Moving Towards Reality

A Survey of Mobility Model

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Abstract

Nowadays, there is tremendous research work about Ad Hoc networks, in which many efforts focus on the performance analysis and protocol behavior design. The selection of the most realistic and the most easy-to-implement mobility model is very crucial for the validity and feasibility of research. 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. What's more, we also choose a specific simulation area which treat SJTU campus as a whole and combine different mobility models to simulate the SJTU campus under different circumstances.

1. INTRODUCTION

Ad hoc wireless networks are networks which do not rely on a pre-existing communication infrastructure. Rather, they maintain a dynamic interconnection topology between mobile users, often via multihoping. Ad hoc networks are expected to play an increasingly important role in future civilian and military settings where wireless access to a wired backbone is either ineffective or impossible. Ad hoc network applications range from collaborative, distributed mobile computing to disaster recovery, law enforcement and digital battle field communications. Some key characteristics of these systems are team collaboration of large number of mobile units, limited bandwidth, the need for supporting multimedia real time traffic and low latency access to distributed resources.

The host in an ad hoc network move according to various patterns. Realistic models for the motion patterns are needed in simulation in order to evaluate system and protocol performance. Most of the earlier research on mobility patterns was based on cellular networks. Mobility patterns have been used to derive traffic and mobility prediction models in the study of various problems in cellular systems, such as handoff, location management, paging, registration, calling time, traffic load. Recently, mobility models have been explored also in ad hoc networks. While in cellular networks, mobility models are mainly focused on individual movements since communications are point to point rather than among groups; in ad hoc networks, communications are often among teams which tend to coordinate their movements. Hence, the need arises for developing efficient and realistic group mobility models.

Clearly, mobility models are application dependent. Moreover, we expect that the various mobility patterns will affect the performance of different network protocols in different ways. Thus, we are developing a flexible mobility framework which allows us to model different applications and network scenarios and to identify the impact of mobility on different scenarios.

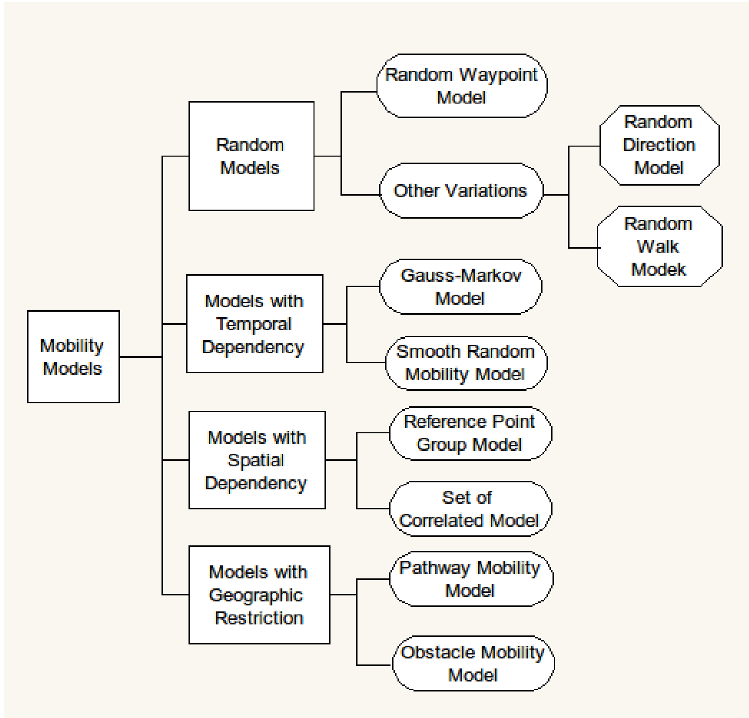

Figure 1: The categories of mobility models in Mobile Ad hoc Network

In Figure1 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.

2. RANDOM MODELS

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

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].

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 noded[6]. The velocity and direction of a node

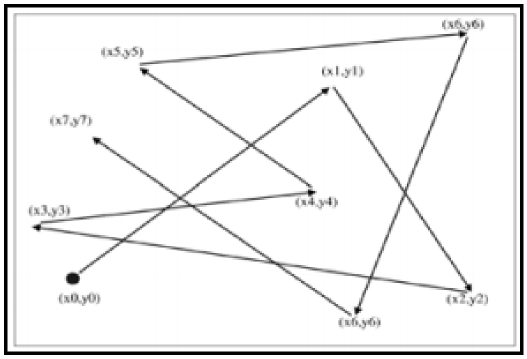

Figure 2: Example of node movement in the Random Waypoint Model

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 choosed 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 and the pause time is small, the topology is expected to be highly dynamic. 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 $T_{pause} = 0$, consider that velocity is uniformly and randomly chosen from $[0, V_{max}]$, we can easily find that the average nodal speed is $0.5V_{max}$. 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 Hedmanental. in Ref.[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

$$RS(i,j,t) = |\overrightarrow{V_i(t)} - \overrightarrow{V_j(t)}| \tag{1}$$

Then, the Mobility metric 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

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

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], the author 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 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.

The transition length L is defined as the distance that the node j moves from one waypoint to another during the ith epoch.

For a discrete time stochastic process[8],the transition length $L_i^{(j)}$ is defined as the distance that the node j moves from one waypoint to another during the ith epoch. Thus, the expected value of transition length L is

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

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

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 as follows.

(a) If the simulation field is a rectangular area with length a and width b. Without losing the generality, we assume that $b \leq a$. The probability density function of transition length L is

$$f_L(l) = \frac{4l}{a^2b^2} f_0(l) \tag{3}$$

with

$$f_0(l) = \begin{cases} \frac{\pi}{2}ab - al - bl + \frac{1}{2}l^2, & \text{for } 0 \leq l \leq b \\ absin^{-1}\frac{1}{b} + a\sqrt{l^2 - b^2 - \frac{1}{2}b^2 - al}, & \text{for } b < l \leq a \\ -abcos^{-1}\frac{a}{l} + b\sqrt{l^2 - a^2 - \frac{1}{2}a^2 - \frac{1}{2}l^2}, & \text{for } a < l \leq \sqrt{a^2+b^2} \\ 0, & \text{otherwise} \end{cases}$$

Correspondingly, the expected value of transition length L is

$$E[L] = \frac{1}{15}[\frac{a^3}{b^2} + \sqrt{a^2+b^2}(3 - \frac{b^2}{a^2} - \frac{b^2}{a^2})] + \frac{1}{6}[\frac{b^2}{a}cos^{-1}\frac{\sqrt{a^2+b^2}}{b} + \frac{a^2}{b}cos^{-1}\frac{\sqrt{a^2+b^2}}{a}] \tag{4}$$

and the variance of transition length L is

$$E[L^2] = \frac{1}{6}(a^2+b^2) \tag{5}$$

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

$$E[L] = \int_0^{2a} l f_L(l) dl = 0.905a \quad (6)$$

and the variance of transition length L is

$$E[L^2] = \int_0^{2a} l^2 f_L(l) dl = a^2 \quad (7)$$

(c) The authors of [8] also take a further step to derive the probability distribution of transition time as follow

$$f_T(t) = \int_{V_{min}}^{V_{max}} v f_L(vt) f_V(v) dv \quad (8)$$

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 the equation above, we are able to get the distribution function of transition time.

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 leacing 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 no the case of mobile nodes in many real life applications, as discussed later.

2.4 Random Direction Model

Ref.[11]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, teh 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 Way point model called *density wave* phenomenon (i.e., the average number of neighbors for a particular node periodically fluctuates along with time) is observed.

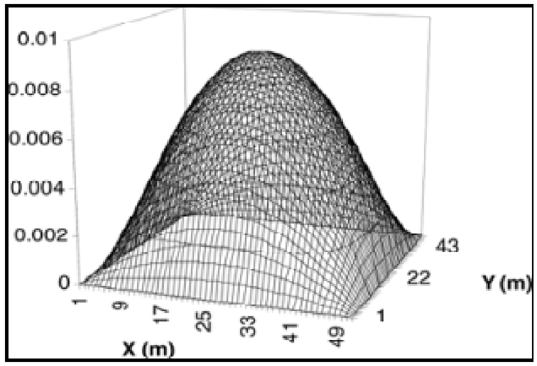

Figure 3: Node Spatial Distribution (Sqare Area)

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 the 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.

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

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

for $x \in [-a/2, a/2]$ and $y \in [-a/2, a/2]$. As is shown in the previous figure. 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. When the position is away from the center, the spatial node density decreases as well.

(b) **Circular area:**
For a circular area with radius a, the analytical expression is

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

for $0 \le r \le a$. As shown in the following figure, 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.

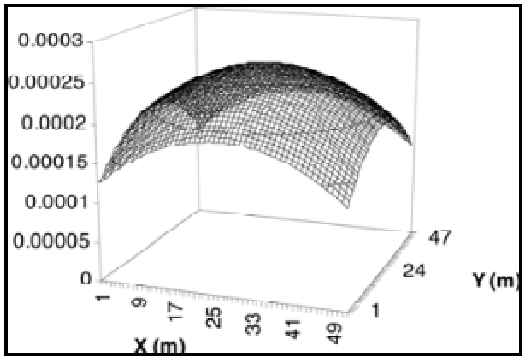

Figure 4: Node Spatial Distribution (Circular Area)

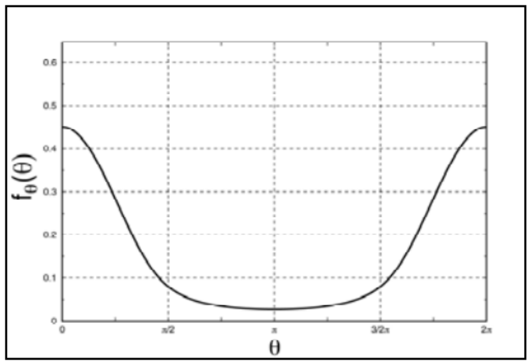

Figure 5: The probability distribution of movement direction

To explain such phenomenon, in a recently published work[8], the authors 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

$$f_\theta = \int_0^{2\pi} \int_0^a f_\theta(\theta|r) \frac{1}{\pi a^2} r dr d\varphi \tag{9}$$

$$= \frac{1}{4pi|sin^3(\theta)|} \{|sin(\theta)|[-2cos^4(\theta) - 2cos^3(\theta)|cos(\theta)| + cos^2(\theta) + cos(\theta)|cos(\theta)| + 1] + sin^{-1}(|sin(\theta)|cos(\theta)|)\} \tag{10}$$

According to this equation, we could see that the probability of taking a direction towards the boundary (within the interval $[\pi/2, 3\pi/2]$) is only 12.5%. However, the node moves toward the center region of area with probability 61.4%. The following figure illustrates the probability distribution of movement angle.
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 Ref.[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 the node density than the Random Waypoint model.

2.5 Drawbacks 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:

- **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.

- **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.

- **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.

3. 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 are proposed. In section 2.1 and 2.1, 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 can be represented by the following equations:

$$\overline{V}_t = \overline{\alpha} \cdot \overline{V}_{t-1} + (1-\overline{\alpha}) \cdot \overline{v} + \overline{\sigma} \cdot \sqrt{1-\overline{\alpha}^2} \cdot \overline{W}_{t-1} \tag{11}$$

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 zero mean and variance σ^2, $\overline{\alpha} = [\alpha^x, \alpha^y]^T$, $\overline{v} = [v^x, v^y]^T$ 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 in two-dimensional field as follows:

$$\begin{aligned} v_t^x &= \alpha v_{t-1}^x + (1-\alpha) v^x + \sigma^x \sqrt{1-\alpha^2} w_{t-1}^x \\ v_t^x &= \alpha v_{t-1}^y + (1-\alpha) v^y + \sigma^y \sqrt{1-\alpha^2} w_{t-1}^y \end{aligned}$$

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:

- If the Gauss-Markov Model is memoryless, i.e.,$\alpha = 0$. The above equation is

  $$\begin{aligned} v_t^x &= v^x + \sigma^x w_{t-1}^x \\ v_t^y &= v^y + \sigma^y w_{t-1}^y \end{aligned}$$

  where the velocity of mobile node at time slot t is only determined by the fixed drift velocity $\overline{\nu} = [\nu^x, \nu^y]^T$ and the Gaussian random variable $\overline{W}_{t-1} = [w_{t-1}^x, w_{t-1}^y]^T$. Obviously, the model described in this case is the Random Walk model.
- If the Gauss-Markov Model has strong memory, i.e., $\alpha = 1$. The eqution is

  $$\begin{aligned} v_t^x &= v_{t-1}^x \\ v_t^y &= v_{t-1}^y \end{aligned}$$

  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.
- If the Gauss-Markov Model has some memory, i.e., $0 < \alpha < 1$. Thevelocity 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 2.2, 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.

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 $\{V_{pref}^1, V_{pref}^2, ..., V_{pref}^n\}$, 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

$$Pr_V(v) = \begin{cases} Pr(v=0)\delta(v), & \text{for } v = 0 \\ Pr(v = 0.5V_{max}\delta(v - 0.5V_{max})), & \text{for } v = 0.5V_{max} \\ Pr(v = V_{max}\delta(v - V_{max})), & \text{for } v = V_{max} \\ \dfrac{1 - Pr(v=0) - Pr(v = 0.5V_{max} - Pr(v = V_{max}))}{V_{max}}, & \text{otherwise} \end{cases}$$

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 the above equation. 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

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

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

$$v(t) = v(t - \triangle t) + a(t)\triangle t \tag{12}$$

Thus, the speed may be controlled to increase or decrease continuously and incrementally. If a(t) is 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

$$Pr_{\Phi}(\Phi) = \frac{1}{2\pi} \quad for 0 \leq \Phi < 2\pi \tag{13}$$

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. When the direction is about to change, the new movement direction is also selected according to the probability distribution function. The direction difference $\triangle\phi(t)$ is the subtraction between the new direction and the old diraction.

Since the value of direction change $\triangle\phi(t)$ 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$\triangle\phi(t)$ 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.

3.3 Discussion

For the Gauss-Markov model, the velocity of a mobile node at any time slot is a function of its previous velocity. The degree of temporal dependency is determined by the memory level parameter α.In the Smooth Random Mobility Model, 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 $\triangle\varphi(t)$.

By adjusting these parameters, we are able to generate various mobility scenarios with different degrees of temporal dependency.

4. 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. Then 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.

4.1 Reference Point Group Mobility Model(RPGM)

In line with the observation that the mobile nodes in MANET tend to coordinate their movement, the RPGM is proposed in Ref.[16]. One example of such mobility is that a number of soldiers may move together in a group of platoon. Another example is during disaster relief where various rescue crews 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

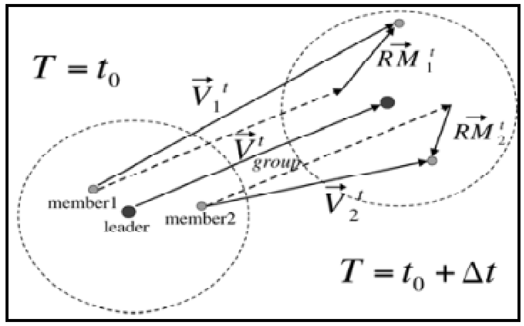

Figure 6: An example of node movement in Reference Point Group Mobility Model, providing two snapshots at time $T = t_0$ (left circle) and time $T = t_0 + \Delta t$ (right circle)

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.

- **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.

- **The Group Member:** 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 node could be randomly placed in the neighborhood. Formally, the motion vector of group member i at time t, $\vec{V}^{t}_{i}$, can be described as

$$\vec{V}^{i}_{i} = \vec{V}^{t}_{group} + \vec{R}\vec{M}^{t}_{i} \tag{14}$$

  where the motion vector $\vec{R}\vec{M}^{t}_{i}$ is a random vector deviated by group member i from its own reference point. The vector $\vec{R}\vec{M}^{t}_{i}$ is an 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 $[0, 2\pi)$.

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, Ref.[16] illustrate that the RPGM model is able to represent various mobility scenarios including

- **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.
- **Overlap Mobility Model:** Different groups with different tasks travel on the same field in an overlapping manner. Disaster relief is a good example.
- **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.

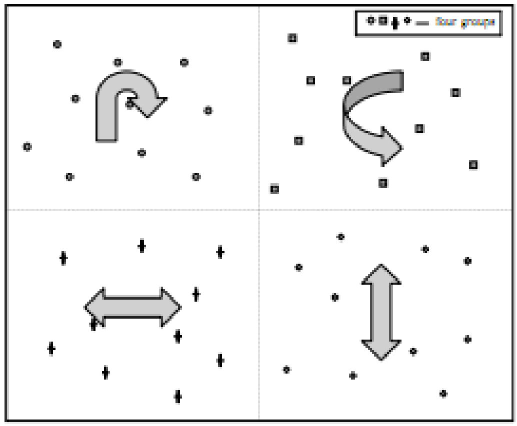

Figure 7: In-Place Mobility Model

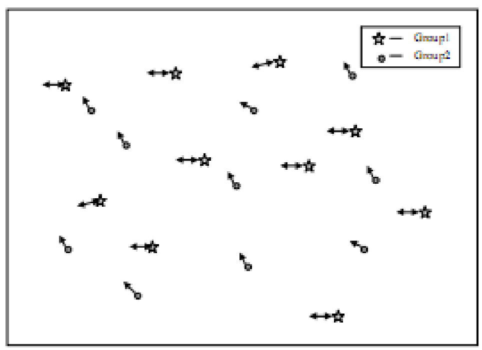

Figure 8: Overlap Mobility Model

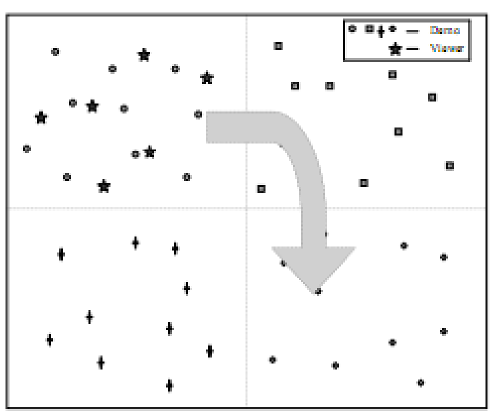

Figure 9: Convention Mobility Model

4.2 A Set of Spatially Correlated Models

Ref.[18] proposes 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.

- **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 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,

  $$RP_i^t = RP_i^{t-1} + \alpha_i^t \tag{15}$$

  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,

  $$P_i^t = RP_i^t + w_i^t \tag{16}$$

  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.

- **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

  $$P_i^t = P_i^{t-1} + v_i^t(P_{target}^t - P_i^{t-1}) + w_i^t \tag{17}$$

  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.

- **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,

  $$P_i^t = RP_i^t + w_i^t \tag{18}$$

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.

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 checkpoint are chosen in advance.

5. MOBILITY MODELS WITH GEOGRAPHIC OBSTACLES

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 pedestrian 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.

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. Ref[9] 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 model[1], the movement of mobile node is also restricted to the pathway in the simulation field. The following figure illustrates

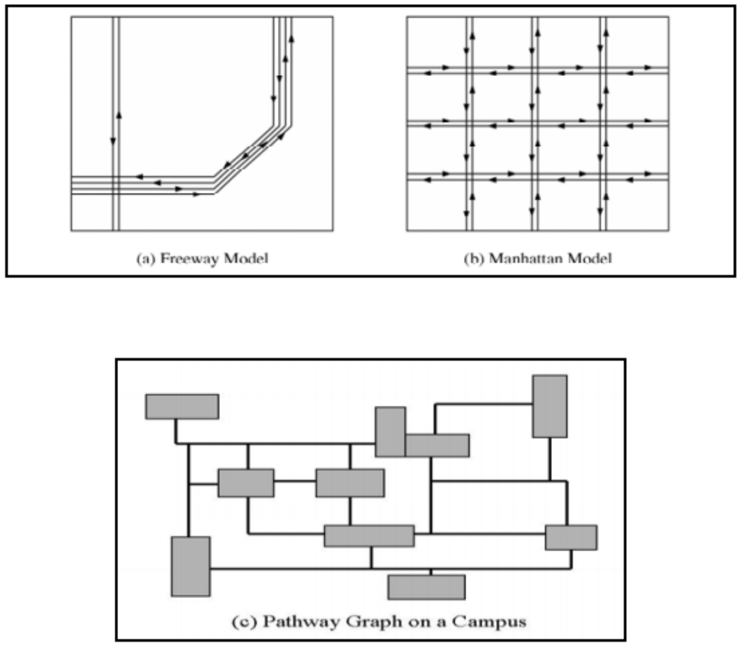

Figure 10: The pathway graphs used in the Freeway, Manhattan and Pathway Model

the maps used for Freeway, Manhattan and Pathway models.

5.2 Obstacle Mobility Model

Another geographic constraint playing an important role in mobility modeling includes the obstacle 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.

Ref.[7] develops 3 'realistic' mobility scenarios to depict the movement of mobile users in real life, including

- **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.
- **Event Coverage scenario** where a group of highly mobile people or vehicles are modeled. Those mobile nodes are frequently changing their positions.
- **Disaster Relief scenarios** where some nodes move very fast and others move very slow.

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.

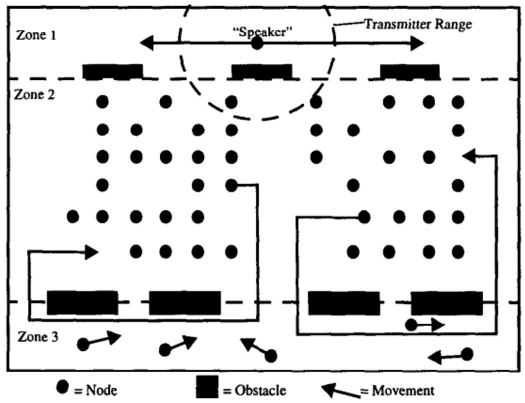

Figure 11: Conference Scenario

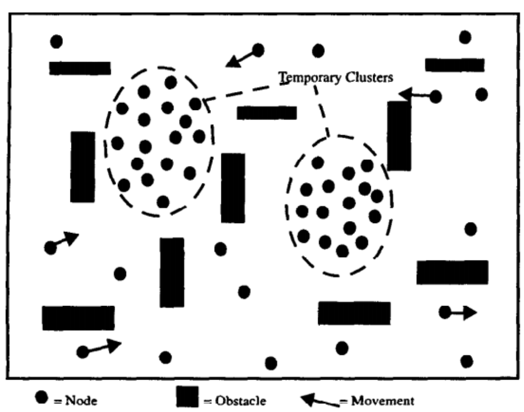

Figure 12: Event Coverage scenario

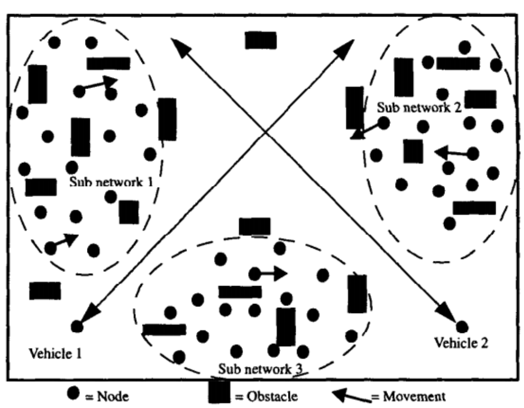

Figure 13: Disaster Relief scenarios

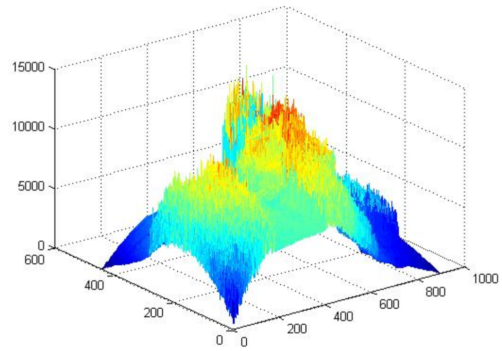

Figure 14: Everyday Scenario of SJTU campus

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 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 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 confiend 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.

6. SIMULATION

In the previous content, we do a overview of various mobility models; however, a survey only can not be a qualified report. So, next we will tell you something interesting and fascinating, with our great creativity and dedication to the simulation of a very special kind of mobility model. It is a combination of random way point model and geographical restriction model, mainly focused on random way point model and have some unique features. We are proud to tell you that It may be the world first mobility model optimized for and specialized for part of the SJTU campus.

Here are some highlight features of the mobility model.

Firstly, as we can see from the previous graph, the SJTU campus is divided into several areas. Every area stands for a place that the students(the Mobile Node) are likely to go in their daily lives, such as the dormitory, D-, E-, F- building, canteens, and so on. The nodes move under the restriction of the building locations and roads distributions. That means, the nodes can only move along the roads and cannot go straight to one place to another like a bird. And after a node reaches the boundary of the area, it will randomly choose a place and head there with a random speed. Thus, we cold see that they are very smart nodes, just like sjtu students.

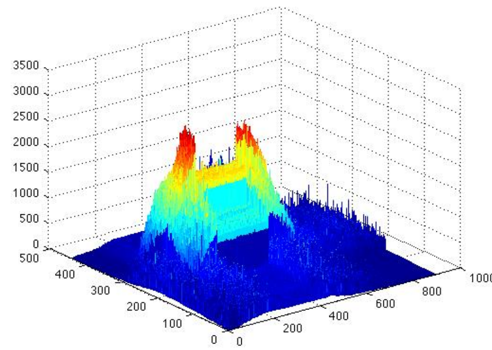

Figure 15: SJTU campus at lunchtime

Secondly, the nodes will adjust their speed according to the distance they will move. If the distance exceeds a limit, such as the students want to go from SEIEE building to the Upper Building, they have a higher probability to go by bike. On the contrary, if the students just leave our dormitory for lunch, they are much more likely to go to the canteen on foot. It's a design on a human scale.

Thirdly, the time of a node staying in one place depends on where it is located. The time students play basketball might range from 30min to 2 hours randomly and we assume it distributes uniformly. However, the time we stay in library may span 2 to 5 hours or even more if we have dinner in Family Mart, a famous place for fast food. That means, in our model, T_{pause} is adjustable according to the region.

Finally, we also consider the time effect. During bed time, most students stay in their dormitory while during the lunch time, most students go to the canteen. However, there are exceptions; Maybe a few girls who are on diet may not, or lazy boys go to the dormitory watching NBA and call a takeout from some restaurants. Our time monitor system tells us where people are most likely to go in every time slot.

Based on these assumptions, our results of probability density of the students in SJTU are $Figure 14$ which is a everyday scenario and $Figure 15$, simulation of lunchtime. $Figure 14$ an overall time distribution of all nodes. We can see that most students are located in the center part of SJTU campus, very similar to the pure random way point model. But, the difference is that in some areas, such as the New Libaray, D- E- F- building, Upper-, Middle- and Lower-Building, dormitories, the probation is higher than other regions, such as the basketball court and the Business Street. $Figure 15$ is another result during the lunch time, As we only arranges two canteens in the map, First Canteen and Second Canteen; so most nodes are located in the two areas and on the path which connect them.

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. Besides the Random Waypoint model and its variants, many other mobility models with unique characteristics such as temporal dependency, spatial dependency are discussed and studied in this survey.

	Temporal Dependency	Spatial Dependency	Geographic Restriction
Random Waypoint Model	$\times$	$\times$	$\times$
Reference Point Group Model	$\times$	$\surd$	$\times$
Freeway Mobility Model	$\surd$	$\surd$	$\surd$
Manhattan Mobility Model	$\surd$	$\times$	$\surd$

Also, we build a specific mobility model of SJTU campus and come to very amazing simulation results.

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Appendices

Group Members and Contributions

- Liushu
  - Search for information and papers online;
  - Establish report framework
  - Complete Part1 and 2 in Survey.
- Zhang Li
  - Complete Simulation part;
  - Read papers
  - Organize group discussion and presentation rehearsal;
- Zhu Zhengyuan
  1. Complete Part3 and 4 in Survey
  2. Read papers.
  3. Make the Presentation Beamer

Figure 16: Liu Shu

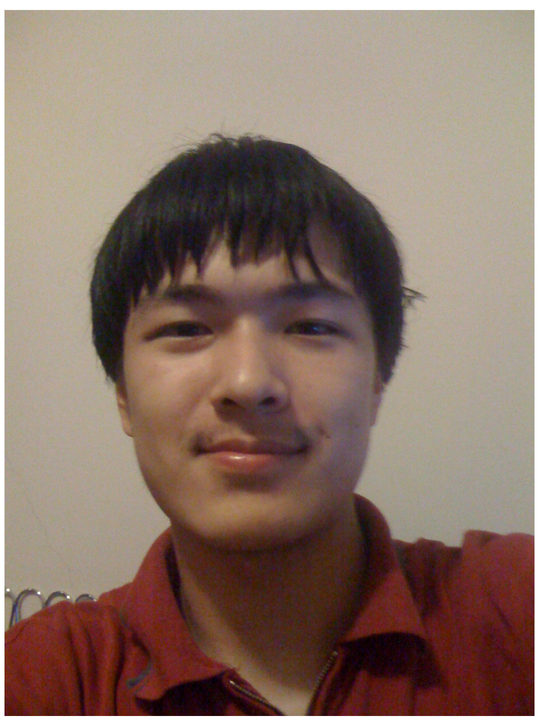

Figure 17: Zhang Li

Figure 18: Zhu Zhengyuan