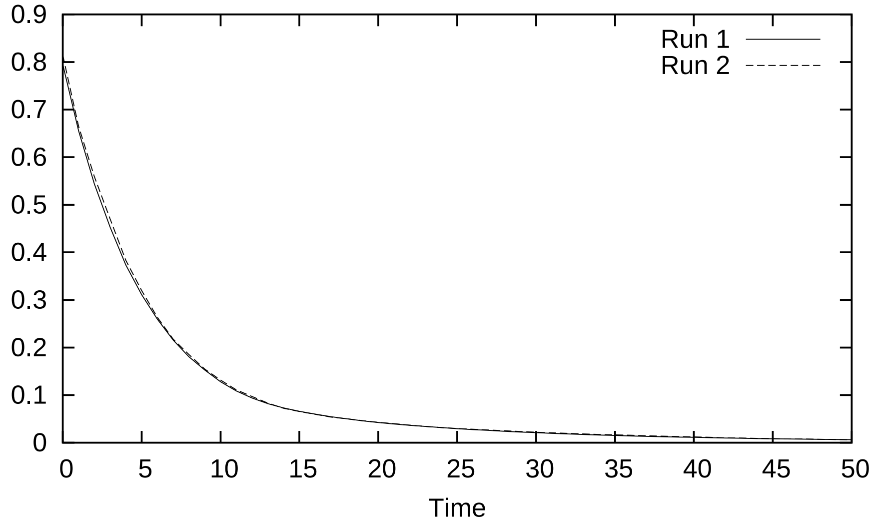

Figure 30: The route lifetime distribution for Gauss-Markov in Scenario 3

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