EVALUATING MOBILITY MODELS WITHIN AN AD HOC NETWORK

by
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A thesis submitted to the Faculty and the Board of Trustees of the Colorado School of Mines in partial fulfillment of the requirements for the degree of Master of Science (Mathematical and Computer Sciences).

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ABSTRACT

With current advances in technology, wireless networks are increasing in popularity. Wireless networks allow users the freedom to travel from one location to another without interruption of their computing services. However, wireless networks require the existence of a wired base station (BS) in order for the wireless user to send/receive messages. Ad hoc networks, a subset of wireless networks, allow the formation of a wireless network without the need for a BS. All participating users in an ad hoc network agree to accept and forward messages, to and from each other. With this flexibility, wireless networks have the ability to form anywhere, at any time, as long as two or more wireless users are willing to communicate.

In an ad hoc network, the ability to send a message to a group of users, based solely on their geographic location, is desirable. A geocast protocol serves this purpose. Rescue missions, military scenarios, and even advertising schemes benefit from this type of message delivery service. However, before implementation occurs, an ad hoc network protocol such as a geocast protocol must be tested under realistic conditions including, but not limited to, a sensible transmission range, limited buffer for storage of messages, and realistic movements of the wireless users (i.e., a mobility model). The results presented in this thesis focus on several mobility models in an attempt to compare

the effects that different mobility models have on an ad hoc network protocol. It is obvious that wireless users will travel from one location to another. However, representing their exact movements is not so simple. The results presented in this thesis illustrate the importance in carefully evaluating and implementing multiple mobility models when evaluating an ad hoc network protocol. We also provide suggestions for researchers as they select mobility models for their specific scenarios.

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ACKNOWLEDGEMENTS

I would like to express my sincere appreciation to the State of Colorado for its generous funding and support of this project. I would like to specifically thank Dr. Willy Hereman for his assistance in obtaining the State's support. Further, I would like to thank my advisor, Dr. Tracy Camp, for her ongoing support and guidance. It is a pleasure, as well as an honor, to work with someone of her knowledge and experience. Also, I would like to extend my gratitude to the entire Mathematical and Computer Sciences Department for their support over the last four years.

Finally, I would like to express my deepest gratitude to my family and friends. I extend a loving thanks to Jennifer Reiter for caring, loving, and supporting me throughout the hardest years of my life. I thank John Pappas, my husband, who has been an endless source of encouragement and support through the most trying of times. I would like to extend my love and thanks to my brother, Drew, who has always been one of my biggest supporters. Finally, I would like to extend my endless gratitude and love to my mother, Debbie, without whom I would never have been able to think of embarking on such a journey.

For my granddad, Andrew P. Diachin…I love and miss you!

CHAPTER 1

AD HOC NETWORKS

Ad hoc networks are dynamically created and maintained by the individual nodes comprising the network. They do not require a pre-existing architecture for communication purposes and do not rely on any type of wired infrastructure; in an ad hoc network all communication occurs through a wireless median. With current technology and the increasing popularity of notebook computers, interest in ad hoc networks has greatly peaked. Future advances in technology will allow us to form small ad hoc networks on campuses, during conferences, and even in our own homes. Further, the need for easily portable ad hoc networks in rescue missions and in situations located in rough terrain are becoming extremely common. Examples of ad hoc networks include:

- Rescue team operations - Members of rescue teams need to be in constant communication during a rescue mission in order to exchange pertinent information. An ad hoc network provides this needed communication.
- Underdeveloped territories - Third world countries with rough terrain would be able to set up ad hoc networks without first spending the time, money, and energy involved in setting up a wired network.

Ad hoc networks comprise a special subset of wireless networks since they do not require the existence of a centralized message-passing device. Simple wireless networks require the existence of static base stations (BS), which are responsible for routing messages to and from mobile nodes (MNs) within the specified transmission area. Ad hoc networks, on the other hand, do not require the existence of any device other than two or more MNs willing to cooperatively form a network. Instead of relying on a wired BS to coordinate the flow of messages to each MN, the individual MNs form their own network and forward packets to and from each other. This adaptive behavior allows a network to be quickly formed even under the most adverse conditions. Other characteristics of ad hoc networks include "team collaboration of a large number of MN units, limited bandwidth, the need for supporting multimedia real time traffic and low latency access to distributed resources (e.g. distributed database access for situation awareness in the battlefield)" (Hong et al., 1999).

Two different architectures exist for an ad hoc network: flat and hierarchical (Haas, 1997). Flat networks are the simplest because all MNs are "equal". Flat networks require each MN to participate in the forwarding and receiving of packets depending on the implemented routing scheme. Hierarchical networks use a tiered approach and consist of two or more tiers. The bottom layer consists of MNs grouped into smaller networks. A single member from each of these groups acts as a gateway to the next higher level. Together, the gateway MNs create the next higher tier. When an MN belonging to group A wants to interact with another MN located in the same group, routing is the same as in a flat ad hoc network. However, if an MN in group A wants to communicate with another MN in group B, more advanced routing techniques incorporating the higher tiers must be implemented. For the purposes of this thesis, further reference to ad hoc networks assumes a flat architecture.

The remainder of this thesis is organized as follows. Mobility models are discussed in the next two chapters. Specifically, Chapter 2 focuses on entity mobility models, including both cellular and ad hoc models, while Chapter 3 describes group mobility models. Chapter 4 provides an overview of Geocast communication. Simulation results of a geocast protocol using different mobility models are then presented in Chapter 5. Chapter 6 presents a new mobility model, as well as simulation results of the Geocast protocol using this new model. Finally, Chapter 7 discusses future work and conclusions.

CHAPTER 2

ENTITY MOBILITY MODELS

Obviously MNs within an ad hoc network move from location to location; however, finding ways to model these movements is not obvious. In order to thoroughly simulate a new protocol such as Geocast (see Chapter 4), it is necessary to develop and use mobility models that accurately represent movements of the MNs that will eventually utilize the given protocol. Only in this type of scenario is it possible to determine whether or not the proposed protocol will be useful when implemented. Therefore, it is imperative that accurate mobility models are chosen.

Currently there are two types of mobility models used in simulations of ad hoc networks: traces and synthetic models (Sanchez and Manzoni, 1999). Traces are those mobility patterns that are observed in real life systems. For instance, if a mobile phone carrier had the ability to trace the exact movements and behaviors of all mobile phone users for a given period of time, they would be able to obtain a trace. Traces provide accurate information, especially when they involve a large number of participants and an appropriately long observation period. Unfortunately, privacy issues, including the confidentiality of certain data, may prohibit the collection and distribution of such statistics. Further, new environments (e.g. ad hoc networks) are not easily modeled if traces have not yet been created. In this type of situation it is necessary to use synthetic models. Synthetic models attempt to realistically represent the behaviors of MNs without the use of traces and other possibly unknown statistics. The purpose of this thesis is to focus upon several popular synthetic mobility models in order to evaluate the performance of an ad hoc protocol. Any further mention of “mobility model(s)” refers solely to synthetic models.

Choosing an appropriate mobility model may not be as simple as it first appears. A decent mobility model should attempt to mimic the movements of real MNs. Changes in speed and direction must occur and they must occur in semi-reasonable time slots. We would not want MNs to travel in straight lines at constant speeds throughout the course of the entire simulation because real MNs would not travel in such a restricted manner. Instead, the speed of each MN must occasionally change and may even decrease to zero. The direction of travel must also change since MNs rarely travel in a single direction for very long. Currently there are two categories of mobility models for representing individual MNs: cellular models and ad hoc models. We discuss these models in Sections 2.1 and 2.2 respectively.

2.1 Cellular Mobility Models

As noted in (Hong et al., 1999), cellular models focus their attention on individual movements since key issues often involve paging and handoffs of a single user or MN. Rarely do more complicated issues such as group management come into play (see

Chapter 3). As a result, mobility models such as the following were developed to test the behavior of cellular protocols and strategies:

- Random Walk Model (including its many derivatives) – A simple mobility model based on random directions and speeds.
- Constant Velocity Fluid-Flow Model – A model that focuses on traffic patterns.
- Random Gauss-Markov Model - A model created to circumvent the deficiencies of the random walk and fluid-flow models.

In Section 2.1.1 we discuss the Random Walk Mobility Model including walks in several dimensions. Section 2.1.2 discusses the Fluid-Flow Mobility Model and why it is not applicable for our simulations. Finally, Section 2.1.3 discusses the Random Gauss-Markov Mobility Model.

2.1.1 Random Walk Mobility Model

The Random Walk Mobility Model has proven to be one of the most widely used mobility models because it describes individual movements relative to cells [(Rubin and Choi , 1997), (Zonoozi and Dassanayake , 1997), (Bar-Noy et al., 1994)]. Many entities in nature move in extremely unpredictable ways. Molecules, for example, move in random directions that do not yield a pattern or sense of direction (Shakhashiri, 2000). The random walk was developed in an attempt to mimic the erratic movements of certain objects. Specifically, in the Random Walk Mobility Model, a host moves from its current location to a new location by randomly choosing a direction and speed in which to travel. The new speed and direction are both chosen from pre-defined ranges, [$speed_{min}$, $speed_{max}$] and [0, 2π] respectively. Each movement in the Random Walk Mobility Model occurs in a constant time interval t, at the end of which a new direction and speed are calculated.

Many derivatives of the Random Walk Mobility Model have been developed including the one-dimensional, two-dimensional, three-dimensional, and d-dimensional walks. We mention only the 1-D and 2-D walks, since the 3-D and d-D walks may easily be extrapolated.

In a 1-D walk, we imagine a gymnast standing in the middle of an infinitely long balance beam. Given the results of a coin flip, the gymnast moves in a particular direction at a random speed for time period t. For example, if the coin flip results in heads, the gymnast moves to the right at the randomly chosen speed. In contrast, if the coin flip results in tails, the gymnast moves to the left. After repeating this pattern for a large number of times, a 1-D walk is mapped.

In a 2-D walk, we visualize the same gymnast moving on a planar surface. For example, using a similar method as that mentioned in the 1-D walk, we generate a 2-D random walk. Specifically, instead of visualizing a gymnast on a balance beam we expand our environment to include an infinite floor mat. Instead of flipping a coin, the gymnast uses a spinning dial. After spinning the dial, the gymnast moves in the direction pointed to by the needle at a random speed for time t. In doing so, the gymnast randomly moves around a 2-D surface thus creating a 2-D walk.

In 1921 Polya proved that a random walk on a one or two-dimensional lattice returns to the origin with complete certainty, i.e., a probability of 1.0 (Weisstein, 2000). This characteristic ensures that the random walk accurately represents a mobility model that tests the movements of entities around their starting points, without worry of the entities wandering away never to return. The two-dimensional walk is of special interest to researchers developing protocols for cell-related technologies, since the Earth's surface is modeled using a two-dimensional representation. Unfortunately, the simplicity of the Random Walk Mobility Model is not always sufficient to produce realistic results in our complex world (see Section 5.3).

Figure 2.1 shows an example of the movement observed from a 2-D model. The MN begins its movement at position (0,0). At each point, the MN randomly chooses a direction between 0 and 2π and a speed between 0 and 10 m/s. The MN is allowed to travel for a total of 1 second before changing direction and speed. We note the restricted behavior of the Random Walk Mobility Model, proven by Polya. The node illustrated in Figure 2.1 rarely travels far from the origin.

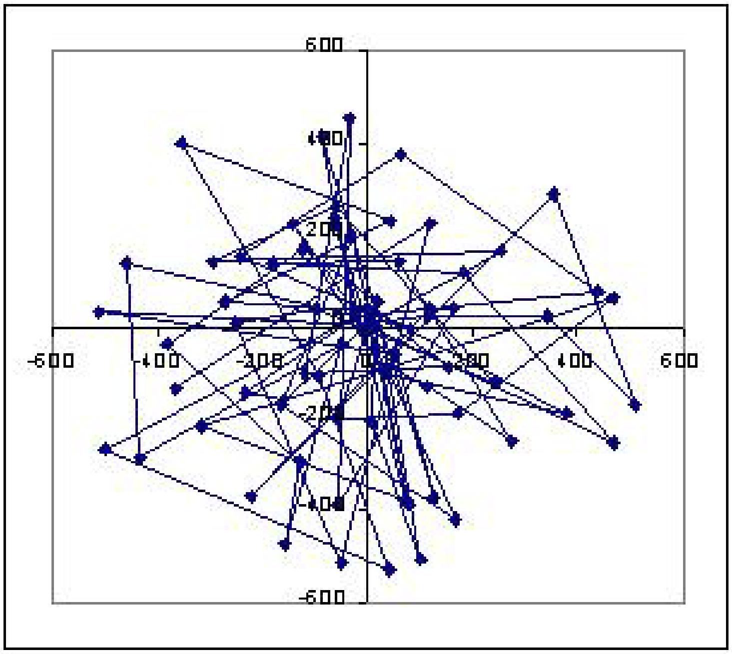

Figure 2.1 – Traveling pattern of an MN using the 2-D Random Walk Mobility Model

In a special case of the Random Walk Mobility Model, an MN no longer travels for a constant time period *t* before changing direction. Instead, an MN changes direction after traveling a specified distance. Figure 2.2 illustrates an example of the movement observed from this modified model.

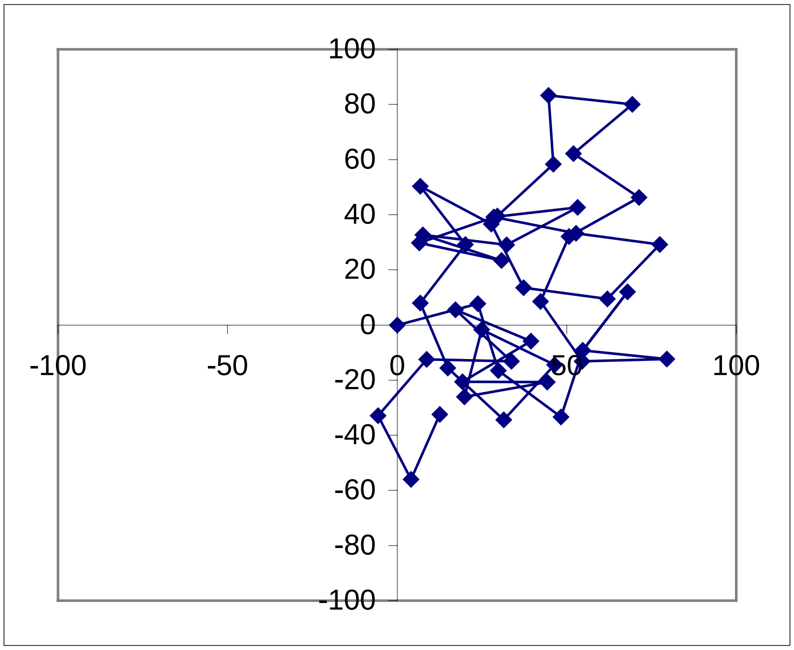

Figure 2.2 – Traveling pattern of an MN using the modified 2-D Random Walk Mobility Model

We note that the figure only illustrates a small region of a 200 x 200 simulation area. The MN begins its movement in the middle of the simulation area (i.e., at position (0,0)). At each point the MN randomly chooses a new direction between 0 and 2π and a speed between 0 and 10 m/s. The MN travels for a total of 10 units before changing its direction and speed.

(Haas and Liang, 1999) describe the Random Walk Mobility Model as a memoryless mobility pattern because it retains no knowledge concerning its past locations and speed values. This characteristic inhibits the practicality of the Random Walk Mobility Model because MNs typically have a pre-defined destination and speed in mind, which in turn affects future destinations and speeds. The Random Gauss-Markov Mobility Model attempts to fix this discrepancy, which we discuss in Section 2.1.3.

2.1.2 Fluid-Flow Mobility Model

According to (Lam et.al., 1997), fluid mobility models describe macroscopic movements instead of individual or microscopic movements. The behavior of the generated traffic is similar to a fluid flowing through a pipe. As a result, the Fluid-Flow Mobility Model best represents traffic on highways and other similar situations with a constant flow of MNs; in other words, the model is unable to accurately represent the movements of individual MNs. As an example, a deterministic Fluid-Flow Mobility Model is used in (Leung et al., 1994) to represent the behavioral characteristics of traffic on a one-way, semi-infinite highway. Cars enter and exit the highway at various locations. (Haas and Liang, 1999) confirm that the Fluid-Flow Mobility Model is insufficient for individual movements including stopping and starting, actions commonly associated with an individual walking around town or from class to class. In Section 2.1.3 we examine a solution to the problems faced by the Fluid-Flow Mobility Models.

2.1.3 Random Gauss-Markov Mobility Model

The Random Gauss-Markov Mobility Model was introduced in order to circumvent the undesirable results mentioned in Sections 2.1.1 and 2.1.2 (Haas and Liang, 1999). In the Random Gauss-Markov Mobility Model, the velocity of an MN at time n is given by the equation

$$v_n = \alpha v_{n-1} + (1-\alpha)\mu + \sqrt{1-\alpha^2} * x_{n-1}$$

where α is the tuning parameter used to vary the randomness, μ is a constant representing the mean value of v_n as $n \to \infty$, and x_{n-1} is a random variable from a Gaussian distribution. Totally random values are obtained by setting $\alpha = 0$ and linear motion is obtained by setting $\alpha = 1$. Intermediate levels of randomness may be obtained by varying the value of α between 0 and 1 (Tolety, 1999). Further, the displacement of an MN is given by the equation $s_n = \sum_{i=0}^{n-1} v_i$. By allowing past velocities and directions to influence future velocities and directions, the Random Gauss-Markov Mobility Model eliminates the problems encountered in the Random Walk Mobility Model (see Section 2.1.1). It also allows study of individual MN movements; thus, eliminating the problems encountered in the Fluid-Flow Mobility Model (see Section 2.1.2).

2.2 Ad Hoc Mobility Models

Ad hoc mobility models differ from cellular mobility models in the network they model. Cellular mobility models require the use of BSs whereas ad hoc mobility models require the cooperation of two or more communicating MNs. Although separate mobility models exist for cellular and ad hoc mobility models, similarities exist between the two categories. In this section we describe eight ad hoc mobility models:

- Random Mobility Model – A simple mobility model based on random directions and speeds.
- Constant Velocity Random Direction Mobility Model - A revised version of the Random Mobility Model.
- Random Waypoint Mobility Model – A model that includes pause times between changes in destination and speed.
- Random Direction Mobility Model - A model that forces MNs to travel to the edge of the simulation area before changing direction and speed.
- A Boundless Simulation Area Mobility Model – A model that converts a 2D rectangular simulation area into a torus-shaped simulation area.
- A Probabilistic Version of the Random Mobility Model – A model that utilizes a probability matrix to determine the next position of an MN.
- City Area, Area Zone, and Street Unit Mobility Models – Three models describing simulation areas representing different granular scales of a city.
- A Hierarchy of Mobility Models by Lam – A hierarchy of mobility models to represent varying degrees of scale for long distance travel.

Section 2.2.1 describes the Random Mobility Model. The Constant Velocity Random Direction Mobility Model is discussed in Section 2.2.2. The Random Waypoint Mobility Model is discussed in Section 2.2.3. Section 2.2.4 presents the Random Direction Mobility Model along with a modified version of this model. A Boundless Simulation Area Mobility Model is discussed in Section 2.2.5 and Section 2.2.6 contains a discussion of a Probabilistic Version of the Random Mobility Model. The last two sections describe the City Area, Area Zone, and Street Unit Mobility Models (Section 2.2.7) as well as a Hierarchy of Mobility Models by Lam (Section 2.2.8).

2.2.1 Random Mobility Model

The Random Mobility Model for ad hoc networks is the Random Walk Mobility Model for cellular networks. In the Random Mobility Model, the current speed and direction of an MN is independent of its past speed and direction (Hong et al., 1999). Thus, we encounter an unrealistic generation of movements such as sudden stopping, sharp turning, and completely random wandering. In order to avoid these problems, many authors modify the Random Mobility Model by changing the calculation of speed, direction, or both.

2.2.2 Constant Velocity Random Direction Mobility Model

(Basagni et al., 1998) and (Gerla et al., 1999) revised the Random Mobility Model to ensure that every node is assigned the same speed throughout the entire simulation. After a random direction is chosen in the range 0 to 2π, an MN begins moving. If the MN reaches a grid boundary, it "bounces" off the simulation border with an angle determined by the incoming direction. The MN then continues along this new path.

2.2.3 Random Waypoint Mobility Model

The Random Waypoint Mobility Model used by Johnson [(Johnson and Maltz, 1996) (Johnson and Maltz , 1996)] and Lee (Lee et al., 1999) includes pause times between changes in direction and/or speed. An MN begins by staying in one location for a certain period of time (i.e., a pause time). Once this time expires, the MN chooses a random destination as well as a speed that is uniformly distributed between [0, MAXSPEED]. It then travels towards the newly chosen destination at the selected speed. Upon arrival, the MN takes another break before starting the process again. Many authors have adopted this model in their simulation studies including (Broch et al., 1998), (Perkins and Royer, 1999), and (Sanchez and Manzoni, 1999).

(Royer and Perkins, 1999) and (Nesargi and Prakash, 1999) modified the Random Waypoint Mobility Model slightly so that an MN travels at a constant speed throughout the entire simulation. In addition, Nesargi and Prakash set pause times to zero in all their simulations. Figure 2.3 shows an example traveling pattern of an MN using the Random Waypoint Mobility Model starting at a randomly chosen point. We note that the movement pattern of an MN using the Random Waypoint Mobility Model is similar to the Random Walk Mobility Model if pause time is zero and [0, MAXSPEED] = [$speed_{min}$, $speed_{max}$].

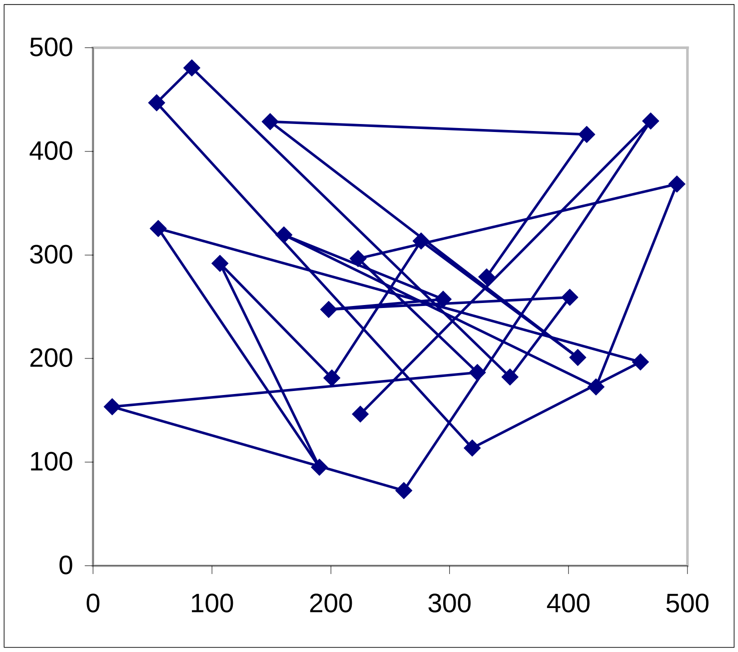

Figure 2.3 - Traveling pattern of an MN using the Random Waypoint Mobility Model

2.2.4 Random Direction Mobility Model

The Random Direction Mobility Model (Royer et al., Submitted) was created in order to overcome a flaw discovered in the Random Waypoint Mobility Model. MNs using the Random Waypoint Mobility Model often choose new destinations, and the probability of choosing a new destination that is located in the center of the simulation area, or requires travel through the middle of the simulation area, is high. This trend is illustrated in Figure 2.4. Royer states that MNs moving with the Random Waypoint Mobility Model appear to converge, disperse, converge again, etc.[1] In order to alleviate

[1] Although we question the conclusion that nodes tend to converge, disperse, etc., we include the conclusion listed in (Royer et al., Submitted) since it is the basis for the Random Direction Mobility Model.

this type of behavior and promote a semi-constant number of neighbors, the Random Direction Mobility Model was developed. In this model, MNs choose a random direction in which to travel instead of a random destination. After choosing a random direction, an MN travels to the border of the simulation area in that direction. As soon as the boundary is reached the MN stops for a certain period of time, chooses another angular direction (between 0 and 180 degrees) and continues the process. Figure 2.4 shows an example path of an MN, which begins at the center of the simulation area or (250,250), using the Random Direction Mobility Model.

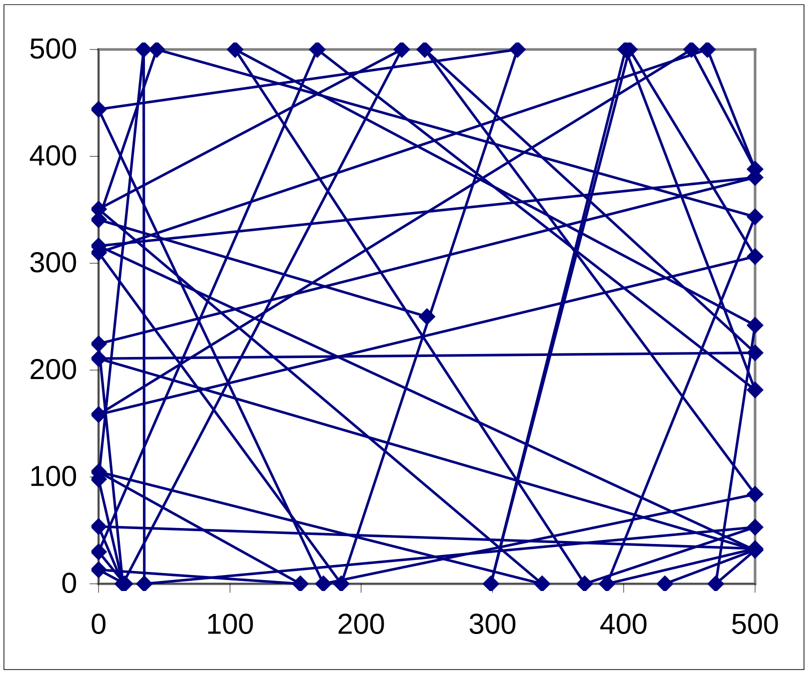

Figure 2.4 - Traveling pattern of an MN using the Random Direction Mobility Model

A slight modification to the Random Direction Mobility Model is the Modified Random Direction Mobility Model (Royer et al., Submitted). In this modified version, MNs continue to choose random directions but they are no longer forced to travel to the simulation boundary before stopping to change direction. Instead, an MN chooses a random direction and selects a destination anywhere along that direction of travel.

2.2.5 A Boundless Simulation Area Mobility Model

In the Boundless Simulation Area Mobility Model by Haas a relationship between the previous direction of travel and velocity of an MN, with its current direction of travel and velocity exists (Haas, 1997). A velocity vector $\bar{v} = (v, \theta)$ is used to describe an MN's velocity v as well as its direction θ, while its position is represented as (x, y). Both the velocity vector and the position are updated at every Δt time steps according to the following formulas:

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

$$\theta(t + \Delta t) = \theta(t) + \Delta\theta,$$

$$x(t + \Delta t) = x(t) + v(t) * \cos\theta(t),$$

$$y(t + \Delta t) = y(t) + v(t) * \sin\theta(t),$$

where $V_{\max}$ is the maximum velocity defined for the simulation, Δv is the change in velocity which is uniformly distributed between $[-A_{\max} * \Delta t, A_{\max} * \Delta t]$, $A_{\max}$ is the maximum acceleration/deceleration of a given MN, $\Delta\theta$ is the change in direction which is uniformly distributed between $[-\alpha * \Delta t, \alpha * \Delta t]$, and α is the maximum angular change in the direction an MN is traveling.

The Boundless Simulation Area Mobility Model is also different in how the boundary of a simulation area is handled. In all the mobility models previously mentioned, MNs reflect off or stop moving once they reach a simulation boundary. In the Haas model, MNs that reach one side of the simulation area continue traveling and reappear on the opposite side of the simulation area. Figure 2.5 illustrates the behavior of an MN whose initial position is represented by a square. The MN begins traveling along path 1 towards the rightmost simulation boundary. When the node encounters the simulation boundary,

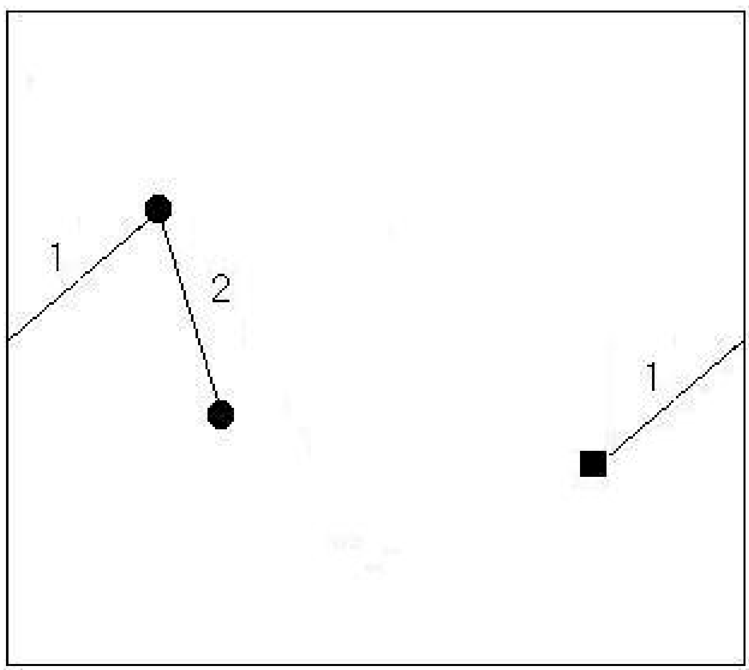

Figure 2.5 – Traveling pattern of an MN using the Boundless Simulation Area Mobility Model

it appears on the opposite side of the simulation area and continues traveling at the same angle and velocity. When Δt time steps finish, the MN chooses a new direction and velocity, denoted by path 2, and begins traveling again. In effect, this technique creates a torus-shaped simulation area allowing MNs to travel unobstructed. Figure 2.6 illustrates this concept.

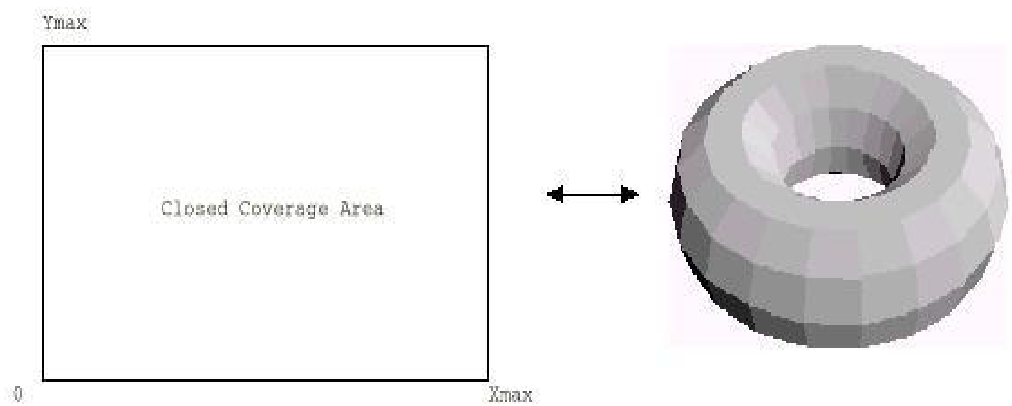

Figure 2.6 - Rectangular simulation area mapped to a torus in the Boundless Simulation Area Mobility Model.

The rectangular area on the left side of Figure 2.6 is transformed into the torus shape on the right side of Figure 2.6 in two steps; first we fold the simulation area so that the top border ($y = Y\max$) lies against the bottom border ($y = 0$), forming a cylinder, and then we fold the resulting cylinder so that both open circular ends connect.

2.2.6 A Probabilistic Version of the Random Mobility Model

Chiang's mobility model utilizes a probability matrix to determine the position of a particular MN in the next time step, which is represented by three different states (Chiang, 1998). State 0 represents the current location of a given MN, state 1 represents the MN's previous location, and state 2 represents the MN's next location if the MN moves forward. The probability matrix used is

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

where each entry $P(a,b)$ represents the probability that an MN will go from state a to state b. In Chiang's simulator each node moves randomly with a preset average speed. The following matrix contains the values Chiang used to calculate x and y movements:

$$\boldsymbol{P1} = \begin{bmatrix} 0 & 0.5 & 0.5 \\ 0.3 & 0.7 & 0 \\ 0.3 & 0 & 0.7 \end{bmatrix}$$

Probability matrix ***P1*** allows an MN to move in any direction as long as it does not return to its previous position. This implementation produces probabilistic rather than purely random movements, which may yield more realistic behaviors. For example, as people complete their daily tasks they tend to continue moving in a semi-constant forward direction. Rarely do we suddenly turn around to retrace our steps and we almost never take random steps hoping that we may eventually wind up somewhere relevant to our tasks. However, choosing appropriate values of $P(a,b)$ may prove difficult, if not impossible, for individual scenarios.

2.2.7 City Area, Area Zone, and Street Unit Mobility Models

In (Markoulidakis et al., 1997), the authors take an in-depth look at desirable characteristics of mobility models including required inputs/outputs and issues that should be considered when designing a specific mobility model. They represent a basic mobility model with a set of input parameters S_{in} and a set of output parameters S_{out}. S_{in} includes a population P, which represents specific groups of MNs, a geographical area G organized into regions, and a time period T. S_{out} includes a collection of functions that determine the location of an MN p over the set G at time t. By combining these elements with transportation theory, the authors created three models: the city area, area zone, and street unit models. Before defining these three models, a brief introduction to transportation theory is presented.

Transportation theory works to determine the load a system should carry given a geographical area of service. In order to calculate a given load, many different variables are considered:

- the purpose of a trip,
- the exact route taken including starting and ending points,
- population groups such as students and working people,

- periods of high MN activity,
- a transportation system's capacity and usage costs, and
- popular areas attracting many MNs.

We view the *city area model* as a representation of user mobility and traffic behavior within a large-scale geographical area. A typical city area model possesses two key characteristics according to transportation theory. First, cities usually develop in such a way that the center of the city comprises a high concentration of workplaces and businesses. Surrounding the center of the city is a fairly dense distribution of dwelling areas for the people of the city, which are commonly referred to as urban areas. As we move away from the center of the city, we see a gradual decrease in population density, thus representing suburban and rural areas. The second key characteristic found in a typical city is a street network that supports movements from the center of the city, through urban areas, into the suburban and rural areas. Obviously, the focus in the city area model is to represent large-scale flows of traffic within city limits.

The *area zone model* takes a slightly more refined look at mobility within a city. Instead of looking at the entire city, the area zone model divides the city into regions. This process is done using square-shaped building blocks and an orthogonal grid representing a street network. Again, this model proves most useful for modeling large-scale interactions.

Finally, the *street unit model* attempts to model movements of individual MNs. The authors attempt to simulate realistic traffic conditions by minimizing the traveling time for all MNs and implementing safe driving characteristics such as a speed limit and a minimum distance allowed between any two MNs.

The city area, area zone, and street unit models lack specific details, such as calculations for the movements of MNs, because they are theoretical models used to describe simulation environments. These theoretic models create realistic simulation environments that introduce obstacles and strictly defined travel paths. When combined, the city area, area zone, and unit street models create a realistic simulation environment. Unfortunately, this high level of accuracy introduces an overwhelming amount of computational effort and complexity if the mobility models are simulated.

2.2.8 A Hierarchy of Mobility Models by Lam

Lam et al., developed a hierarchy of mobility models to represent varying degrees of scale (Lam et al., 1997). The Metropolitan, National, and International Mobility Models each focus on a different range of movement.

The Metropolitan Mobility Model (METMOD) focuses on movements of MNs in a metropolitan area. The geographical region is divided into smaller regions or subsets. A movement connectivity matrix is created and used to describe the probability of an MN moving into an adjacent area within the metropolitan area. Each element, (x, y), within this matrix represents the probability of an MN in area x moving into area y.

The National Mobility Model (NATMOD) models behavior of MNs moving between metropolitan areas. Again, the NATMOD model divides the entire simulation region into smaller geographical areas; however, these subsets are now entire metropolitan areas. The authors assume that the most popular mode of travel between metropolitan areas is by aircraft. Thus, they use flight information from the Department of Transportation, distances between major metropolitan airports, and the assumption that an equal number of flights exist to and from each airport to derive a traffic volume for the mobility model.

Finally, the International Mobility Model (INTMOD) describes the behavior of MNs traveling between the United States and foreign countries. Data from the US and ten other countries were compiled in an attempt to create an accurate traffic volume. Therefore, in this model traffic flows to and from objects representing individual countries.

CHAPTER 3

GROUP MOBILITY MODELS

So far we have discussed mobility models that represent multiple MNs whose actions are completely independent of each other. However, in many situations it is necessary to model the behavior of MNs that move together. For example, many military scenarios occur where a group of soldiers must collectively search a particular plot of land in order to destroy land mines, capture enemy attackers, or simply work together in a cooperative manner to accomplish a common goal. In order to model such situations, group mobility models exist to account for these new cooperative characteristics. We discuss two proposed group mobility models in this chapter:

- Simple Group Mobility Models by Sanchez – Three models that account for dependencies resulting from the interactions between MNs.
- Reference Point Group Mobility Model – A model that represents random motion of a group of MNs as well as a random motion of each individual MN within a given group.

In Section 3.1 we discuss the Column Mobility Model (Section 3.1.1), Pursue Mobility Model (Section 3.1.2) and Nomadic Community Mobility Model (Section 3.1.3). In Section 3.2 we discuss three versions of the Reference Point Group Mobility Model.

Section 3.2.1 discusses the In-Place Mobility Model, Section 3.2.2 discusses the Overlap Mobility Model and Section 3.2.3 discusses the Convention Mobility Model.

3.1 Simple Group Mobility Models by Sanchez

Sanchez notes that a random walk/random movement model may not be sufficient to describe many "real-life" situations (Sanchez, 2000). Typically, we should account for dependencies resulting from the interactions between MNs. The Column, Pursue, and Nomadic Community Mobility Models were thus created [(Sanchez, 2000) and (Sanchez and Manzoni, 1999)].

3.1 1 Column Mobility Model

The Column Mobility Model proves useful for scanning or searching purposes. This model represents a set of MNs that have formed a line and are uniformly moving forward in a particular direction. For example, consider a row of soldiers marching together towards their enemy. Each soldier stands next to his/her companions while marching in a uniform manner. A slight modification of the Column Mobility Model allows the individual MNs to follow one another. For example, consider a group of young children that walk in a single-file line to and from their classroom.

Sanchez describes a version of the Column Mobility Model in which individual MNs are placed in a single-file line and are allowed to move about their initial positions. This process begins by calculating a new_reference_position for an MN using the equation:

new_reference_position = old_reference_position + advance_vector

where old_reference_position is a static variable indicating the initial location of an MN, advance_vector is a predefined offset, and new_reference_position is the sum of the MNs initial location (old_reference_position) and the offset (advance_vector). A second equation is used to calculate the new position of an MN:

new_position = new_reference_position + random_vector

where random_vector is a random offset and new_position is the sum of the random offset (random_vector) and the current point of reference (new_reference_position). Consider the example in Figure 3.1.

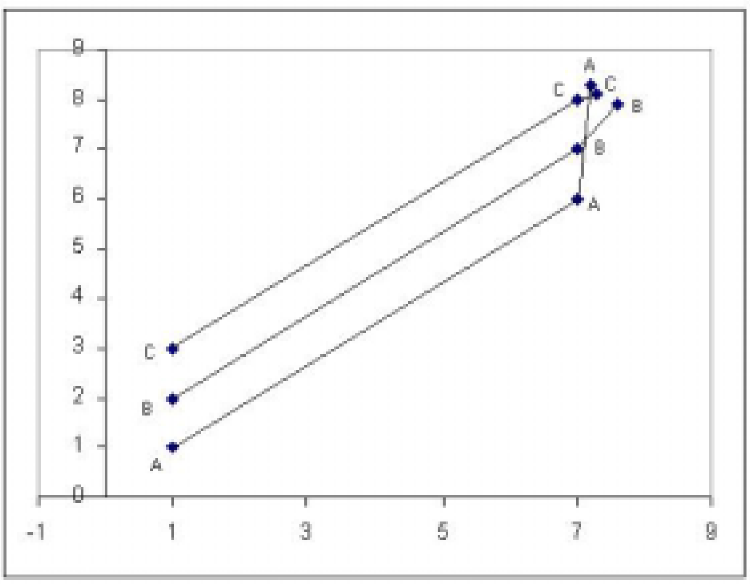

Figure 3.1 – Movements of three MNs using the Column Mobility Model

In Figure 3.1, three MNs are initially lined up in the lower left-hand corner. The MNs begin moving by traveling six units to the right and five units up, as specified by their advance vector: (6,5). In order to determine their final positions, the MNs calculate the sum of their new position with a random vector.

Figure 3.2 illustrates the military example with 12 MNs. In this figure the MNs start at the lower left-hand corner of the simulation area and travel towards the upper right-hand corner.

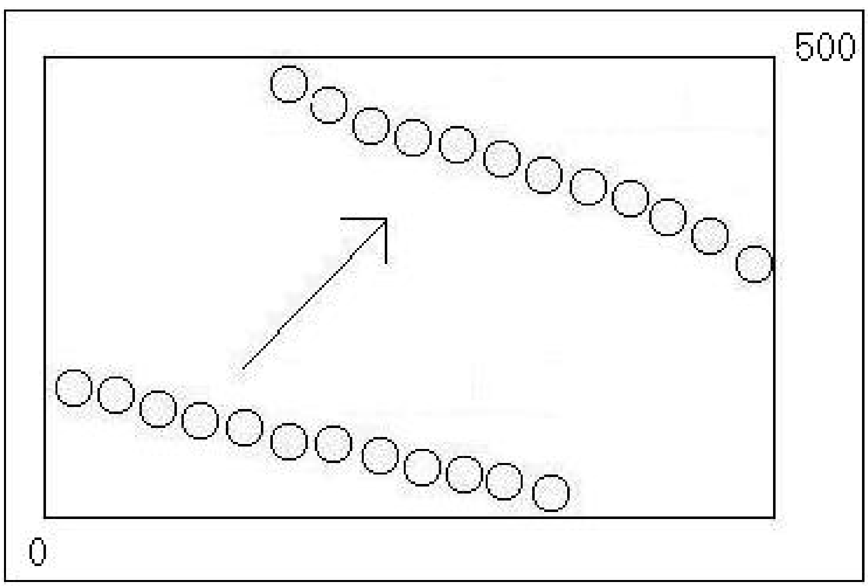

Figure 3.2 - Traveling pattern of 12 MNs using the Column Mobility Model

3.1.2 Pursue Mobility Model

Sanchez also describes the Pursue Mobility Model (Sanchez, 2000). As the name implies, the Pursue Mobility Model attempts to represent MNs tracking a particular target. For example, this model represents police officers attempting to catch an escaped criminal or a swarm of bees attempting to attack a careless camper who inadvertently disturbed their dwelling. The Pursue Mobility Model consists of a single update equation for the new position of each MN:

new_position = old_position + acceleration(target-old_position) + random_vector

The current position of an MN, a random vector, and an acceleration function are combined to calculate the next position of the MN. The acceleration function is used to allow only a limited maximum step in each new movement. The random vector ensures the random motion of each MN. Figure 3.3 illustrates the movements of MNs using the Pursue Mobility Model. The solid black node represents the node being pursued and the white nodes represent the pursuing nodes.

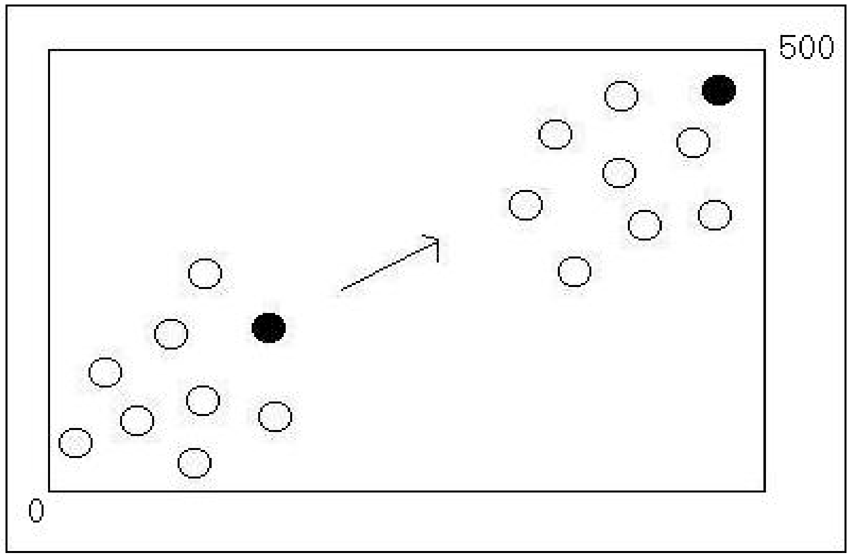

Figure 3.3 – Traveling pattern of MNs using the Pursue Mobility Model

3.1.3 Nomadic Community Mobility Model

Finally, Sanchez describes a Nomadic Community Mobility Model, which is useful for representing both military and agricultural situations (Sanchez, 2000). Just as ancient nomadic societies moved from location to location, this model represents groups of MNs that collectively move from one position to another. Within each community or group of MNs, individuals maintain their own personal "spaces" where they move in random ways. This is similar to bedrooms within a house. Each member of the household is assigned their own bedroom where they move in semi-random patterns, yet all household members reside in close proximity to each other. Many situations may benefit from this type of behavior, in particular agricultural scenarios. Consider a large plot of land divided into smaller subsets that are maintained by a single entity. After each entity finishes tending a particular subset of land, the entire group moves to another large plot of land, divides it into individual subsets, and continues the process. The position update equation for the Nomadic Community Mobility Model is

new_position = reference_position + random_vector

where reference_position marks the center of an individual's plot of land and random_vector ensures the random motion of each MN. Figure 3.4 illustrates the movements observed using the Nomadic Community Mobility Model. The figure illustrates the rigid movements associated with the Nomadic Community Mobility Model as the group travels from one location to another. Comparing Figures 3.3 and 3.4 we see that the Pursue Mobility Model described in Section 3.1.2 offers greater flexibility in the placement of an MN. The Nomadic Community Mobility Model allows individual movements as long as an MN remains located near the reference position. In other words, the random vector defines how near the MN must be to the reference position. Further information on the Column, Pursue, and Nomadic Community Mobility Models, along with a JAVA-based simulator for ad hoc networks, can be found online (Sanchez and Manzoni, 2000).

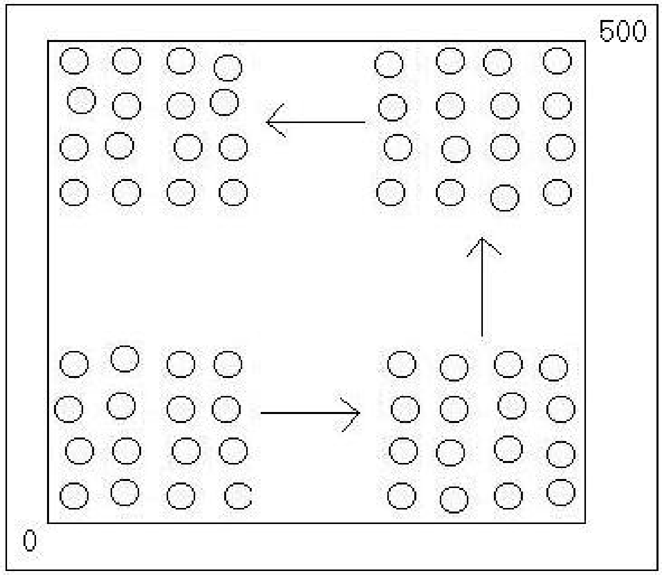

Figure 3.4 – Traveling pattern of MNs using the Nomadic Community Mobility Model

3.2 Reference Point Group Mobility Model

Hong et al. presents the Reference Point Group Mobility (RPGM) model, which represents a random motion of a group of MNs as well as a random motion of each individual MN within the group (Hong et al., 1999). Group movements are based upon the path traveled by a logical center, which may be pre-defined or completely random. This group motion is represented with a group motion vector, $\overline{GM}$. The motion of the group center completely characterizes the movement of its corresponding group of MNs, including their direction and speed. Individual MNs randomly move about their own pre-defined reference points, whose movements depend on the group movement. As the individual reference points move from time t to $t+1$, their locations are updated according to the group's logical center. Once the updated reference points, $RP(t+1)$, are calculated, they are combined with a random motion vector, $\overrightarrow{RM}$, to represent the random motion of each MN about its individual reference point. An example of RPGM is given in Figure 3.5.

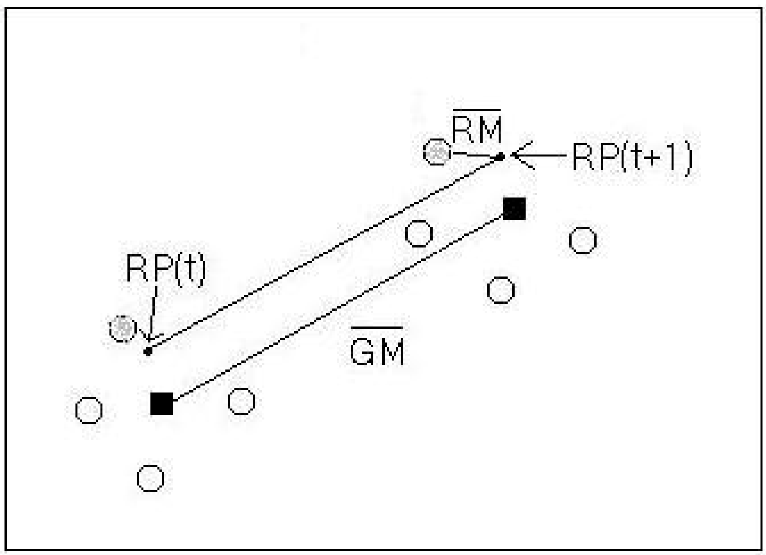

Figure 3.5 - Traveling pattern of MNs using RPGM

In Figure 3.5, four MNs are initially placed in the lower left-hand corner of the simulation area. A black square is the group center; the circles near the group center are MNs in the group. One circle in Figure 3.5 is gray in order to distinguish it from the other MNs in the group. RPGM first calculates each MN's reference point using the group motion vector $\overline{GM}$. As stated above, $\overline{GM}$ may be randomly chosen or predefined. The current reference point of the gray MN, $RP(t)$, moves towards the right-hand corner of the simulation area alongside the group center. This location becomes the new reference point, $RP(t+1)$, for the gray MN. Finally, the new position for the gray MN is calculated by summing a random motion vector, $\overline{RM}$, with the new reference point. The length of $\overline{RM}$ is uniformly distributed within a specified radius centered at $RP(t+1)$ and its direction is uniformly distributed between 0 and 2π. This process is repeated for each MN in the group.

The RPGM model was designed to depict scenarios such as an avalanche rescue. During an avalanche rescue, the responding team consisting of human and canine members work cooperatively. The human guides tend to set a general path for the dogs to follow, since they usually know the approximate location of victims. The dogs each create their own “random” paths around the general area chosen by their human counterparts.

If appropriate group paths are chosen, along with proper initial locations for various groups, many different mobility applications may be represented with the RPGM model. Specifically, the In-place, Overlap, and Convention Mobility Models (see Sections 3.2.1-3.2.3) are variations of the RPGM model. The RPGM model was originally defined in (Hong et.al., 1999) and then used in (Pei et al., 1999).

3.2.1 In-Place Mobility Model

The In-place Mobility Model is used to partition a given geographical area. Each subset of the original area is assigned to a specific group, which operates only within that geographic subset. This model is useful for simulating situations in which groups of people, who have similar goals, are assigned to limited areas. For example, Hong suggests this model for “large scale disaster recovery, where different paramedic, police, and firemen teams work in separated neighborhoods.” Each neighborhood is assigned its own paramedic, police and firemen teams, who never interact with the rescue personnel of nearby neighborhoods. Figure 3.6 illustrates this model. Within the simulation area we see five distinct groups of MNs. Each MN within a single group may participate in an activity different from every other MN in the group. However, the MNs work together in a specific area and leave the rest of the simulation area to be tended by other groups.

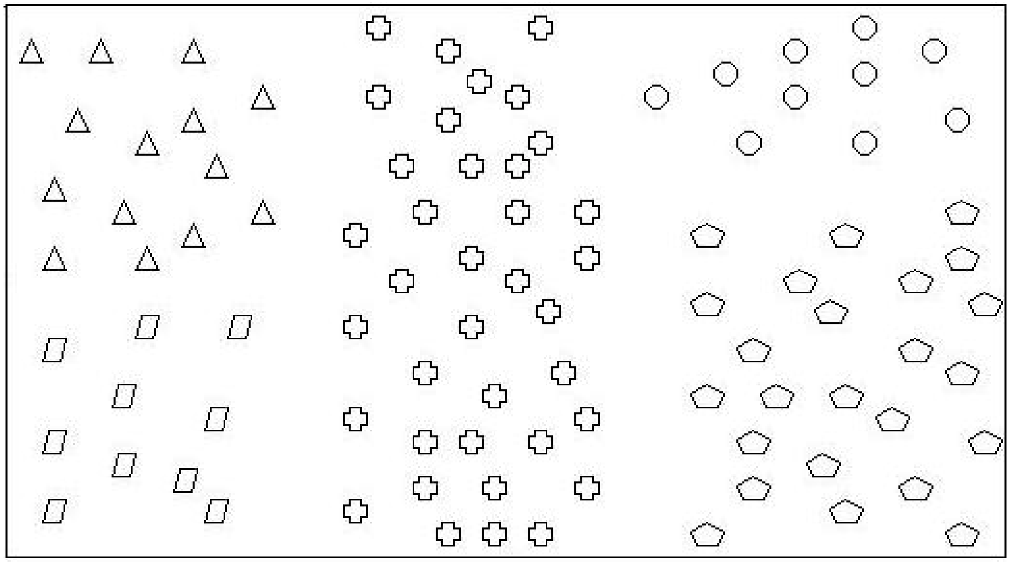

Figure 3.6 - Groups of MNs using the In-Place Mobility Model

Figure 3.6 illustrates an example of the In-Place Mobility Model. The position of an MN in Figure 3.6 is calculated similar to the position of an MN in Figure 3.5. Specifically, each group of MNs moves in conjunction with $\overline{GM}$. After updating their individual RPs, each MN calculates its new position by calculating $\overline{RM}$ and summing that result with their updated RP.

3.2.2 Overlap Mobility Model

The second variation of the RPGM model is the Overlap Mobility Model. The Overlap Mobility Model simulates several different groups, each of which has a different purpose, working in the same geographic region. Each group within this model may have different characteristics than other groups within the same geographical boundary. For example, in disaster recovery, one might encounter a rescue personnel team, a medical team, and a psychologist team, each of which have unique traveling patterns, speeds, and behaviors. In the Overlap Mobility Model, the entire town or disaster area shares the various rescue teams. Figure 3.7 illustrates this concept. Each MN within a single group participates in an identical task and each group is responsible for providing their talents to the entire simulation area.

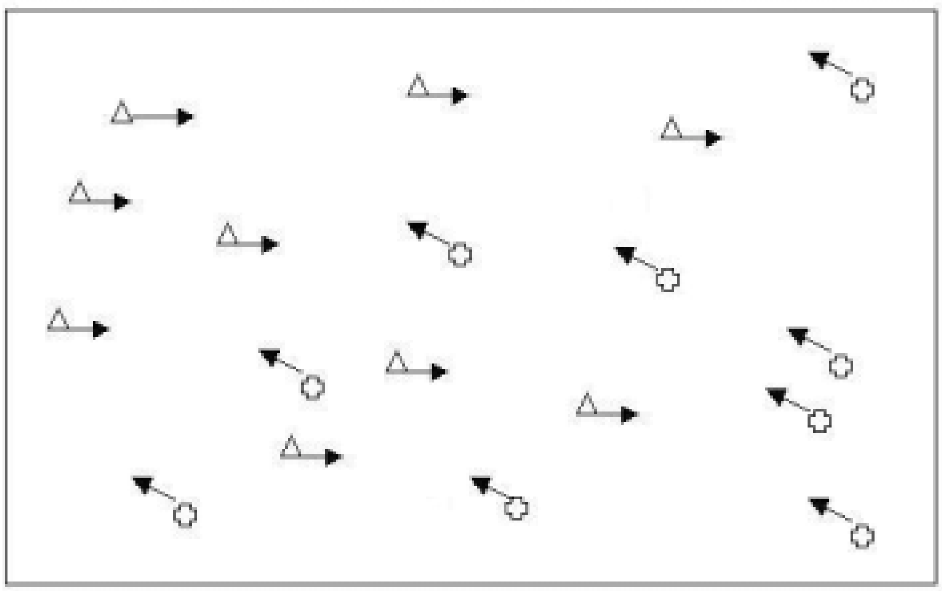

Figure 3.7 - Traveling pattern of MNs using the Overlap Mobility Model

Figure 3.7 illustrates two groups of MNs using the Overlap Mobility Model. The cross symbol group follows a $\overline{GM}$ directed towards the upper left-hand corner while the triangle symbol group follows a $\overline{GM}$ directed toward the right simulation border. RPs and $\overline{RM}s$ of individual MNs are updated as described in Section 3.2.

3.2.3 Convention Mobility Model

The last variation of the RPGM model described in (Hong et al., 1999) is the convention scenario. In this scenario, both the conference attendees and the exhibits are represented. In addition, different exhibits are housed in different rooms. These rooms are connected to offer travel between exhibits. Similarly, the Convention Mobility Model divides a given area into smaller subsets and allows the groups to move in a similar pattern throughout each subset. Again, some groups travel faster than others within a subset. Therefore, the Convention Mobility Model allows one group of attendees to take their time at an interesting exhibit, while others move quickly past a less interesting exhibit.

Figure 3.8 shows an example for the Convention Mobility Model. In this example, the simulation area is divided into several sections or exhibits. Participants at a convention set up as Figure 3.8 depicts will tend to travel from exhibit A to B to D to C as their respective $\overline{GM}s$ specify. Some groups may spend a significant amount of time at exhibit B and little time at exhibit D. All groups, however, will travel in a semi-regular pattern around the room, and all MNs will travel within each exhibit as dictated by their RPs and $\overline{RM}s$.

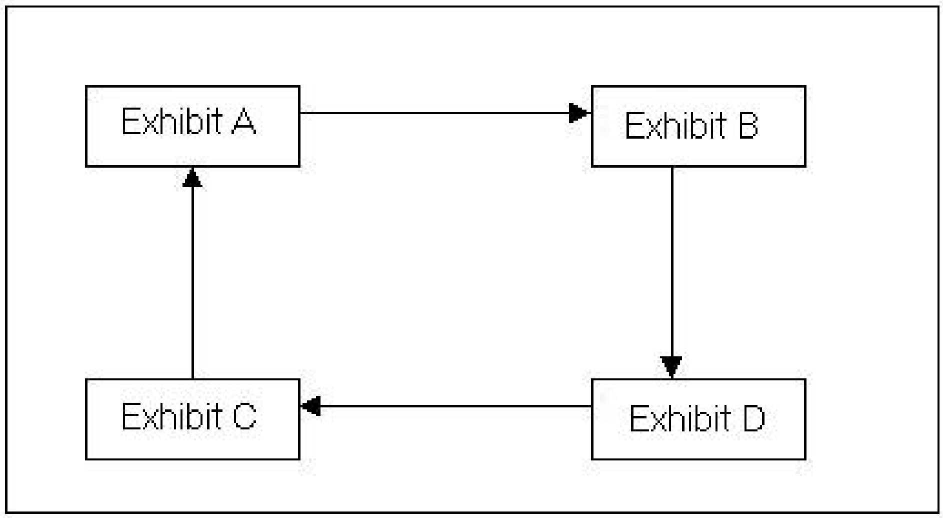

Figure 3.8 - Traveling pattern of MNs using the Convention Mobility Model

CHAPTER 4

GEOCAST COMMUNICATION

Geographic messaging is the ability to transmit messages to MNs in a particular geographic area (i.e., a geocast region). It is similar to multicast communication in that a sender intends to distribute a specific message to a select group of MNs. However, geocast communication specifies the group of MNs for a message instead of allowing MNs to specify whether or not they would like to join the group. The ability to send messages to groups of MNs based solely on their location would enable emergency messages to be delivered to possible victims and/or rescue personnel during times of crisis, strategic planning messages to be distributed to various military groups, and advertisement messages to be relayed to mobile users as they travel down the street [(Navas and Imielinski, 1997) and (Navas and Imielinski, 1999)]. Since all mobile users may not welcome flashing advertisements, each MN would need the option to ignore Geocast advertisement messages. Obtaining information pertaining to a particular business without actually inquiring within, i.e., accessing a homepage being transmitted by a particular building is a forthcoming commercial application. Geocast communication will provide this new technology.

4.1 Global Positioning System (GPS)

In order to offer geocast communication, geographical location information is required. As (National Air and Space Museum, 2000) states, the earliest days of navigation used the stars and major landmarks as guides; however, with current demands, a more precise method to aid in navigation is required. Therefore, a new constellation of artificial stars (i.e., satellites) has been installed. The most common location information system using these artificial stars is the Global Positioning System (GPS).

All GPS satellites synchronize their time with the atomic clocks located at the United States Naval Observatory. Periodically, all GPS satellites broadcast this information along with their location at the exact same moment. Due to the differences in location of the GPS satellites, the satellite signals reach a specific point on Earth at different instances. When a GPS receiver receives four or more of these signals, the receiver can calculate its position. Timing errors were originally introduced into the GPS system to keep non-military users from obtaining highly accurate results. Such limitations were removed in May 2000.

4.2 Geocast Communication in a Wired Network

(Navas and Imielinski, 1997) and (Navas and Imielinski, 1999) propose three solutions for delivering geographical messages to specific locations in a wired network: geographic routing, geographic-multicast routing, and a domain name service (DNS) solution. Geographic routing provides unicast communication to a given location, geographic-multicast routing provides geocast communication, and the DNS solution provides a geographic addressing scheme. The ultimate receiver(s) of the geographical message is either a static node(s) attached to the wired network or an MN(s) using the wired network for communication. Since all three solutions assume that receivers know their own geographic positions, MNs require the ability to determine their position. This task is simple when the MN is outdoors because of the availability of GPS. However, when the MN ventures indoors, another solution must exist to provide GPS locations. To provide GPS locations indoors, (Navas and Imielinski, 1997) and (Navas and Imielinski, 1999) propose the installation of a radio beacon in every room of every building. Periodically, these beacons would transmit their own geographical address, which would then be adopted by all MNs inside that room.

To provide geographical communication, location information for the destination is required. Three shapes which represent the geographic location are given in (Navas and Imielinski, 1997) and (Navas and Imielinski, 1999):

1. point – a simple point or location.;
2. circle – a circle encompassing an area around a given point with a given radius;
3. polygon – a polygon created from several points, i.e. [$point_1$(latitude, longitude), $point_2$(latitude, longitude), …, $point_n$(latitude, longitude)]. Each point represents a vertex of the desired polygon.

Unicast communication occurs when a message is transmitted to a given geographic point; geocast communication occurs when a message is transmitted to a defined circle or polygon. In our simulation study (see Chapter 5), geocast messages are transmitted to a polygon (i.e., a rectangle). For further details on geocast communication in a wired network, we refer interested readers to (Navas and Imielinski, 1997) and (Navas and Imielinski, 1999).

4.3 Multicast Communication in an Ad Hoc Network

Geocast communication is a specialized version of multicast communication. When a message needs to be sent to a varying number of receivers, it is more efficient to multicast the message to a multicast group instead of unicasting an identical message to many different receivers. Unfortunately, as noted in (Chiang et al., 1997) multicast communication is difficult in an ad hoc network. Ad hoc networks are fundamentally dynamic in nature; thus, multicast protocols that handle this dynamic nature are needed. In a static network, multicast protocols build a tree to route multicast messages. The root of the tree is either the multicast source or a core, which is strategically located near the middle of the multicast receivers. Unfortunately, tree-based approaches for multicast communication do not work well in an ad hoc network because the tree often changes as the MNs move. Thus, recent multicast protocols developed for an ad hoc network are based on either flooding multicast messages (Ho et al., 1999) or on building a mesh to transmit multicast messages [(Chiang, 1998), (Lee et al., 1999), (Garcia-Luna-Aceves and Madrga, 1999), (Madruga and Garcia-Luna-Aceves, 1999)].

Flooding creates many more duplicate messages than are truly needed; however, it is this characteristic that makes flooding robust in nature. Within an MN environment links will continuously go up and down as MNs move in and out of range. By flooding extra copies of a given message on every line, we increase the probability that at least one of those messages will find its way to the intended destination. Unfortunately, during the evaluation of using flooding to transmit multicast messages in an ad hoc network, the following problem was discovered. If a particular MN moves out of range of all other MNs for even a brief period of time, it is possible that the MN will miss the "flooding wave." Under these circumstances the MN may not receive a copy of the flooded packet unless it happens to move to a region of the network that will experience the flooding wave in the future. Upon measuring packet loss Ho et al. noticed that flooding became less and less efficient as mobility increased. Similarly, the number of duplicate packets seen by a given MN decreases as mobility increases. In conclusion, although flooding works well under situations of low mobility it tends to lose its effectiveness as mobility increases.

Due to the fragile tree problem of source/core-based multicast approaches and the flooding problem of a flooding-based multicast approach, building a mesh to transmit multicast messages in an ad hoc network may be the preferred solution. With a mesh, multiple paths between multicast senders and receivers are created. Thus, delivery of a multicast message may still be possible as the topology of the ad hoc network dynamically changes. Currently, two mesh-based protocols have been proposed: the On-

Demand Multicast Routing Protocol (ODMRP) [(Chiang, 1998), (Lee et al., 1999)] and the Core-Assisted Mesh protocol (CAMP) [(Garcia-Luna-Aceves and Madrga, 1999), (Madruga and Garcia-Luna-Aceves, 1999)]. In the following discussion, we give specifics of ODMRP since we refer to this protocol in Section 4.4.

In ODMRP [(Chiang, 1998), (Lee et al., 1999)], a multicast source periodically floods a JOIN-REQUEST message in the network; to receive (or continue to receive) the multicast messages transmitted by the source, a receiver responds to the JOIN-REQUEST message by transmitting a JOIN-TABLE message to its neighbors. When a router receives a JOIN-REQUEST message, it maintains upstream neighbor information towards the source. Thus, a multicast mesh is formed as the JOIN-TABLE messages propagate to the source along the path created by the JOIN-REQUEST messages.

4.4 Geocast Communication in an Ad Hoc Network

Currently, three articles have been proposed to provide geocast communication in an ad hoc network [(Ko and Vaidya, 1999), (Ko and Vaidya, 2000), (Boleng et al., Submitted)]. Geocast communication in (Ko and Vaidya, 1999) is based on a unicast routing protocol that uses location information to limit the search for a route to some destination MN (see (Ko and Vaidya, 1998) for details). Using this technique, geocast messages flood a forwarding area instead of the whole ad hoc network. The Temporally Ordered Routing Algorithm (TORA) (Park and Corson, 1997) is extended in (Ko and Vaidya, 2000) to provide geocast communication. TORA is a unicast routing protocol;

thus, geocast communication is provided by unicasting a geocast message to the geographical location via TORA and then flooding the geocast message in the geographical area desired.

In (Boleng et al., Submitted), a mesh is built between the sender and the geocast region in order to provide geocast communication. Since a mesh-based approach creates redundant paths between the sender and the geocast receivers, a single link failure should not prevent the delivery of a geocast message. The protocol that builds the mesh is ODMRP (see Section 4.3), with two modifications. First, JOIN-REQUEST messages in ODMRP are replaced with JOIN-DEMAND messages. A JOIN-REQUEST message in ODMRP allows an MN to accept or decline membership in a multicast group. A JOIN-DEMAND message in (Boleng et al., Submitted) requires each MN in the geocast region to become a member of the geocast group. Second, similar to ODMRP, a geocast source periodically sends a JOIN-DEMAND message; however, unlike ODMRP, only one version of the protocol in (Boleng et al., Submitted) floods these messages. The other two versions of the protocol in (Boleng et al., Submitted) limit the number of MNs that forward the JOIN-DEMAND messages via a forwarding zone. The protocol we use to evaluate different mobility models (see Chapter 5) is one of these two versions. Specifically, we use the BOX approach defined in (Boleng et al., Submitted). In the BOX approach, a box-shaped forwarding zone is created such that the sender is located in one corner of the box and the geocast region is located in the opposite corner of the box. JOIN-DEMAND messages are then forwarded through the box to the geocast region. We refer to this protocol as the Geocast protocol in the remainder of this thesis. Figure 4.1 illustrates the BOX approach.

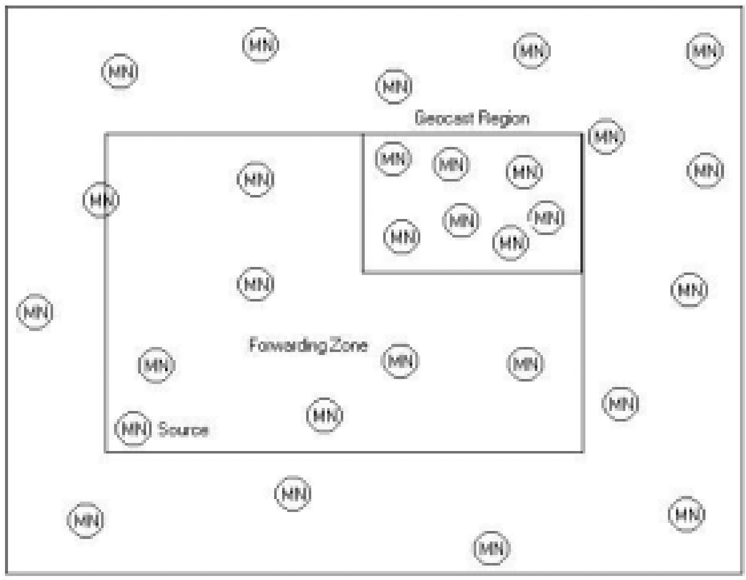

Figure 4.1 – Example simulation area using the Box approach

CHAPTER 5

SIMULATION RESULTS FOR THREE MOBILITY MODELS

In order to accurately depict various mobility models and study their effects on the Geocast protocol, it is necessary to simulate an ad hoc network. We implemented our simulation in Network Simulator, Version 2 (NS2), which is a discrete event simulator designed for networking research. The NS2 simulator includes a simulation of both a physical layer (e.g., wireless communication) and a median access layer (e.g., IEEE 802.11). NS2 is supported by organizations such as DARPA, University of California, Berkeley, Xerox PARC, NSF and Sun Microsystems (NS2 homepage, 2000).

Chapter 5 is organized as follows. Section 5.1 describes our simulation environment. An analysis of each model including its suitability for our purposes is in Section 5.2. Finally, our simulation results are presented in Section 5.3.

5.1 Simulation Environment

All simulation results in this thesis are obtained from the following simulation environment. Our simulation area is 700 x 700 meters and contains a geocast region starting at (500,500). The geocast region extends 200 units in both the x and y directions, resulting in a square area of 200 x 200 meters in the upper right-hand corner. A single stationary MN functions within this geocast region at all times. This

MN ensures the existence of at least one MN capable of accepting and processing geocast messages throughout the simulation. Further, each simulation contains 30 MNs in addition to the stationary MN in the geocast region. These MNs move according to the specified mobility model for a total of 10,000 seconds. The maximum speed of MNs varies between runs and ranges from 0 to 20 m/s in increments of 5 m/s. During a simulation, the source transmits a data message every second and a JOIN-DEMAND message every other second. Each MN transmits up to 250 meters and has a limited buffer allowing a maximum storage of 20 messages.

Results from three mobility models are presented in Section 5.3 (the three mobility models chosen are listed in Section 5.2). Each data point found in Figures 5.1-5.5 represents the mean of 15 runs. Each run initially places the 30 MNs in predefined locations; the MNs then move according to the mobility model being tested. In other words, all simulations start out with identical topologies at time t=0.

5.2 Analysis of Models

In this section, we summarize each mobility model from Chapters 2 and 3. We also discuss the criteria used to select a mobility model for our simulations. In other words, although some mobility models were appropriate for the purposes of our simulations, others were not.

5.2.1 Entity Mobility Models

In Chapter 2 entity mobility models are discussed. Section 2.1 discusses three cellular mobility models: Random Walk, Fluid-Flow, and Random Gauss-Markov. We do not evaluate these three models because they are cellular mobility models and not applicable to our ad hoc simulation environment. (We include cellular mobility models in Chapter 2 for completeness.)

Section 2.2 discusses eight ad hoc mobility models, three of which we evaluate. The Random Mobility Model, discussed in Section 2.2.1, creates random movements and speeds independent of previous locations and speeds. We attempted to simulate this model but discovered that NS2 is not capable of handling the associated computational complexity. Specifically, we wanted to model a version of the Random Mobility Model that had the MN choose a new direction after each time step. (This version of the Random Mobility Model is often used by researchers to model mobility.) Unfortunately, the mobility file created by this model (i.e., approximately 300,000 lines) is too large for NS2 to handle. Section 2.2.2 discusses the Constant Velocity Random Direction Mobility Model. We do not simulate this model for the same reason mentioned for the Random Mobility Model.

The Random Waypoint Mobility Model is discussed in Section 2.2.3. This model randomly chooses destinations instead of directions and includes pause times. We simulate the Random Waypoint Mobility Model because of its popularity in other research groups (e.g. (Broch et al., 1998), (Johansson et.al., 1999), (Chiang, 1998)) . The

Random Direction Mobility Model is discussed in Section 2.2.4. The Random Direction Mobility Model has each MN travel in a random direction until it reaches a simulation boundary. Since the purpose of this model is to improve the Random Waypoint Mobility Model, we simulate this model. Section 2.2.5 discusses a Boundless Simulation Area Mobility Model proposed by Haas. When an MN using this mobility model encounters a simulation boundary, it continues traveling and appears on the opposite side of the simulation area. This model alters the environment usually simulated; thus we simulate this model.

The Probabilistic Version of the Random Mobility Model is discussed in Section 2.2.6. This model creates a probability matrix to describe the likelihood of an MN moving from one location to another. We do not implement this model because it is difficult, if not impossible, to assign realistic values to the matrix. In addition, simulating this model in NS2 has the same problem as the Random Mobility Model. The City Area, Area Zone, and Street Unit Mobility Models are discussed in Section 2.2.7. These models describe simulation areas representing different granular scales of a city. They each describe the paths available to nodes, but fail to give descriptions of individual MN movements. However, as discussed in Chapter 6, we propose the City Section Mobility Model to describe node movements within this type of scenario. Finally, Chapter 2 concludes with a discussion of several mobility models described by Lam (see Section 2.2.8). These models are appropriate for high-speed movements over large distances, which is not appropriate for evaluating a protocol that sends messages to a specific geographical area.

5.2.2 Group Mobility Models

Chapter 3 discusses two group mobility models, each with three variations. Section 3.1 discusses the Column, Pursue, and Nomadic Community Mobility Models by Sanchez. The Column Mobility Model is discussed in Section 3.1.1 and forces all nodes to travel in a single-file line. Section 3.1.2 discusses the Pursue Mobility Model, which creates movements for MNs following a target. Finally, Section 3.1.3 discusses the Nomadic Community Mobility Model, which produces movements of a group of nodes traveling together in a semi-rigid configuration. Section 3.2 discusses the Reference Point Group Mobility (RPGM) Model along with its three variations: In-Place, Overlap, and Convention. Section 3.2.1 discusses the In-Place Mobility Model. The In-Place Mobility Model restricts groups, with different individual behavior, to specific regions of the simulation area. The Overlap Mobility Model allows a group, with identical individual behavior, to interact with other groups across the entire simulation area. This model is discussed in Section 3.2.2. Finally, we discuss the Convention Mobility Model in Section 3.2.3, which restricts the movement of MN groups as well as the movements of individual nodes within each group.

Although the Sanchez models in Section 3.1 and the RPGM variations in Section 3.2 are applicable in many real world situations, it is not necessary to model them for our purposes. For example, consider the RPGM model. The RPGM model requires each group to contain a leading MN. The leading MN, which travels using the Random Waypoint Mobility Model, dictates the movement patterns of all other MNs in the group. If a leading MN in the RPGM model is within the forwarding zone of the Geocast protocol, all MNs in the group will (most likely) be in the forwarding region. Thus, each MN will receive and rebroadcast a copy of every message sent to the geocast region. Since all MNs in the group are located near each other, the rebroadcasts have high overhead cost with little benefit. Thus a slight modification of the current Geocast protocol is preferred. Specifically, instead of forcing every MN in the group to forward a copy of every received message, the group leader takes responsibility for forwarding the message on behalf of the entire group. Thus, we represent the entire group with a single MN. Using this modification to the Geocast protocol, the RPGM model reduces to the Random Waypoint Mobility Model and we would obtain the same results if the model were simulated. Thus, it is not necessary to simulate the RPGM model. The same logic may be applied to the Column, Pursue, and Nomadic Mobility Models.

5.3 Simulation Results

As mentioned in Section 5.1, the speed of MNs varies between sets of simulations to include 0, 5, 10, 15, and 20 m/s. These speeds represent maximum values. Thus, a simulation run with a maximum speed of 20 m/s has an average speed of (approximately) 10 m/s. By examining statistics including average number of hops, control overhead, data overhead, average end-to-end delay, and goodput (i.e., reliability) we are able to compare the effects of a mobility model on an ad hoc network protocol (i.e., the Geocast protocol). In Figures 5.1-5.5, Haas represents the Boundless Simulation Area Mobility Model defined in Section 2.2.5. RandDir represents the Random Direction Mobility Model defined in Section 2.2.4 and RandWay represents the Random Waypoint Mobility Model defined in Section 2.2.3. For simplicity, we use Haas, RandDir and RandWay in the discussion of the results.

A 90% confidence interval is calculated for each data point. These intervals are placed on all figures except Figures 5.2 and 5.4. Confidence intervals were removed from Figures 5.2 and 5.4 since including the intervals made it difficult to view the data points.

5.3.1 Mesh Diameter

Figure 5.1 plots the average number of hops vs. speed. At speed = 0, the average number of hops is the same for all mobility models because all three mobility models begin with the same initial configuration and zero speed equates to a static network. Our results show that, on average, the initial configurations have three hops from the source to the geocast region. The large confidence interval for zero speed is due to the wide variability in the 15 different initial configurations. As speed increases to 5 m/s, the mean number of hops slightly increases for RandDir but decreases for both Haas and RandWay. Figures 2.3 and 2.4 explain these results. As Figure 2.4 illustrates, RandDir disperses MNs throughout the simulation area, which is similar to the initial configurations. On the other hand, Figure 2.3 shows that MNs traveling with RandWay often travel in the middle of the simulation area, which decreases the number of hops to the geocast region. In addition, since Haas creates individual movements similar to RandWay, Haas and RandWay produce similar results. Lastly, RandDir keeps a higher number of hops than both RandWay and Haas for speeds greater than 5 m/s. At 5 m/s, RandDir appears to have a higher number of hops than both RandWay and Haas; however, since the confidence intervals for the three mobility models overlap, we are uncertain which mobility model produces the highest number of hops at 5 m/s.

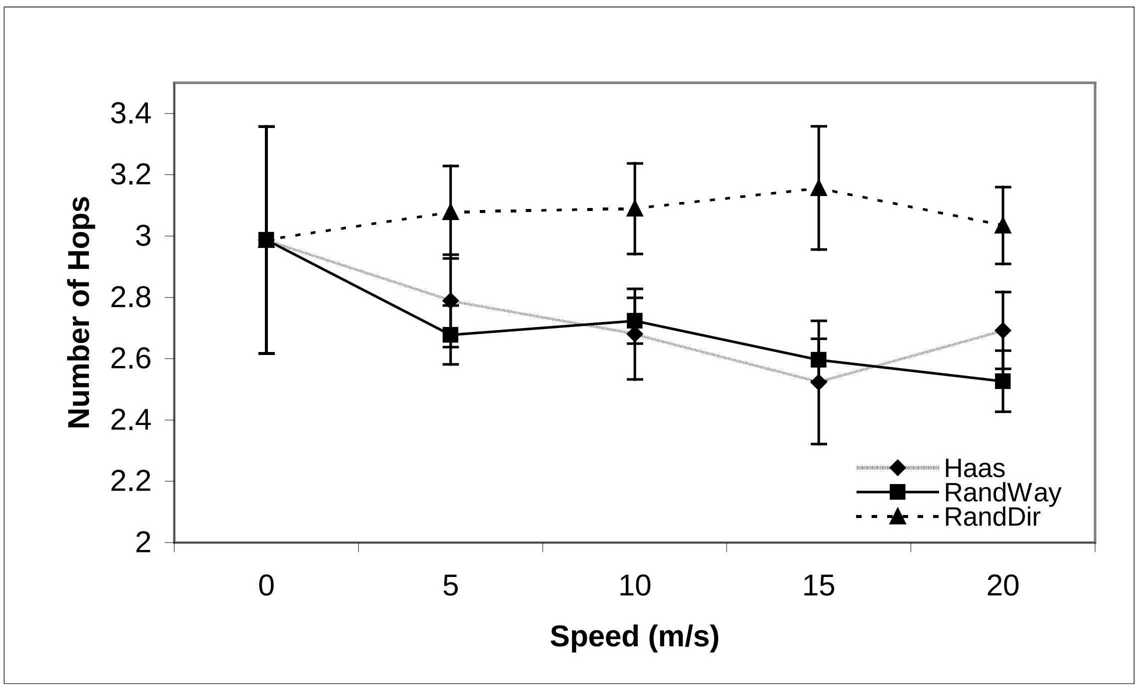

Figure 5.1 – Mesh Diameter

5.3.2 Overhead/Load

Figure 5.2 plots the number of control messages that are transmitted in the network vs. speed. (As mentioned in Section 5.3, confidence intervals are not shown in Figure 5.2; however, we note the confidence intervals for the three mobility models overlap at all speeds except 5 m/s.) Each data point in Figure 5.2 is a summation of all the hops every control message takes in the network. The number of JOIN-DEMAND messages transmitted is approximately the same for each mobility model because a JOIN-DEMAND message is transmitted every other second. Therefore, only the number of transmitted JOIN-TABLE messages differs in the results of the three mobility models. The number of JOIN-TABLE messages provides a numerical representation of the redundancy in our mesh. Specifically, one JOIN-TABLE message is unicast to the source for each path that exists in the mesh between the source and the geocast region.

Figure 5.2 shows that all three models have the same control overhead at speed = 0. As speed increases we initially see a slight increase in the mean for Haas and RandWay and a decrease in the mean for RandDir. However, between 5 and 15 m/s, the mean for Haas and RandDir experience a decrease while the mean for RandDir increases. This trend reverses again at 15 m/s. Finally, at 20 m/s the mean of all three protocols converge. Three characteristics of the Geocast protocol explain the results in Figure 5.2: partitions in the forwarding zone, hop count, and mesh density.

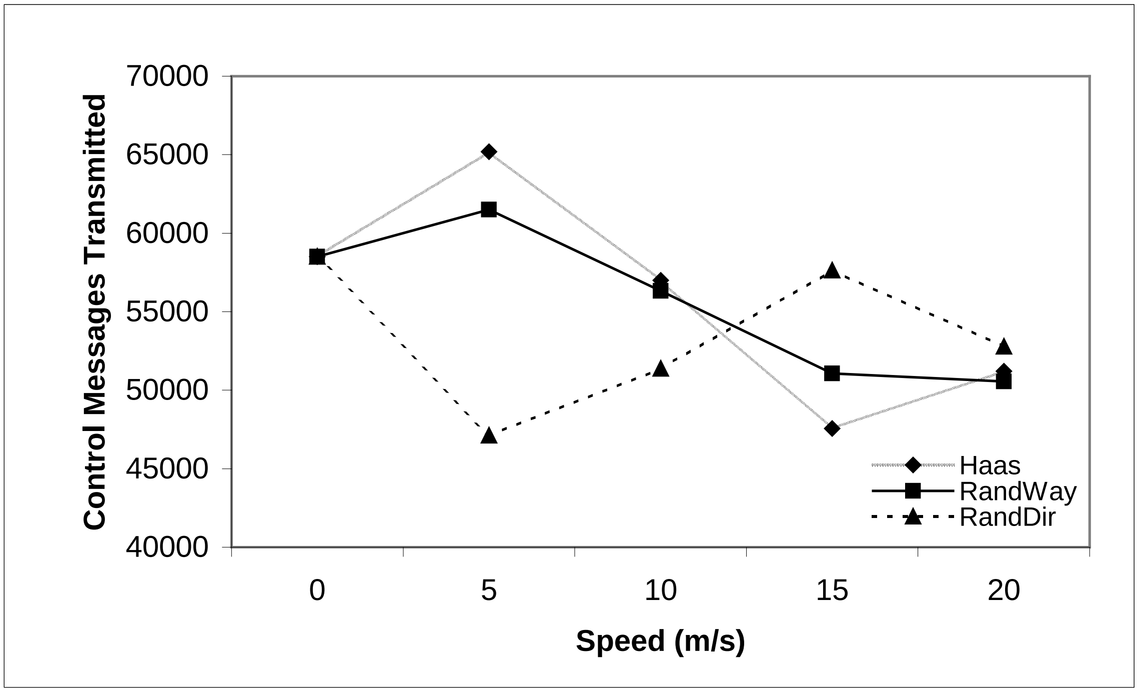

Figure 5.2 – Network-wide control overhead

The first network characteristic affecting control overhead involves partitions within the forwarding zone. Partitions prevent messages from reaching the geocast region, which decreases control overhead. Second, as hop count increases control overhead must also increase. Finally, the density of our mesh affects control overhead; a dense mesh provides a larger number of redundant paths than a sparse mesh, which in turn increases control overhead. Unfortunately, we do not have a thorough understanding of mesh density and its properties. Such analyses are beyond the scope of this thesis but will be included in our future work. However, we know that RandDir has a higher hop count than RandWay and Haas (see Figure 5.1), which subsequently increases control overhead. We also know that RandDir experiences more partitions within its forwarding zone (see Figure 5.5), which decreases control overhead. These two competing factors affect which protocol has higher control overhead at any given time.

Figure 5.3 plots network-wide data load vs. speed. Similar to the number of control messages transmitted in Figure 5.2, Figure 5.3 is derived by summing the number of hops taken by every data packet in the network. At speed = 0 all three models produce the same results because we simulate identical static networks. However, as speed increases, the mean number of data packets remains semi-constant for RandDir but decreases for both Haas and RandWay. In other words, RandDir has higher data load than both RandWay and Haas for speeds greater than 5 m/s. At 5 m/s, RandDir appears to have a higher data load than both RandWay and Haas; however, we note the confidence intervals for the three mobility models overlap. The trends in Figure 5.3 are directly related to the trends in the average hop count (Figure 5.1). Both figures produce similar results because the data packets described in Figure 5.3 must travel along the hops that are described in Figure 5.1.

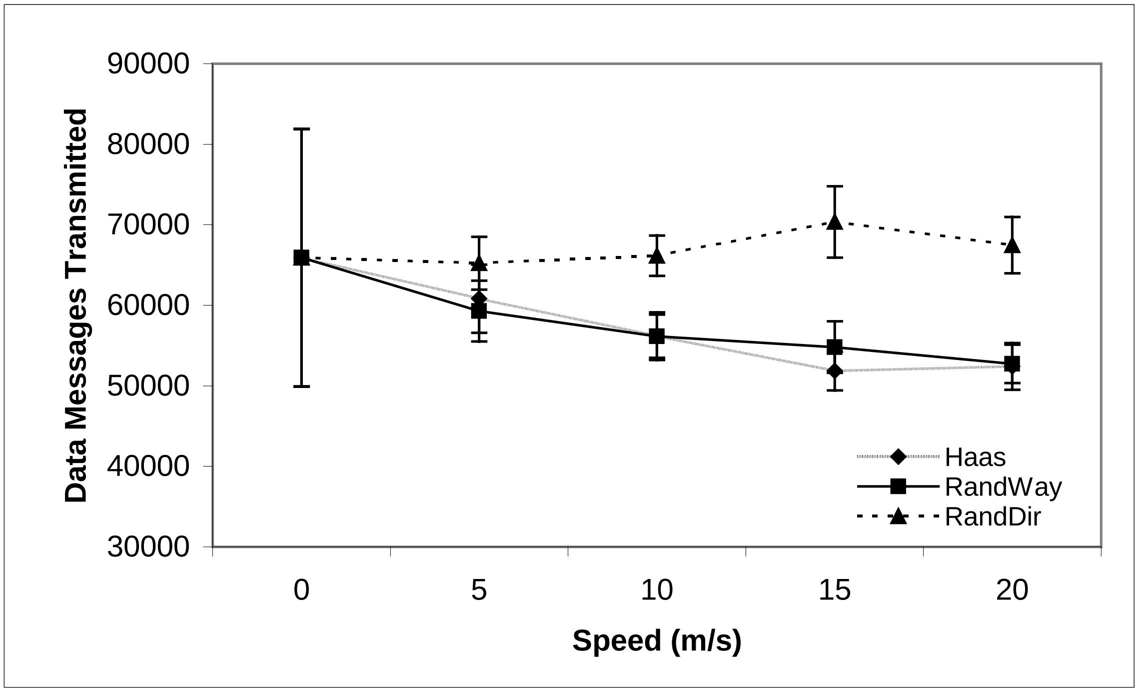

Figure 5.3 - Network-wide data load

5.3.3 Performance

As mentioned earlier, confidence intervals are not shown in Figure 5.4 because their presence hampers the viewing of the data points. However, we note that the confidence intervals for the three mobility models overlap at all speeds except 15 m/s. At 15 m/s, the end-to-end delay for RandDir is higher than both RandWay and Haas. Since the hop count of RandDir is higher than the hop counts of both RandWay and Haas, this result is not surprising. The range of values on the y-axis is quite small. In other words, end-to-end delay is small for all three mobility models.

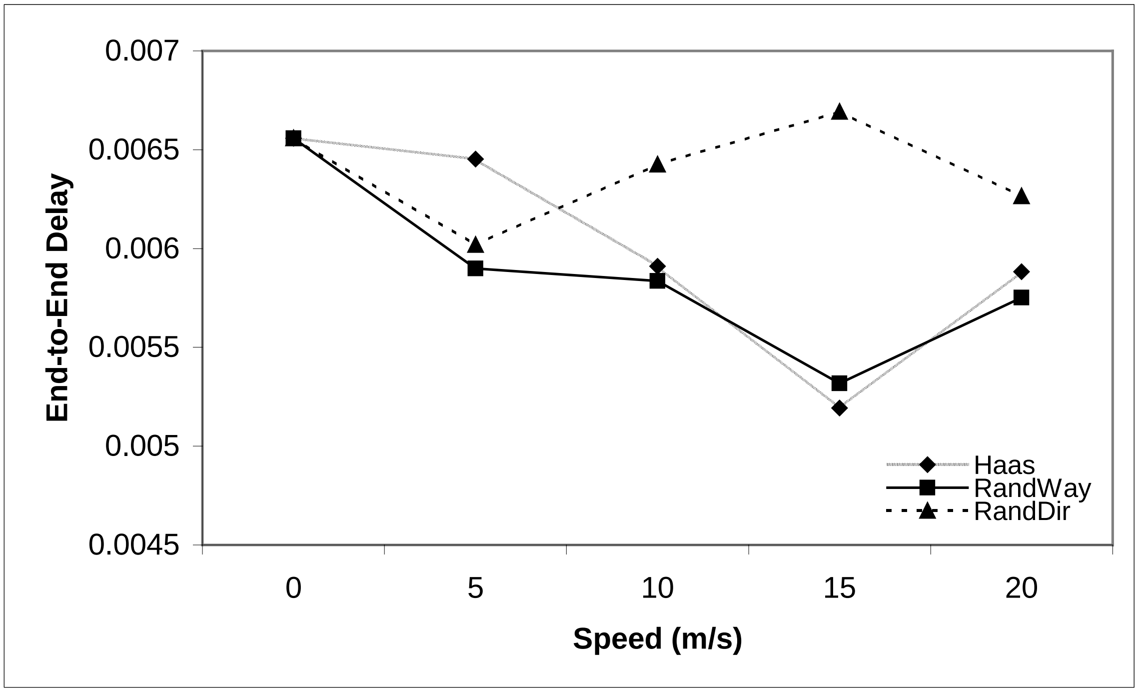

Figure 5.4 - Transmission delay

Figure 5.5 plots the goodput ratio vs. speed. Recall that the goodput ratio is a measure of reliability; it is the number of bytes received by the geocast members divided by the number of bytes transmitted by the source. We consider a data message to be "received" if at least one MN in the geocast region receives a copy of the message. Once an MN in the geocast region receives a data message, the MN initiates a localized flooding algorithm in order to distribute the message to the remaining members of the geocast group.

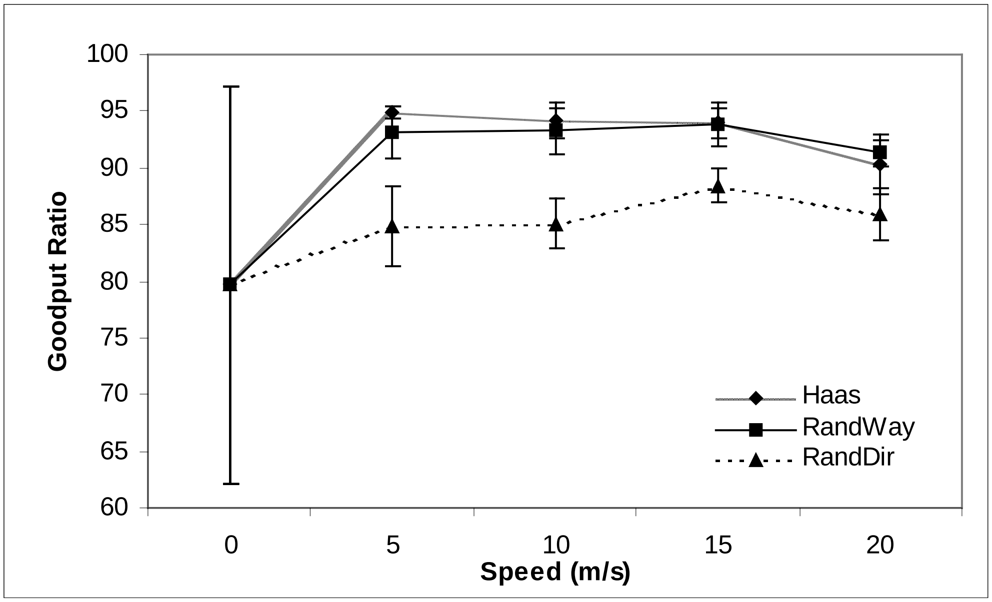

Figure 5.5 – Measure of reliability

At speed = 0, the identical initial static networks produce the same results for all three mobility models. The large confidence interval for zero speed is a result of the all-or-none behavior associated with static networks using the Geocast protocol. Within a static network, the individual MNs are either located in such a way that all messages get to the geocast region (i.e., 100% reliability) or no messages get to the geocast region (i.e., 0% reliability). Thus, a large confidence interval exists for zero speed. As we increase speed to 5 m/s, the mean values for all three mobility models experience an increase in goodput. As we continue to increase speed the goodput ratio for all three models becomes steady. Figure 5.5 shows that RandDir fails to perform as well as the other two models. This low performance is due to the inherent nature of the model; i.e., the fact that RandDir produces a higher hop count than both RandWay and Haas. With a higher hop count network partitions in the forwarding zone are more likely, which affects the reliability of the protocol.

5.4 Observations

The results in Section 5.3 illustrate that an educated analysis of mobility models must occur before the performance evaluation of an ad hoc network. In fact, since a single mobility model cannot accurately depict the behavior of MNs in all scenarios, researchers should consider evaluating their protocol with multiple mobility models. In today's literature the Random Waypoint Mobility Model is the most common mobility model used, partly because the code for this model is available in NS2 and partly because it was the model used in an early article comparing ad hoc network protocols (see (Broch et al., 1998)). However, the Random Waypoint Mobility Model is not a perfect mobility model. For example, although the speed and destination for an MN are randomly chosen, an MN moves at a constant speed from it current location to its next destination. Having the MN's speed vary during movement from one location to another is preferred; however, the method NS2 uses for implementing mobility files prohibits this more realistic movement pattern. The Random Direction Mobility Model is also an unrealistic model because people rarely spread themselves evenly throughout an area. Instead, people tend to gather in the center of an area, whether the area is a room or a city. Therefore, instead of defaulting to the Random Waypoint Mobility Model for every simulation, or implementing a model that fails to model accurate MN behavior, we strongly advise researchers to conduct a thorough analysis of appropriate mobility models before beginning their simulations.

CHAPTER 6

PROPOSAL FOR A NEW MOBILITY MODEL

In this chapter, we propose a new mobility model and then compare it against the results presented in Chapter 5. In the City Section Mobility Model, the simulation area, represented by a grid, symbolizes horizontal and vertical streets within a city. Within the simulation environment, the centermost vertical and horizontal streets are designated as mid-speed roads, similar to main thoroughfares within a city. All other roads are considered to be slow residential roads. The City Section Mobility Model is tested using the same simulation environment and parameters listed in Chapter 5, with the exception of MN speed. Instead of assigning a maximum speed to all MNs and varying this speed between simulations, we assign speeds of 20.12 m/s (45 miles/hr), and 11.18 m/s (25 miles/hr) to our mid-speed and residential roads, respectively. It should also be noted that we place roads 160 meters apart in the 700 x 700 meter simulation area.

Each MN begins the simulation at a predefined intersection of two streets. An MN then randomly chooses a destination, also represented by the intersection of two streets. Moving to this destination involves (at most) one horizontal and one vertical movement. Upon reaching the destination, the MN randomly chooses another destination (i.e., an intersection of two streets) and repeats the process. In other words, the MN does not pause between movements. Figure 6.1 shows the movements of an MN starting at (1,1), moving to (5,4) and then moving to (1,4).

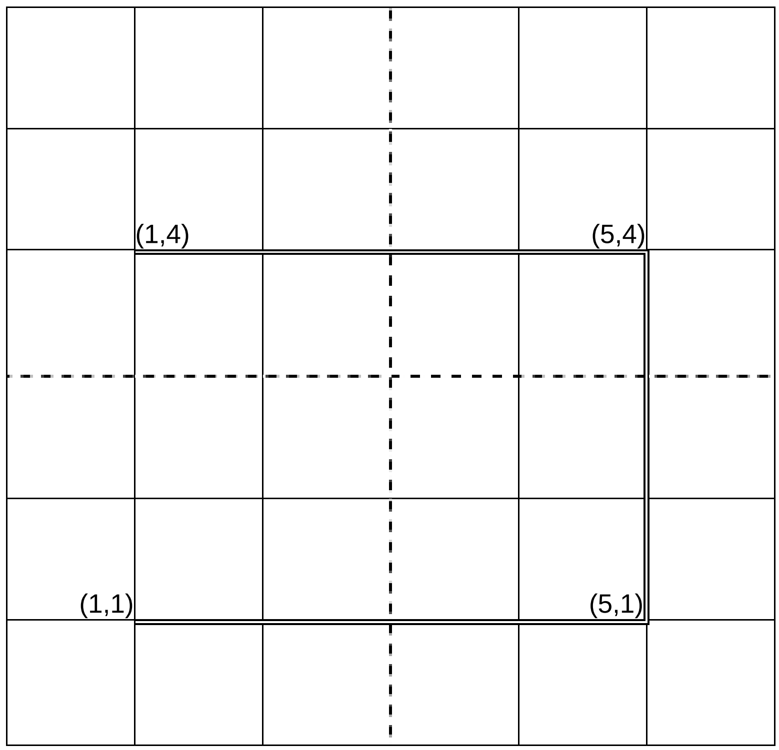

Figure 6.1 – Traveling pattern of an MN using the City Section Mobility Model.

The dashed lines in Figure 6.1 indicate the mid-speed roads and the double lines represent streets traveled by the MN in our example. In this example, the MN begins at (1,1) and randomly chooses (5,4) as its first destination. It also randomly chooses to begin travel in a horizontal direction[2]. These two decisions allow the MN to begin

[2] A preferred algorithm would attempt to find a path corresponding to the shortest travel time between two points. Unfortunately, limitations of NS2 would not allow us to implement this preferred algorithm.

traveling in a horizontal direction to (5,1). In order to arrive at (5,4), the MN then changes direction and travels in a vertical direction. With a successful arrival, the MN chooses a new destination, i.e., (1,4). Since there is no need to travel in a vertical direction, the MN simply moves horizontally until it reaches its new destination.

The City Section Mobility Model provides realistic movements for a section of a city since it severely restricts the traveling behavior of MNs. All MNs must follow predefined paths similar to those found in the real world. MNs participating in an ad hoc setting would not have the ability to roam about freely without regard to obstacles and other traffic regulations. Further, people typically tend to travel in similar patterns when driving across town or walking across campus. The City Section Mobility Model defines an example pattern. The results for the Geocast protocol using the City Section Mobility Model are given in Table 1.

Collected Statistic	**Average**	**Confidence**
Average Number of Hops	5.0521	0.0084
Number of Control Messages Transmitted	149242.2000	353.9214
Number of Data Messages Transmitted	78119.8000	538.7335
Average End-to-End Delay	0.0147	0.0000
Average Goodput Ratio	68.2484	0.5709

Table 1 - Results for the City Section Mobility Model

Table 1, compared with Figures 5.1-5.5, illustrates the difference between realistic and nonrealistic mobility models in an ad hoc simulation. As illustrated in Figure 5.1, RandDir produces the highest hop count with an average of three hops. The City Section

Mobility Model (CitySec) produces two more hops on average. This increase in hops between the source and the geocast region has an effect on all other results obtained. For example, the number of data messages transmitted and the average end-to-end delay for CitySec is higher than RandDir, RandWay, and Haas due to the higher hop count in CitySec. Further, Figure 5.5 illustrates that RandDir produces the least amount of reliability with an average goodput ratio of 85%. Table 1 shows that CitySec produces an average goodput ratio of only 68%. As shown, a realistic mobility model such as CitySec imposes hardships on simulations that other unrealistic models do not. Therefore, we conclude that an appropriate analysis of mobility models must accompany all research simulations.

CHAPTER 7

FUTURE WORK AND CONCLUSIONS

Further study should modify the City Section Mobility Model to include pause times at certain intersections and destinations, incorporate acceleration and deceleration, and account for higher/lower concentrations of MNs depending on the time of day. In addition, our model should expand to include a larger simulation area, an increased number of streets, a high-speed road along the border of the simulation area, and other novel path-finding algorithms.

In conclusion, we reiterate the need for careful examination of the mobility model chosen to represent the behavior of MNs in a simulation of an ad hoc network protocol. Our results clearly demonstrate the extreme difference in statistical data gathered for each of the mobility models. Further time and effort should be devoted to examining the movements of entities in the real world to produce accurate mobility models.

Further study should also be devoted to the Random Waypoint Mobility Model. The detection of patterns and behaviors within this model would help identify whether scenarios exist in our world that inherently use the Random Waypoint Mobility Model. This model may not accurately represent any scenario in our world, simply because real MNs must travel around obstacles and along pre-defined paths. For example, a member of the educational community at the Colorado School of Mines cannot travel from one classroom to another in a completely random fashion. First, obstacles such as other buildings, trees, cars, and fellow colleagues must be avoided. Second, a member of this community will not travel with the speeds assigned by the Random Waypoint Mobility Model. As an example, a fellow student/professor does not travel through campus with a speed of 1 m/s for a given distance followed by an abrupt change of speed to 6 m/s. Instead, students/professors tend to walk quickly if they are late or slowly if they have enough time to enjoy their walk. In addition, the speed of the walk varies as the student/professor walks from one location to the next.

We would also like to take a closer look at the methods used to choose a future MN location. Similarities and differences between mobility models that randomly select directions and mobility models that select specific locations should be analyzed.

We realize that the Random Waypoint Mobility Model has been the default mobility model for many years and we advocate its continued usage for the purpose of comparing current simulation results with previously obtained simulation results. However, the Random Waypoint Mobility Model should not be the only mobility model implemented within a simulation. Careful analysis must be performed to determine how MNs move in the scenario being tested, followed by implementation of an appropriate mobility model. Finally, an examination of the created geocast mesh and its associated properties would provide us with a better understanding of the internal behaviors of the Geocast protocol.

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