Chapter 1

A SURVEY OF MOBILITY MODELS
in Wireless Adhoc Networks

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Abstract: A Mobile Ad hoc NETwork (MANET) is a collection of wireless mobile nodes forming a self-configuring network without using any existing infrastructure. Since MANETs are not currently deployed on a large scale, research in this area is mostly simulation based. Among other simulation parameters, the mobility model plays a very important role in determining the protocol performance in MANET. Thus, it is essential to study and analyze various mobility models and their effect on MANET protocols. In this chapter, we survey and examine different mobility models proposed in the recent research literature. Beside the commonly used Random Waypoint model and its variants, we also discuss various models that exhibit the characteristics of temporal dependency, spatial dependency and geographic constraint. Hence, we attempt to provide an overview of the current research status of mobility modeling and analysis.

Key words: mobility model; Mobile Ad hoc Network; review.

1. INTRODUCTION

In general, a Mobile Ad hoc NETwork (MANET) is a collection of wireless nodes communicating with each other in the absence of any infrastructure. Due to the availability of small and inexpensive wireless communicating devices, the MANET research field has attracted a lot of attention from academia and industry in the recent years. In the near future, MANETs could potentially be used in various applications such as mobile classrooms, battlefield communication and disaster relief applications.

To thoroughly and systematically study a new Mobile Ad hoc Network protocol, it is important to simulate this protocol and evaluate its protocol performance. Protocol simulation has several key parameters, including mobility model and communicating traffic pattern, among others. In this chapter and the next chapter we focus on the analysis and modeling of mobility models. We are also interested in studying the impact of mobility on the performance of MANET routing protocols. We present a survey of the status, limitations and research challenges of mobility modeling in this chapter.

The mobility model is designed to describe the movement pattern of mobile users, and how their location, velocity and acceleration change over time. Since mobility patterns may play a significant role in determining the protocol performance, it is desirable for mobility models to emulate the movement pattern of targeted real life applications in a reasonable way. Otherwise, the observations made and the conclusions drawn from the simulation studies may be misleading. Thus, when evaluating MANET protocols, it is necessary to choose the proper underlying mobility model. For example, the nodes in Random Waypoint model behave quite differently as compared to nodes moving in groups [1]. It is not appropriate to evaluate the applications where nodes tend to move together using Random Waypoint model. Therefore, there is a real need for developing a deeper understanding of mobility models and their impact on protocol performance.

One intuitive method to create realistic mobility patterns would be to construct trace-based mobility models, in which accurate information about the mobility traces of users could be provided. However, since MANETs have not been implemented and deployed on a wide scale, obtaining real mobility traces becomes a major challenge. Therefore, various researchers proposed different kinds of mobility models, attempting to capture various characteristics of mobility and represent mobility in a somewhat 'realistic' fashion. Much of the current research has focused on the so-called *synthetic* mobility models [2] that are not trace-driven.

In the previous studies on mobility patterns in wireless cellular networks[3][4], researchers mainly focus on the movement of users relative to a particular area (i.e., a cell) at a macroscopic level, such as cell change rate, handover traffic and blocking probability. However, to model and analyze the mobility models in MANET, we are more interested in the movement of individual nodes at the microscopic-level, including node location and velocity relative to other nodes, because these factors directly determine when the links are formed and broken since communication is peer-to-peer.

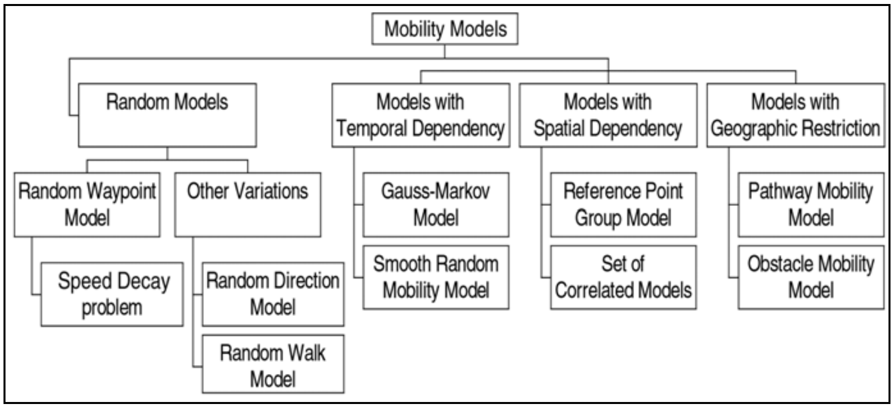

Figure 1-1. The categories of mobility models in Mobile Ad hoc Network

One frequently used mobility model in MANET simulations is the Random Waypoint model[5], in which nodes move independently to a randomly chosen destination with a randomly selected velocity. The simplicity of Random Waypoint model may have been one reason for its widespread use in simulations. However, MANETs may be used in different applications where complex mobility patterns exist. Hence, recent research has started to focus on the alternative mobility models with different mobility characteristics. In these models, the movement of a node is more or less restricted by its history, or other nodes in the neighborhood or the environment.

In Fig.1-1 we provide a categorization for various mobility models into several classes based on their specific mobility characteristics. For some mobility models, the movement of a mobile node is likely to be affected by its movement history. We refer to this type of mobility model as *mobility model with temporal dependency*. In some mobility scenarios, the mobile nodes tend to travel in a correlated manner. We refer to such models as *mobility models with spatial dependency*. Another class is the *mobility model with geographic restriction*, where the movement of nodes is bounded by streets, freeways or obstacles.

The remainder of this chapter is organized as follows. In Section 2, we describe the commonly used Random Waypoint model, some of its stochastic properties and two of its variants. In Section 3 we discuss two mobility models with temporal dependency, the Gauss-Markov Mobility Model and the Smooth Random Mobility Model. Section 4 illustrates several mobility models with spatial dependency. The mobility models with geographic restriction are discussed in Section 5. One key problem in mobility modeling, called the *speed decay* problem, and its solution are presented in Section 6. Finally, we conclude this chapter and lay out the background for the next chapter in Section 7.

2. RANDOM-BASED MOBILITY MODELS

In random-based mobility models, the mobile nodes move randomly and freely without restrictions. To be more specific, the destination, speed and direction are all chosen randomly and independently of other nodes. This kind of model has been used in many simulation studies.

One frequently used mobility model, the Random Waypoint model, and some of its stochastic properties are discussed in section 2.1 and section 2.2. Then, two variants of the Random Waypoint model, namely the Random Walk model and the Random Direction model, are described in section 2.3 and section 2.4, respectively. Finally, in section 2.5, we point out some limitations of the random-based models and their potential impact on the accuracy of the simulations.

2.1 The Random Waypoint Model

The Random Waypoint Model was first proposed by Johnson and Maltz[5]. Soon, it became a 'benchmark' mobility model to evaluate the MANET routing protocols, because of its simplicity and wide availability. To generate the node trace of the Random Waypoint model the *setdest* tool from the CMU Monarch group may be used. This tool is included in the widely used network simulator *ns-2* [25].

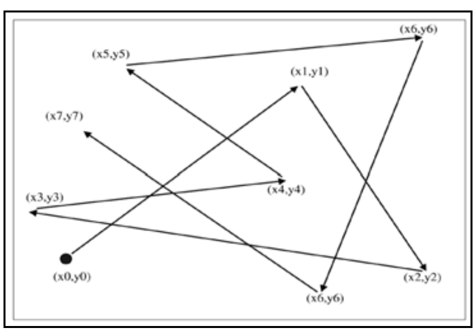

Figure 1-2. Example of node movement in the Random Waypoint Model

In the network simulator *(ns-2)* distribution, the implementation of this mobility model is as follows: as the simulation starts, each mobile node randomly selects one location in the simulation field as the destination. It then travels towards this destination with constant velocity chosen uniformly and randomly from $[0, V_{\max}]$, where the parameter $V_{\max}$ is the maximum allowable velocity for every mobile node[6]. The velocity and direction of a node are chosen independently of other nodes. Upon reaching the destination, the node stops for a duration defined by the 'pause time' parameter T_{pause}. If T_{pause}=0, this leads to continuous mobility. After this duration, it again chooses another random destination in the simulation field and moves towards it. The whole process is repeated again and again until the simulation ends. As an example, the movement trace of a node is shown in Fig.1-2.

In the Random Waypoint model, $V_{\max}$ and T_{pause} are the two key parameters that determine the mobility behavior of nodes. If the $V_{\max}$ is small and the pause time T_{pause} is long, the topology of Ad Hoc network becomes relatively stable. On the other hand, if the node moves fast (i.e., $V_{\max}$ is large) and the pause time T_{pause} is small, the topology is expected to be highly dynamic[1]. Varying these two parameters, especially the $V_{\max}$ parameter, the Random Waypoint model can generate various mobility scenarios with different levels of nodal speed. Therefore, it seems necessary to quantify the *nodal speed*.

Intuitively, one such notion is average node speed. If we could assume that the pause time $T_{pause} = 0$, considering that $V_{\max}$ is uniformly and randomly chosen from $[0, V_{\max}]$, we can easily find that the average nodal speed is $0.5V_{\max}$ [2]. However, in general, the pause time parameter should not be ignored. In addition, it is the relative speed of two nodes that determines whether the link between them breaks or forms, rather than their individual speeds. Thus, average node speed seems not to be the appropriate metric to represent the notion of *nodal speed*.

Johansson, Larsson and Hedman et al.[7] took a further step and proposed the *Mobility* metric to capture and quantify this nodal speed notion. The measure of relative speed between node *i* and *j* at time *t* is

$$RS(i,j,t) = |\vec{V}_i(t) - \vec{V}_j(t)| \qquad (1)$$

Then, the Mobility metric $\overline{M}$ is calculated as the measure of relative speed averaged over all node pairs and over all time. The formal definition is as follow

[1] However, to our best knowledge, until now, no work provides quantitative analysis for the impact of maximum allowed velocity and pause time on the network topology.

[2] Even if the T_{pause} parameter is small, we can still claim that average nodal speed is approximated as $0.5\,V_{\max}$.

$$\overline{M} = \frac{1}{|i,j|}\sum_{i=1}^{N}\sum_{j=i+1}^{N}\frac{1}{T}\int_0^T RS(i,j,t)dt \qquad (2)$$

where $|i,j|$ is the number of distinct node pair *(i,j)*, *n* is the total number of nodes in the simulation field (i.e., ad hoc network), and *T* is the simulation time.

Using this *Mobility* metric, we are able to roughly measure the level of nodal speed and differentiate the different mobility scenarios based on the level of mobility. In Ref.[1], Bai, Sadagopan and Helmy define another mobility metrics *Average Relative Speed* in a similar way. The experiments show that the *Average Relative Speed* linearly and monotonically increases with the maximum allowable velocity.

2.2 Stochastic Properties of Random Waypoint Model

Even though the Random Waypoint model is commonly used in simulation studies, a fundamental understanding of its theoretical characteristics is still lacking. Currently, researchers are investigating its stochastic properties, such as probability distribution of transition length and transition time for each epoch.

Bettstetter, Hartenstein and Perez-Costa[8] describe Random Waypoint model as a discrete time stochastic process. Then, the transition length $L_i^{(j)}$ is defined as the distance that the node *j* moves from one waypoint to another during the *i*th epoch. Thus, the expected value of transition length *L* is

$$E[L] = \underbrace{\lim_{m\to\infty}\frac{1}{m}\sum_{i=1}^{m} l_i^{(j)}}_{\text{time average}} = \underbrace{\lim_{n\to\infty}\frac{1}{n}\sum_{j=1}^{n} l_i^{(j)}}_{\text{ensemble average}} \qquad (3)$$

The above equation indicates that the average of the transition length in a single epoch *i* over all the nodes (i.e., *ensemble average*) is equal to the average of the transition length of a single Random Waypoint node *j* over time (i.e., *time average*). According to the theory of random process, **the Random Waypoint process has mean-ergodic property**[3].

Once we know the Random Waypoint model is mean ergodic, the problem of determining the probability distribution of transition length can be simplified. Then, the problem is to only consider the distribution of the Euclidian distance between two independent random points in the simulation field. Therefore, by applying the standard geometrical probability theory, the probability density functions of transition length and duration are provided[8] as follows.

[3] Ref.[8] illustrates a method to prove the mean-ergodicity of Random Waypoint model.

1. If the simulation field is a rectangular area with length a and width b. Without losing the generality, we assume that $b \le a$. The probability density function of transition length L[4] is

$$f_L(l) = \frac{4l}{a^2 b^2} f_0(l) \qquad (4)$$

with

$$f_0(l) = \begin{cases} \frac{\pi}{2}ab - al - bl + \frac{1}{2}l^2 & \text{for } 0 \le l \le b \\ ab\sin^{-1}\frac{b}{l} + a\sqrt{l^2 - b^2} - \frac{1}{2}b^2 - al & \text{for } b < l < a \\ ab\sin^{-1}\frac{b}{l} + a\sqrt{l^2 - b^2} - \frac{1}{2}b^2 - al & \text{for } a \le l \le \sqrt{a^2 + b^2} \\ \quad - ab\cos^{-1}\frac{a}{l} + b\sqrt{l^2 - a^2} - \frac{1}{2}a^2 - \frac{1}{2}l^2 & \\ 0 & \text{otherwise} \end{cases}$$

Correspondingly, the expected value of transition length L is

$$E[L] = \frac{1}{15}\left[\frac{a^3}{b^2} + \frac{b^3}{a^2} + \sqrt{a^2 + b^2}\left(3 - \frac{b^2}{a^2} - \frac{b^2}{a^2}\right)\right] + \frac{1}{6}\left[\frac{b^2}{a}\cos^{-1}\frac{\sqrt{a^2 + b^2}}{b} + \frac{a^2}{b}\cos^{-1}\frac{\sqrt{a^2 + b^2}}{a}\right] \qquad (5)$$

and the variance of transition length L is

$$E[L^2] = \frac{1}{6}(a^2 + b^2) \qquad (6)$$

2. If the simulation field is a circular area with radius a. The probability density function of transition length L is

$$f_L(l) = \frac{8l}{2\pi a^2}\left[\cos^{-1}\frac{l}{2a} - \frac{l}{2a}\sqrt{1 - \left(\frac{l}{2a}\right)^2}\right] \qquad (7)$$

Correspondingly, the expected value of transition length L is

$$E[L] = \int_0^{2a} l f_L(l)\,dl = 0.905a \qquad (8)$$

and the variance of transition length L is

$$E[L^2] = \int_0^{2a} l^2 f_L(l)\,dl = a^2 \qquad (9)$$

3. Bettstetter, Hartenstein and Perez-Costa also take a further step to derive the probability distribution of transition time as follow

[4] Due to the limited space, we omit the relevant derivations. For more details refer to Ref.[8].

$$f_T(t) = \int_{V_{\min}}^{V_{\max}} v f_L(vt) f_V(v) dv \qquad (10)$$

where $f_V(v)$ is the probability distribution function of movement velocity v and $f_L(l)$ is the probability distribution function of transition length. By inserting the appropriate distribution function of movement velocity into Eq.10, we are able to get the distribution function of transition time.

The Random Waypoint model has several variations. In the following two subsections, we will discuss two of them, the Random Walk model and the Random Direction model.

2.3 Random Walk Model

The Random Walk model was originally proposed to emulate the unpredictable movement of particles in physics. It is also referred to as the *Brownian Motion*. Because some mobile nodes are believed to move in an unexpected way, Random Walk mobility model is proposed to mimic their movement behavior[2]. The Random Walk model has similarities with the Random Waypoint model because the node movement has strong randomness in both models. We can think the Random Walk model as the specific Random Waypoint model with zero pause time.

However, in the Random Walk model, the nodes change their speed and direction at each time interval. For every new interval t, each node randomly and uniformly chooses its new direction $\theta(t)$ from $(0, 2\pi]$. In similar way, the new speed $v(t)$ follows a uniform distribution or a Guassian distribution from $[0, V_{\max}]$. Therefore, during time interval t, the node moves with the velocity vector $(v(t)\cos\theta(t), v(t)\sin\theta(t))$. If the node moves according to the above rules and reaches the boundary of simulation field, the leaving node is bounced back to the simulation field with the angle of $\theta(t)$ or $\pi - \theta(t)$, respectively. This effect is called *border effect*[9].

The Random Walk model is a memoryless mobility process where the information about the previous status is not used for the future decision. That is to say, the current velocity is independent with its previous velocity and the future velocity is also independent with its current velocity. However, we observe that is not the case of mobile nodes in many real life applications, as discussed in section 2.5.

2.4 Non-uniform Spatial Distribution and Random Direction Model

Bettstetter[10] and Blough et al.[11] respectively observe that the spatial node distribution of Random Waypoint model is transformed from uniform distribution to non-uniform distribution after the simulation starts. As the simulation time elapses, the unbalanced spatial node distribution becomes even worse. Finally, it reaches a steady state. In this state, the node density is maximum at the center region, whereas the node density is almost zero around the boundary of simulation area. This phenomenon is called *non-uniform spatial distribution*. Another similar pathology of Random Waypoint model called *density wave* phenomenon (i.e., the average number of neighbors for a particular node periodically fluctuates along with time) is observed by Royer, Melliar-Smith and Moser[12].

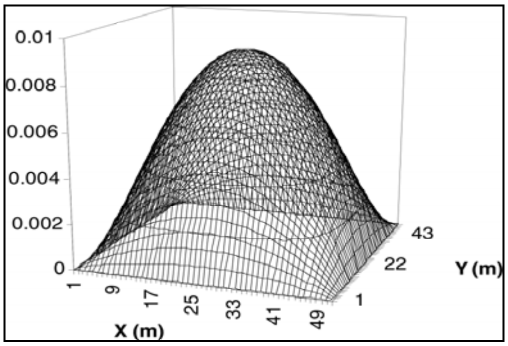

Figure 1-3. Node Spatial Distribution (Square Area)

This phenomenon results from the certain mobility behavior of Random Waypoint model. In Random Waypoint model, since the nodes are likely to either move towards the center of simulation field or choose a destination that requires movement through the middle, the nodes tend to cluster near the center region of simulation field and move away from the boundaries. Therefore, a non-uniform distribution is formed[9][11]. At the same time, the nodes appear to converge, disperse and converge at center region periodically, resulting in the fluctuation of the node density of neighbors (i.e., density wave)[12].

Following we provide the analysis for the above phenomenon. Let the random variable $P_i(t) = (X_i(t), Y_i(t))$ indicate the geographic location of the mobile node i at time t.

1. **Rectangular Area:** In Ref.[9], to approximate the spatial node distribution in the square simulation field of size a by a, Bettstetter and Wagner use the analytical expression

$$f_P(P) = f_{X,Y}(x,y) \approx \frac{36}{a^6}(x^2 - \frac{a^2}{4})(y^2 - \frac{a^2}{4}) \qquad (11)$$

for $x \in [-a/2, a/2]$ and $y \in [-a/2, a/2]$. As shown in Fig.1-3, for the position near the center region, the probability that a node may exist at this position is expected to be the maximum value (i.e., $f_P(0,0) = \frac{9}{4a^2}$); On the other hand, a node is unlikely to exist near the boundary of simulation field (i.e., $f_P(x, \pm a/2) = f_P(\pm a/2, y) = 0$). When the position is away from the center, the spatial node density decreases as well.

2. **Circular Area:** For a circular area with radius *a*, the analytical expression is

$$f_P(P) = f_{r,\theta}(r,\theta) = f_r(r) = \frac{2}{\pi a^2} - \frac{2}{\pi a^4} r^2 \qquad (12)$$

for $0 \le r \le a$. As shown in Fig.1-4, the maximum value is also achieved at the center of simulation field (i.e., $f(r=0) = \frac{2}{\pi a^2}$). As *r* increases, the spatial node density also decreases.

Moreover, these two formulas imply that the node spatial distribution is not a function of node velocity. In other words, in Random Waypoint model, no matter how fast the nodes move, the spatial node distribution at a certain position is only determined by its Cartesian location.

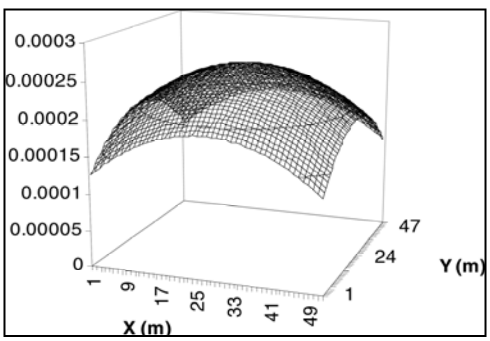

Figure 1-4. Node Spatial Distribution (Circular Area)

To explain such phenomenon, in a recently published work[8], Bettstetter, Hartenstein and Perez-Costa suggest that the underlying reason for the non-uniform spatial node distribution and density wave phenomenon is the non-uniform distribution of the direction angle at the beginning of each movement epoch. The probability density function of the direction angle is given as

$$f_\theta(\theta) = \int_0^{2\pi}\int_0^a f_\theta(\theta \mid r)\frac{1}{\pi a^2} r dr d\varphi$$
$$= \frac{1}{4\pi|\sin^3(\theta)|}\{|\sin(\theta)|[-2\cos^4(\theta) - 2\cos^3(\theta)|\cos(\theta)| \quad (13)$$
$$+\cos^2(\theta) + \cos(\theta)|\cos(\theta)| + 1] + \sin^{-1}(|\sin(\theta)|\cos(\theta))\}$$

According to this equation, Bettstetter, Hartenstein and Perez-Costa point out the probability of taking a direction towards the boundary (within the interval $[\frac{\pi}{2}, \frac{3\pi}{2}]$) is only 12.5%. However, the node moves toward the center region of area (in the interval $[-\frac{\pi}{4}, \frac{\pi}{4}]$) with probability 61.4%. Fig.1-5 illustrates the probability distribution of movement angle.

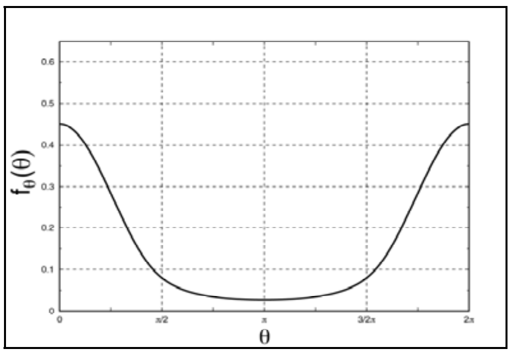

Figure 1-5. The probability distribution of movement direction

Therefore, it seems that the non-uniform spatial node distribution and density wave problem is inherent to the Random Waypoint model. Hence, a modified version of the Random Waypoint model is required to achieve the uniform spatial node distribution.

In line with the observation that distribution of movement angle is not uniform in Random Waypoint model, the Random Direction model based on similar intuition is proposed by Royer, Melliar-Smith and Moser[12]. This model is able to overcome the non-uniform spatial distribution and density wave problems. Instead of selecting a random destination within the simulation field, in the Random Direction model the node randomly and uniformly chooses a direction by which to move along until it reaches the boundary. After the node reaches the boundary of the simulation field and stops with a pause time T_{pause}, it then randomly and uniformly chooses another direction to travel. This way, the nodes are uniformly distributed within the simulation field.

Another variant of the Random Direction model is the Modified Random Direction model that allows a node to stop and choose another new direction before it reaches the boundary of the simulation field. For both versions of Random Direction model, Royer, Melliar-Smith and Moser report that the Random Direction model incurs less fluctuation in node density than the Random Waypoint model.

2.5 Limitations of the Random Waypoint Model and other Random Models

The Random Waypoint model and its variants are designed to mimic the movement of mobile nodes in a simplified way. Because of its simplicity of implementation and analysis, they are widely accepted. However, they may not adequately capture certain mobility characteristics of some realistic scenarios, including temporal dependency, spatial dependency and geographic restriction:

1. **Temporal Dependency of Velocity:** In Random Waypoint and other random models, the velocity of mobile node is a memoryless random process, i.e., the velocity at current epoch is independent of the previous epoch. Thus, some extreme mobility behavior, such as sudden stop, sudden acceleration and sharp turn, may frequently occur in the trace generated by the Random Waypoint model. However, in many real life scenarios, the speed of vehicles and pedestrians will accelerate incrementally. In addition, the direction change is also smooth.
2. **Spatial Dependency of Velocity**: In Random Waypoint and other random models, the mobile node is considered as an entity that moves independently of other nodes. This kind of mobility model is classified as *entity mobility model* in Ref.[2]. However, in some scenarios including battlefield communication and museum touring, the movement pattern of a mobile node may be influenced by certain specific 'leader' node in its neighborhood. Hence, the mobility of various nodes is indeed correlated.
3. **Geographic Restrictions of Movement:** In Random Waypoint and other random models, the mobile nodes can move freely within simulation field without any restrictions. However, in many realistic cases, especially for the applications used in urban areas, the movement of a mobile node may be bounded by obstacles, buildings, streets or freeways.

Random Waypoint model and its variants fail to represent some mobility characteristics likely to exist in Mobile Ad Hoc networks. Thus, several other mobility models were proposed. In the following few sections, we shall discuss those models, according to the classification in Fig.1-1. In the next chapter, we aim to systematically analyze the impact of those mobility models on routing protocol performance, and propose several metrics to quantify those mobility characteristics.

3. MOBILITY MODELS WITH TEMPORAL DEPENDENCY

Mobility of a node may be constrained and limited by the physical laws of acceleration, velocity and rate of change of direction. Hence, the current velocity of a mobile node may depend on its previous velocity. Thus the velocities of single node at different time slots are 'correlated'. We call this mobility characteristic the *Temporal Dependency* of velocity.

However, the memoryless nature of Random Walk model, Random Waypoint model and other variants render them inadequate to capture this temporal dependency behavior. As a result, various mobility models considering temporal dependency are proposed. In Section 3.1 and Section 3.2, Gauss-Markov Mobility Model and Smooth Random Mobility Model are described in details. Finally, we briefly summarize the key characteristic of temporal dependency in Section 3.3.

3.1 Gauss-Markov Mobility Model

The Gauss-Markov Mobility Model was first introduced by Liang and Haas[13] and widely utilized[14][2]. In this model, the velocity of mobile node is assumed to be correlated over time and modeled as a Gauss-Markov stochastic process. In a two-dimensional simulation field, the Gauss-Markov stochastic process can be represented by the following equations:

$$\overline{V}_t = \overline{\alpha} \circ \overline{V}_{t-1} + (1-\overline{\alpha}) \circ \overline{\upsilon} + \overline{\sigma} \circ \sqrt{1-\overline{\alpha}^2} \circ \overline{W}_{t-1} \qquad (14)$$

where $\overline{V}_t = [v_t^x, v_t^y]^T$ and $\overline{V}_{t-1} = [v_{t-1}^x, v_{t-1}^y]^T$ are the velocity vector at time t and time $t-1$, respectively. $\overline{W}_{t-1} = [w_{t-1}^x, w_{t-1}^y]^T$ is the uncorrelated random Gaussian process with mean 0 and variance σ^2, $\overline{\alpha} = [\alpha^x, \alpha^y]^T$, $\overline{\upsilon} = [\upsilon^x, \upsilon^y]^T$ and $\overline{\sigma} = [\sigma^x, \sigma^y]^T$ are the vectors that represent the memory level, asymptotic mean and asymptotic standard deviation, respectively.

For the sake of simplicity, we may write the general form (Eq.14) in a two-dimensional field as follows:

$$\begin{cases} v_t^x = \alpha v_{t-1}^x + (1-\alpha)\upsilon^x + \sigma^x \sqrt{1-\alpha^2}\, w_{t-1}^x \\ v_t^y = \alpha v_{t-1}^y + (1-\alpha)\upsilon^y + \sigma^x \sqrt{1-\alpha^2}\, w_{t-1}^y \end{cases} \qquad (15)$$

When the node is going to travel beyond the boundaries of the simulation field, the direction of movement is forced to flip 180 degree. This way, the nodes remain away from the boundary of simulation field.

Based on these equations, we observe that the velocity $\overline{V_t} = [v_t^x, v_t^y]^T$ of mobile node at time slot *t* is dependent on the velocity $\overline{V_{t-1}} = [v_{t-1}^x, v_{t-1}^y]^T$ at time slot *t-1*. Therefore, the Gauss-Markov model is a temporally dependent mobility model whereas the degree of dependency is determined by the memory level parameter α. α is a parameter to reflect the randomness of Gauss-Markov process. By tuning this parameter, Liang and Haas[13] state that this model is capable of duplicating different kinds of mobility behaviors in various scenarios[5]:

1. If the Gauss-Markov Model is memoryless, i.e., $\alpha = 0$. The Eq.15 is

$$\begin{cases} v_t^x = \upsilon^x + \sigma^x w_{t-1}^x \\ v_t^y = \upsilon^y + \sigma^x w_{t-1}^y \end{cases} \quad (16)$$

   where the velocity of mobile node at timeslot *t* is only determined by the fixed drift velocity $\overline{\upsilon} = [\upsilon^x, \upsilon^y]^T$ and the Gaussian random variable $\overline{W_{t-1}} = [w_{t-1}^x, w_{t-1}^y]^T$. Obviously, the model described in Eq.16 is the Random Walk model.

2. If the Gauss-Markov Model has strong memory, i.e., $\alpha = 1$. The Eq.15 is

$$\begin{cases} v_t^x = v_{t-1}^x \\ v_t^y = v_{t-1}^y \end{cases} \quad (17)$$

   where the velocity of mobile node at time slot *t* is exactly same as its previous velocity. In the nomenclature of vehicular traffic theory, this model is called as fluid flow model.

3. If the Gauss-Markov Model has some memory, i.e., $0 < \alpha < 1$. The velocity at current time slot is dependent on both its velocity $\overline{V_{t-1}} = [v_{t-1}^x, v_{t-1}^y]^T$ at time *t-1* and a new Gaussian random variable $\overline{W_{t-1}} = [w_{t-1}^x, w_{t-1}^y]^T$. The degree of randomness is adjusted by the memory level parameter α. As α increases, the current velocity is more likely to be influenced by its previous velocity. Otherwise, it will be mainly affected by the Gaussian random variable.

In the Gauss-Markov model, the temporal dependency plays a key role in determining the mobility behavior. In the Section 3.2, by emulating the mobility behavior of users in real life, it is also observed that the temporal dependency is an important mobility characteristic that should be captured.

[5] Please check Ref.[13] for the detailed discussion if the readers are interested.

3.2 Smooth Random Mobility Model

Another mobility model considering the temporal dependency of velocity over various time slots is the Smooth Random Mobility Model. In Ref.[15], it is also found that the memoryless nature of Random Waypoint model may result in unrealistic movement behaviors. Instead of the sharp turn and sudden acceleration or deceleration, Bettstetter also proposes to change the speed and direction of node movement incrementally and smoothly.

It is observed that mobile nodes in real life tend to move at certain preferred speeds $\{V_{pref}^1, V_{pref}^2, \cdots, V_{pref}^n\}$, rather than at speeds purely uniformly distributed in the range $[0, V_{\max}]$. Therefore, in Smooth Random Mobility model, the probability distribution of node velocity is as follows: the speed within the set of preferred speed values has a high probability, while a uniform distribution is assumed on the remaining part of entire interval $[0, V_{\max}]$. For example, if the node has the preferred speed set $\{0, 0.5V_{\max}, V_{\max}\}$, then the probability distribution is

$$\Pr_V(v) = \begin{cases} \Pr(v=0)\delta(v) & v=0 \\ \Pr(v=0.5V_{\max})\delta(v-0.5V_{\max}) & v=0.5V_{\max} \\ \Pr(v=V_{\max})\delta(v-V_{\max}) & v=V_{\max} \\ \dfrac{1-\Pr(v=0)-\Pr(v=0.5V_{\max})-\Pr(v=V_{\max})}{V_{\max}} & 0<V_{\max}<1 \\ 0 & otherwise \end{cases} \quad (18)$$

where $\Pr(v=0)+\Pr(v=0.5V_{\max})+\Pr(v=V_{\max})<1$.

In Smooth Random Mobility Model, the frequency of speed change is assumed to be a Poisson process. Upon an event of speed change, a new target speed $v(t)$ is chosen according to the probability distribution function of speed as shown in Eq.18. Then, the speed of mobile node is changed incrementally from the current speed $v(t')$ to the targeted new speed $v(t)$ by acceleration speed or deceleration speed *a(t)*. The probability distribution function of acceleration or deceleration *a(t)* is uniformly distributed among $[0, a_{\max}]$ and $[a_{\min}, 0]$ respectively

$$\Pr_a(a) = \begin{cases} \dfrac{1}{a_{\max}} & for\ acceleration\ 0<a\le a_{\max} \\ \dfrac{1}{a_{\min}} & for\ deceleration\ a_{\min}\le a<0 \\ 0 & otherwise \end{cases} \quad (19)$$

For each time slot t, the new speed is calculated as

$$v(t)=v(t-\Delta t)+a(t)\Delta t \quad (20)$$

Thus, the speed may be controlled to increase or decrease continuously and incrementally. If *a(t)* is a small value, then the speed is changed slowly and the degree of temporal correlation is expected to be strong. Otherwise, the speed can be changed quickly and the temporal correlation is small.

Unlike speed, the movement direction is assumed to be purely uniformly distributed in the interval $[0, 2\pi]$, as

$$\Pr_{\phi}(\phi) = \frac{1}{2\pi} \qquad for\ 0 \le \phi < 2\pi \qquad (21)$$

Once a movement direction is chosen, the node moves in a straight line until the direction changes. The frequency of direction change is assumed to have an exponential distribution in [15]. When the direction is about to change, the new movement direction is also selected according to the probability distribution function described by Eq.21. The direction difference $\Delta\phi(t)$ between the new direction $\phi(t)$ and old direction $\phi(t')$ is defined as

$$\Delta\phi(t) = \begin{cases} \phi(t) - \phi(t') + 2\pi & for\ -2\pi < \phi(t) - \phi(t') \le -\pi \\ \phi(t) - \phi(t') & for\ -\pi < \phi(t) - \phi(t') \le \pi \\ \phi(t) - \phi(t') - 2\pi & for\ \pi < \phi(t) - \phi(t') \le 2\pi \end{cases} \qquad (22)$$

Since the value of direction change $\Delta\phi(t)$ is distributed in the interval $[-\pi, \pi]$, this change may be a large value. However, the change of movement direction also should be smooth and incremental. Therefore, the large value of $\Delta\phi(t)$ should be divided into several incremental small direction changes $\Delta\varphi(t)$. Here, the value of $\Delta\varphi(t)$ should be a small value, and it represents the maximum allowable value of direction change per time slot. Hence, the direction change can be achieved in $\frac{\Delta\phi(t)}{\Delta\varphi(t)}$ time slots.

For each time slot in the period of direction change, the mobile node only changes its movement direction by $\Delta\varphi(t)$ degree, as follows

$$\phi(t) = \phi(t - \Delta t) + \Delta\varphi(t) \qquad (23)$$

This small change in direction is repeated for $\frac{\Delta\phi(t)}{\Delta\varphi(t)}$ time slots until the node reaches the new direction $\phi(t)$. Then, the node continues to move in the new chosen direction.

In Section 3.1 and Section 3.2, we have discussed two mobility models that capture the temporal dependency of velocity over time. In the next subsection, we will briefly summarize their properties.

3.3 Discussion

For the Gauss-Markov model, as illustrated in Eq.15, the velocity of a mobile node at any time slot is a function of its previous velocity. We could say that the Gauss-Markov Model is a mobility model with temporal dependency. The degree of temporal dependency is determined by the memory level parameter α. In the Smooth Random Mobility Model, as observed in Eq.20 and Eq.23, both the speed and movement direction of nodes are also partly decided by their previous values. Thus, it is also a mobility model that captures the characteristic of temporal dependency. The degree of temporal dependency is affected by its acceleration speed a and the maximum allowed direction change per time slot $\Delta\varphi(t)$.

By adjusting these parameters, we are able to generate various mobility scenarios with different degrees of temporal dependency. In order to quantitatively study the temporal dependency characteristic and its impact, we formally define the temporal dependency metric in the next chapter.

4. MOBILITY MODELS WITH SPATIAL DEPENDENCY

In the Random Waypoint model and other random models, a mobile node moves independently of other nodes, i.e., the location, speed and movement direction of mobile node are not affected by other nodes in the neighborhood. As previously mentioned, these models do not capture many realistic scenarios of mobility. For example, on a freeway to avoid collision, the speed of a vehicle cannot exceed the speed of the vehicle ahead of it. Moreover, in some targeted MANET applications including disaster relief and battlefield, team collaboration among users exists and the users are likely to follow the team leader. Therefore, the mobility of mobile node could be influenced by other neighboring nodes. Since the velocities of different nodes are 'correlated' in space, thus we call this characteristic as the *Spatial Dependency* of velocity.

We begin this section by discussing the Reference Point Group Mobility Model in Section 4.1. Then in Section 4.2 we illustrate a set of spatially correlated mobility models including Column Mobility Model, Pursue Mobility Model and Nomadic Community Mobility Model. Finally, we briefly summarize the properties of those models in Section 4.3.

4.1 Reference Point Group Mobility Model

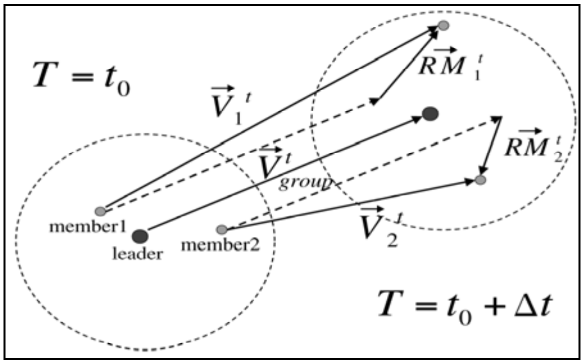

Figure 1-6. An example of node movement in Reference Point Group Mobility Model, providing two snapshots at time *T=t0* (left circle) and time *T=t0+Δt* (right circle)

In line with the observation that the mobile nodes in MANET tend to coordinate their movement, the Reference Point Group Mobility (RPGM) Model is proposed in [16]. One example of such mobility is that a number of soldiers may move together in a group or platoon. Another example is during disaster relief where various rescue crews (e.g., firemen, policemen and medical assistants) form different groups and work cooperatively.

In the RPGM model, each group has a center, which is either a logical center or a group leader node. For the sake of simplicity, we assume that the center is the group leader. Thus, each group is composed of one leader and a number of members. The movement of the group leader determines the mobility behavior of the entire group. The respective functions of group leaders and group members are described as follows.

1. **The Group Leader:**

The movement of group leader at time t can be represented by motion vector $\vec{V}^{t}_{group}$. Not only does it define the motion of group leader itself, but also it provides the general motion trend of the whole group. Each member of this group deviates from this general motion vector $\vec{V}^{t}_{group}$ by some degree. The motion vector $\vec{V}^{t}_{group}$ can be randomly chosen or carefully designed based on certain predefined paths.

2. **The Group Members:**

The movement of group members is significantly affected by the movement of its group leader. For each node, mobility is assigned with a *reference point* that follows the group movement. Upon this predefined reference point, each mobile node could be randomly placed in the neighborhood.

Formally, the motion vector of group member *i* at time *t*, $\vec{V}_i^{\,t}$, can be described as

$$\vec{V}_i^{\,t} = \vec{V}_{group}^{\,t} + \overrightarrow{RM}_i^{\,t} \quad (23)$$

where the motion vector $\overrightarrow{RM}_i^{\,t}$ is a random vector deviated by group member *i* from its own reference point. The vector $\overrightarrow{RM}_i^{\,t}$ is an independent identically distributed (i.i.d) random process whose length is uniformly distributed in the interval $[0, r_{\max}]$ (where $r_{\max}$ is maximum allowed distance deviation) and whose direction is uniformly distributed in the interval $[0, 2\pi)$.

Fig.1-6 illustrates an example for the Reference Point Group Mobility Model. In Fig.1-6, $\vec{V}_{group}^{\,t}$ is the motion vector for the group leader, it is also the motion vector for the whole group. $\overrightarrow{RM}_i^{\,t}$ is the random deviation vector for group member *i*, and the final motion vector of group member *i* is represented by vector $\vec{V}_i^{\,t}$.

With appropriate selection of predefined paths for group leader and other parameters, the RPGM model is able to emulate a variety of mobility behaviors. For example, in Ref.[16], Hong, Gerla, Pei and Chiang illustrate that the RPGM model is able to represent various mobility scenarios including

1. **In-Place Mobility Model:** The entire field is divided into several adjacent regions. Each region is exclusively occupied by a single group. One such example is battlefield communication.
2. **Overlap Mobility Model:** Different groups with different tasks travel on the same field in an overlapping manner. Disaster relief is a good example.
3. **Convention Mobility Model:** This scenario is to emulate the mobility behavior in the conference. The area is also divided into several regions while some groups are allowed to travel between regions.

In Ref.[17], the Mobility Vector framework, an extension of Reference Point Group Mobility model, is proposed. In this framework, Hong, Kwon, Gerla et al. point out that many realistic mobility scenarios could be modeled and generated with this framework, by properly choosing the checkpoints along the preferred motion path of group leader. If those checkpoints can reflect the motion behavior in realistic scenarios, then the Mobility Vector model provide a general and flexible framework for describing and modeling mobility patterns. However, in practice, it is not a trivial task to generate those checkpoints.

In RPGM model, the vector $\overrightarrow{RM}_i$ indirectly determines how much the motion of group members deviate from their leader. So, we are not able to generate the various mobility scenarios with different levels of spatial dependency, by simple adjustment of model parameters. In order to solve this problem, in Ref.[1], a modified version of RPGM model is proposed. The movement can be characterized as follows:

$$\begin{cases} |V_{member}(t)| = |V_{leader}(t)| + random() * SDR * \max\_speed \\ \theta_{member}(t) = \theta_{leader}(t) + random() * ADR * \max\_angle \end{cases} \quad (24)$$

where $0 < SDR, ADR < 1$. SDR is the Speed Deviation Ratio and ADR is the Angle Deviation Ratio. SDR and ADR are used to control the deviation of the velocity (magnitude and direction) of group members from that of the leader. By simply adjusting these two parameters, different mobility scenarios can be generated.

Because of the inherent characteristic of spatial dependency between nodes, the RPGM model is expected to behave different from the Random Waypoint model. Hong, Gerla, Pei and Chiang report that RPGM incurs less link breakage and achieves a better performance for various routing protocols than Random Waypoint model[16]. In the next chapter, a detailed investigation on the characteristics of RPGM model is conducted.

4.2 A Set of Spatially Correlated Models

Sanchez and Manzoni[18] propose a set of mobility models in which the mobile nodes travel in a cooperative manner. This set of mobility models, including Column Mobility Model, Pursue Mobility Model and Nomadic Mobility Model, are expected to exhibit strong spatial dependency between nearby nodes.

Let $P_i^t = (X_i^t, Y_i^t)$ be the position of node *i* at time *t* and $RP_i^t = (X_i^t, Y_i^t)$ be the reference point of node *i* at time *t*. Following we describe these mobility models and their applications.

1. **Column Mobility Model:**

The Column Mobility Model represents a set of mobile nodes (e.g., robots) that move in a certain fixed direction. This mobility model can be used in searching and scanning activity, such as destroying mines by military robots.

At time slot *t*, the mobile node *i* is to update its reference point RP_i^t by adding an advance vector α_i^t to its previous reference point RP_i^{t-1}. Formally,

$$RP_i^t = RP_i^{t-1} + \alpha_i^t \quad (25)$$

where the advance vector α_i^t is the predefined offset used to move the reference grid of node *i* at time *t*. After the reference point is updated, the new position of mobile node *i* is to randomly deviate from the updated reference point by a random vector w_i^t. Formally,

$$P_i^t = RP_i^t + w_i^t \quad (26)$$

When the mobile node is about to travel beyond the boundary of a simulation field, the movement direction is then flipped 180 degree. Thus, the mobile node is able to move towards the center of simulation field in the new direction.

2. **Pursue Mobility Model:**

The Pursue Mobility Model emulates scenarios where several nodes attempt to capture single mobile node ahead. This mobility model could be used in target tracking and law enforcement. The node being pursued (i.e., target node) moves freely according to the Random Waypoint model.

By directing the velocity towards the position of the targeted node, the pursuer nodes (i.e., seeker nodes) try to intercept the target node. Formally, this can be written as

$$P_i^t = P_i^{t-1} + v_i^t(P_{target}^t - P_i^{t-1}) + w_i^t \qquad (27)$$

where P_{target}^t is the expected position of targeted node being pursued at time t and w_i^t is a small random vector used to offset the movement of mobile node i.

3. **Nomadic Community Mobility Model:**

The Nomadic Mobility Model is to represent the mobility scenarios where a group of nodes move together. This model could be applied in mobile communication in a conference or military application.

The whole group of mobile nodes moves randomly from one location to another. Then, the reference point of each node is determined based on the general movement of this group. Inside of this group, each node can offset some random vector to its predefined reference point. Formally,

$$P_i^t = RP_i^t + w_i^t \qquad (28)$$

where w_i^t is a small random vector used to offset the movement of mobile node i at time t.

Compared to the Column Mobility Model which also relies on the reference grid, it is observed in Ref.[2] that the Nomadic Community Mobility Model shares the same reference grid while in Column Mobility Model each column has its own reference point. Moreover, the movement in the Nomadic Community Model is sporadic while the movement is more or less constant in Column Mobility Model.

This set of mobility models has been utilized to analyze the protocol performance. Both Hu and Johnson[14] and Camp, Boleng and Davies[2] report that this set of mobility models behaves different than Random Waypoint model.

4.3 Discussion

It is apparent from the previous descriptions that the definition of Column, Nomadic Community and Pursue Models is similar to that of

RPGM model. Both of them exhibit the characteristic of spatial dependency of velocity. Ref.[2] states that the Column, Nomadic Community and Pursue model could be easily produced using RPGM model, if the proper predefined checkpoints are chosen in advance.

As shown in Eq.24, in modified version of RPGM model, parameter *SDR* and *ADR* are the key parameters to adjust the level of spatial dependency. By adjusting these parameters in RPGM model, we could create various mobility scenarios with different level of spatial dependency. We formally define the spatial dependency metric in the next chapter. Using this metric, it is easier to gain a deeper understanding towards this characteristic and its influence on protocol performance.

5. MOBILITY MODELS WITH GEOGRAPHIC RESTRICTION

In this section, we examine and revisit another limitation of Random Waypoint model, the unconstraint motion of mobile node. Mobile nodes, in the Random Waypoint model, are allowed to move freely and randomly anywhere in the simulation field. However, in most real life applications, we observe that a node's movement is subject to the environment. In particular, the motions of vehicles are bounded to the freeways or local streets in the urban area, and on campus the pedestrians may be blocked by the buildings and other obstacles. Therefore, the nodes may move in a pseudo-random way on predefined pathways in the simulation field. Some recent works address this characteristic and integrate the paths and obstacles into mobility models. We call this kind of mobility model a *mobility model with geographic restriction*.

We describe two such mobility models, Pathway Mobility Model and Obstacle Mobility Model, in the Section 5.1 and Section 5.2, respectively. We then conclude this section by briefly discussing their characteristics in Section 5.3.

5.1 Pathway Mobility Model

One simple way to integrate geographic constraints into the mobility model is to restrict the node movement to the pathways in the map. The map is predefined in the simulation field. Tian, Hahner and Becker et al.[19] utilize a random graph to model the map of city. This graph can be either randomly generated or carefully defined based on certain map of a real city. The vertices of the graph represent the buildings of the city, and the edges model the streets and freeways between those buildings.

Initially, the nodes are placed randomly on the edges of the graph. Then for each node a destination is randomly chosen and the node moves towards this destination through the shortest path along the edges. Upon arrival, the node pauses for T_{pause} time and again chooses a new destination for the next movement. This procedure is repeated until the end of simulation.

Unlike the Random Waypoint model where the nodes can move freely, the mobile nodes in this model are only allowed to travel on the pathways. However, since the destination of each motion phase is randomly chosen, a certain level of randomness still exists for this model. So, in this graph based mobility model, the nodes are traveling in a pseudo-random fashion on the pathways.

Similarly, in the Freeway mobility model and Manhattan mobility model[1], the movement of mobile node is also restricted to the pathway in the simulation field. Fig.1-7 illustrates the maps used for Freeway, Manhattan and Pathway models.

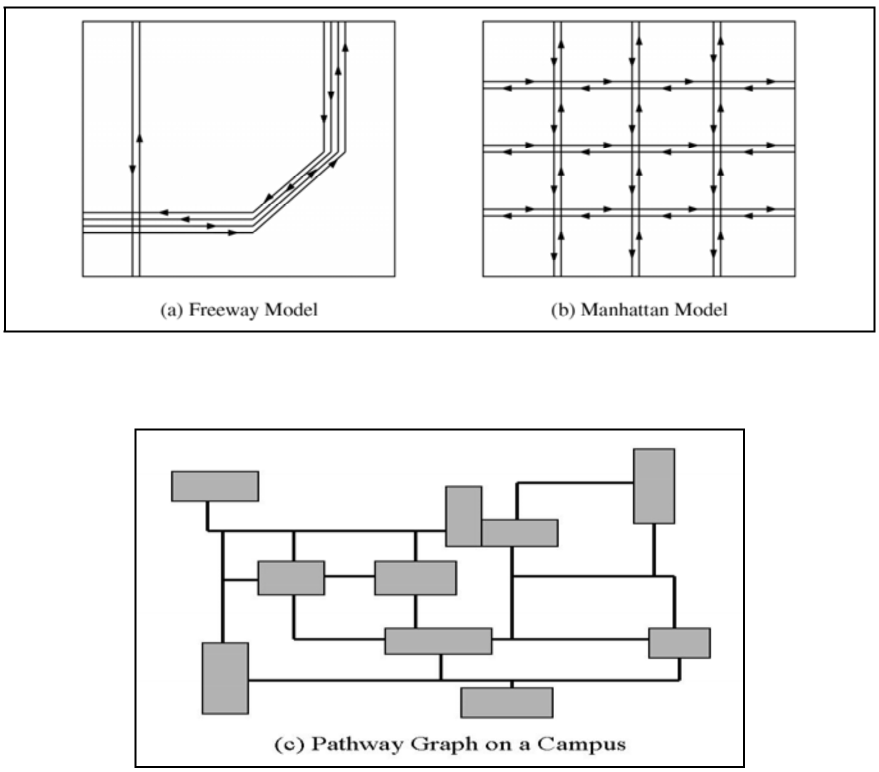

Figure 1-7. The pathway graphs used in the Freeway, Manhattan and Pathway Model

5.2 Obstacle Mobility Model

Another geographic constraint playing an important role in mobility modeling includes the obstacles in the simulation field. To avoid the obstacles on the way, the mobile node is required to change its trajectory. Therefore, obstacles do affect the movement behavior of mobile nodes. Moreover, the obstacles also impact the way radio propagates. For example, for the indoor environment, typically, the radio system could not propagate the signal through obstacles without severe attenuation. For the outdoor environment, the radio is also subject to the radio shadowing effect. When integrating obstacles into mobility model, both its effect on node mobility and on radio propagation should be considered.

Johansson, Larsson and Hedman et al.[7] develop three 'realistic' mobility scenarios to depict the movement of mobile users in real life, including

1. **Conference scenario** consisted of 50 people attending a conference. Most of them are static and a small number of people are moving with low mobility.
2. **Event Coverage scenario** where a group of highly mobile people or vehicles are modeled. Those mobile nodes are frequently changing their positions.
3. **Disaster Relief scenarios** where some nodes move very fast and others move very slowly.

In all the above scenarios, obstacles in the form of rectangular boxes are randomly placed on the simulation field. The mobile node is required to choose a proper movement trajectory to avoid running into such obstacles. Moreover, when the radio propagates through an obstacle, the signal is assumed to be fully absorbed by the obstacle. More specifically, if an obstacle is in-between two nodes, the link between these nodes is considered broken until one moves out of the shadowed area of the other. Due to these effects, the three proposed mobility scenarios seem to differ from the commonly used Random Waypoint model.

Jardosh, Belding-Royer and Almeroth et al.[20] also investigate the impact of obstacles on mobility modeling in details. After considering the effects of obstacles into the mobility model, both the movement trajectories and the radio propagation of mobile nodes are somehow restricted.

In the simulation field, a number of obstacles are placed to model the buildings within the UCSB campus environment. The authors realize that people in real life may follow the predefined the pathways between buildings, instead of walking randomly and reflecting off of the buildings. Thus, based on the locations of those building or obstacles, a Voronoi graph

[21] is computed to construct the pathways[6]. The mobile nodes are only allowed to move on the pathways that interconnect the buildings. The Voronoi graph constructs pathways that are equidistant from the nearby buildings. This observation is consistent with the common sense that the pathways tend to lie halfway in-between the adjacent buildings. Moreover, in this model, the nodes (e.g., students on campus) are allowed to enter and exit buildings.

Once the pathway graph is defined, the movements of mobile nodes are restricted on the pathways. Thus, the mobile nodes are likely to travel in a semi-definitive (i.e., pseudo random) way. After the mobile node randomly chooses a new destination on the pathway graph, it moves towards it by following the shortest path through the predefined pathway graph. This shortest path is calculated by the Dijikstra's algorithm in the Voronoi Diagram.

5.3 Discussion

In this section, we have discussed three mobility models considering the geographic constraints of node movement. Same as pedestrians and vehicles in the real world, the mobile nodes in the Pathway mobility model are confined to the pathways. Even in the Obstacle model, the nodes are also moving along the pathways calculated from the locations of obstacles. Therefore, the predefined pathway graph is an important factor determining the motion behavior of mobile nodes. For mobility models with geographic restrictions, those pathways are supposed to restrict and partly define the movement trajectories of nodes, even though certain level of randomness appears to exist.

Realizing that the pathway of the map is one key element for the characteristic of geographic constraint of mobility models, we propose two mobility models (Freeway mobility model and Manhattan mobility model) in the next chapter.

6. UNSTEADY STATE PROBLEM IN RANDOM WAYPOINT MODEL AND ITS SOLUTION

In the recent studies [22][23], Yoon, Liu and Noble observe that the Random Waypoint model is unable to reach a steady state in terms of the level of mobility. In particular, the average nodal speed of Random

[6] Please refer to Ref.[20] and Ref.[21] for the detailed method to compute the Voronoi Diagram based on the obstacle graph.

Waypoint model with zero pause time is constantly decreasing over time. For the non-zero pause time Random Waypoint model, the general trend of average nodal speed also decays, even though the long pause time may result in the fluctuations.

Intuitively, we know once the mobile node chooses a faraway destination with a slow speed; it takes a long period for the node to finish this trip. During this period, the mobile node moves slowly. As the simulation advances, on average more and more nodes are trapped in such long trip. Then such slow-motion mobility pattern will become the dominating behavior of Random Waypoint model. Therefore, the average nodal speed keeps decreasing over time.

The authors also provide a formal explanation for this phenomenon. Based on following three reasonable assumptions[7] made for Random Waypoint model,

1. The mobile node is supposed to uniformly choose a new destination from a circle of radius $R_{\max}$ center at the current location and move towards it;
2. The pause time is set to 0;
3. The node travels with speed uniformly distributed in the interval $[V_{\min}, V_{\max}]$.

Similar to the discussion in Section 2.2, we can get the expected travel distance of each movement epoch $E[L]$ is

$$E[L] = \frac{2}{3} R_{\max} \qquad (29)$$

Considering that the node speed follows a uniform distribution in the interval $[V_{\min}, V_{\max}]$, based on the Eq.10, we can get the expected travel time of each movement epoch $E[S]$ is

$$E[S] = \frac{2R_{\max}}{3(V_{\max} - V_{\min})} \ln\left(\frac{V_{\max}}{V_{\min}}\right) \qquad (30)$$

In Section 2.2, we know that Random Waypoint is a mean-ergodic random process. Thus, the time average speed for a given node over time is equal to the ensemble average nodal speed for all the nodes in a single epoch. Let $v(t)$ be the nodal speed at time *t*, the time average of nodal speed $\overline{V}$ is

[7] Ref.[22] gives a detailed discussion on the underlying rationale for those assumptions to isolate the key reason for this behavior. The study shows that the conclusion still holds for the original Random Waypoint model.

$$\overline{V} = \lim_{T\to\infty}\frac{1}{T}\int_0^T v(t)dt = \frac{\lim_{N\to\infty}\frac{1}{N}\sum_{i=1}^{N} L_i}{\lim_{N\to\infty}\frac{1}{N}\sum_{i=1}^{N} S_i} = \frac{E[L]}{E[S]} = \frac{V_{\max} - V_{\min}}{\ln(\frac{V_{\max}}{V_{\min}})} \quad (31)$$

Obviously, as $V_{\min} \to 0$, the expected travel time $E[S] \to \infty$, and the time average speed $\overline{V} \to 0$. That is to say, as the minimum allowed velocity $V_{\min}$ approaches zero, the expected travel time approaches to infinity. Consequently, the average nodal speed $\overline{V}$ approaches to zero as well.

Realizing the zero minimum speed is the key reason of non-steady state problem, Yoon, Liu and Noble[22] propose to limit the minimum speed of Random Waypoint model, in order to achieve the steady state. Through comparing the simple improved Random Waypoint model with the original one, they observe that the modified version significantly improves the stability of Random Waypoint model.

Later in a recent work[23], Yoon, Liu and Noble claim that the speed decay problem is not an exclusive problem to Random Waypoint model. It seems to exist for all random mobility models that independently choose the destination and movement speed. However, if the speed for the initial trip is selected from a steady state distribution and the subsequent speeds are chosen from the original speed distribution, the speed decay problem can be completely removed. Thus, a stationary random mobility process could be generated for the simulations. Lin, Noubir and Rajaraman[24] apply the renewal theory to Random Waypoint model and also confirm the observations about the speed decay problem made in Ref.[22].

7. CONCLUSION AND DISCUSSION

By studying various mobility models, we attempt to conduct a survey of the mobility modeling and analysis techniques in a thorough and systematic manner. Beside the Random Waypoint model and its variants, many other mobility models with unique characteristics such as temporal dependency, spatial dependency or geographic restriction are discussed and studied in this chapter. We believe that the set of mobility models included herein reasonably reflect the state-of-art researches and technologies in this field.

Table 1-1. The characteristics of mobility models used in IMPORTANT framework

	Temporal Dependency	Spatial Dependency	Geographic Restriction
Random Waypoint Model	No	No	No
Reference Point Group Model	No	Yes	No
Freeway Mobility Model	Yes	Yes	Yes
Manhattan Mobility Model	Yes	No	Yes

Having examined those mobility models, we observe that the mobility models may have various properties and exhibit different mobility characteristics. As a consequence, we expected that those mobility models behave differently and influence the protocol performance in different ways. Therefore, to thoroughly evaluate ad hoc protocol performance, it is imperative to use a rich set of mobility models instead of single Random Waypoint model. Each model in the set has its own unique and specific mobility characteristics. Hence, a method to choose a suitable set of mobility models is needed.

In the next chapter, we propose a framework for analyzing the Impact of Mobility on the Performance Of RouTing protocols in Adhoc NeTworks (IMPORTANT). In this framework, the mobility space is viewed as a multi-dimensional space, where each dimension represents a specific and unique mobility characteristic. By properly choosing mobility models with different characteristics, we are able to produce set of various mobility scenarios spanning the mobility space. We list the set of mobility models used in the IMPORTANT framework and their characteristics in Table 1-1.

Moreover, in the next chapter we illustrate, through experimentation, how the mobility can significantly affect the protocol performance. Finally we develop a deeper insight into the interaction between protocol mechanisms and mobility.

8. ACKNOWLEDGEMENT

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