Design and Applications of A Smooth Mobility Model for Mobile Ad Hoc Networks

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***Abstract*— Existing mobility models used in the simulation tools have two major limitations. First, these models invoke unrealistic moving behaviors, such as sudden stop and sharp turn during the simulation. Hence, the study of mobile ad-hoc networks (MANETs) based on these models could lead to wrong conclusions. Second, because the node speed and direction do not change within each movement, they are insufficient to mimic the minute moving behaviors of mobile users. Therefore, we *design* a novel *smooth* mobility model, which can characterize the real-life moving behaviors of mobile users in accordance with the physical law of a smooth motion. Moreover, we *apply* the *smooth* model to evaluate the routing performance and network connectivity of MANETs. Compared with the most commonly used mobility model, random waypoint (RWP) model, we find that the routing performance and network connectivity evaluation based on the RWP model is over optimistic. To demonstrate the applications of the *smooth* model, we present the easy adaptation of the *smooth* model to group mobility and geographic restrictions.**

I. Introduction

A mobile ad hoc network (MANET) is an infrastructure-less wireless network, which can be deployed in various scenarios to support rich applications having complex node mobility and network environments. Since node mobility may induce network topology to change randomly and rapidly at unpredictable times, it has a significant effect on network performance. Thus, the knowledge of node mobility and its effect on MANETs is essential to all kinds of applications to achieve their full potential. The real traces from an existing mobile system can provide accurate and realistic information of node mobility. However, there exists no theoretical mobility models based on these real trace files for the study of MANETs [1], [2]. Therefore, mobility models are designed to describe different types of user moving behaviors for a variety of applications and network scenarios. Because of this, mobility modeling is an essential means in analytical and simulation-based studies of MANETs, and it is critical to the research areas such as routing protocol design, path duration analysis, topology control, and location and mobility management.

However, almost all mobility models used in current simulation tools, such as ns-2, are not realistic [3]. Because these models describe completely uncorrelated mobility, the unrealistic moving behaviors, such as sudden stop, sudden acceleration, and sharp turn frequently occur during the simulation [1]. These abrupt speed and direction change events strongly influence the network topology change rate, which further significantly affects the routing performance of the network. Therefore, the simulation results and theoretical derivations based on current mobility models may not correctly indicate the real-life network performance and effects of system parameters.

On the other hand, in order to support a wide variety of application scenarios, a desired mobility model should be flexible to serve for different types of user mobility within different network environments. For instance, it is expected to describe individual nodal movements with diverse moving trajectories including straight lines or curves; short or long trips; and constant or varying speed. Besides, in many applications, a group of users move together to accomplish a mission. For example, soldiers always move in a tactical group manner for pursuing enemies and attacking their targets in a battlefield. Moreover, MANET applications are often restricted by the network environments. For instance, vehicles traveling in a city can only move along the streets at a specified speed limit. Therefore, a desired mobility model should also be flexibly adapted to group mobility and geographic constraints.

On the objective to acquire correct performance evaluation and parameter analysis for MANETs, a mobility model based on reality is necessary. Since all the real-life user moving behaviors are restricted by the *physical law of motion*, a realistic model should also abide by this physical law. According to the fundamental physical law of a smooth motion, an moving object would experience *speed acceleration*, *stable speed*, and *speed deceleration* during a movement. This implies that a smooth movement should contain multiple moving stages, and a temporal correlation exists during the speed transition. Furthermore, a realistic model should take the correlation of speed and direction change into account. In addition, the spatial correlation of velocity among mobile nodes are needed to simulate group mobility. Regarding to different geographic constraints, such as streets and obstacles, a realistic model should allow mobile nodes to select and change pathways and speeds during the travel.

In this paper, we *design* a novel mobility model, namely *smooth* model, which includes three consecutive phases: *Speed Up* phase, *Middle Smooth* phase, and *Slow Down* phase. Since the model abides by the physical law of a smooth motion, it can provide more accurate system evaluation and analysis for MAENTs. Thus, we *apply* the smooth model to estimate the routing performance of the AODV protocol [4] including: average end-to-end packet delay, network throughput, and routing overhead. Also, we *apply* the smooth model to study the network connectivity regarding to the average node degree and the distribution of relative speed and link lifetime between neighboring nodes. By comparing these simulation results with the most commonly used mobility model for MANETs, *random waypoint* (*RWP*) model [5], we find that both the routing performance and network connectivity evaluation based on the RWP model is over optimistic. In order to support rich applications and different network scenarios, we demonstrate how to apply the smooth model to simulate group mobility and nodal movements in a Manhattan-like city map.

The remainder of the paper is organized as follows: Section II briefly discusses the related work of mobility models applied to MANETs. Section III describes the mobility pattern and demonstrates the nice properties of the smooth model. Section IV presents the multiple applications of the smooth model according to system evaluation and the adaptation to group mobility and geographical constraints. Finally, the paper is concluded in Section V.

II. Related Work

Random mobility models, in which each node moves without any constraints on its velocity, are most widely used in current research for MANETs [1]. Typical random mobility models include *random walk* (*RW*) model [6], *Random Waypoint* (*RWP*) model [5], *random direction* (*RD*) model [7], and *Random Trip* (*RT*) model [8] as well as their variants. Because nodal movements in random mobility models are total randomness, the unrealistic moving behaviors are invoked and could cause invalidate or wrong conclusions on the network evaluations [9]. Moreover, random mobility models are insufficient to mimic the minute moving behaviors of mobile users, such as speed acceleration and direction change within each movement. However, in reality, pedestrians or soldiers are very often change their speeds and directions during a movement.

Temporal mobility models that consider the temporal correlation of node's moving behavior [1] can provide smooth movements by avoiding the unrealistic behaviors, such as *Smooth Random* (*SR*) model [9] and *Gauss-Markov* (*GM*) model [10]. However, these two models also have their application limitations. In the SR model, a node moves at a constant speed along a specific direction until either a speed or direction change event occurs according to independent Poisson process, whereas in real life, the speed and direction change are *correlated*. For example, vehicles typically slow down their speed when making a smooth turn. Moreover, an SR movement does not stop unless the zero speed is the next targeting speed based on Poisson process. Hence, the movement duration of SR nodes cannot be controlled. In the GM model, the velocity of a mobile node at any time slot is a function of its previous velocity with a Gaussian random variable. GM nodes cannot stop and can hardly travel along a straight line [6]. However, in reality, mobile users always move in an intermittent way with a random pause time, and cars usually move along a straight line for a period of time.

III. Design of Smooth Mobility Model

In this section, we describe the microscopic mobility patterns defined in a novel *smooth* mobility model. Then, we demonstrate the nice properties of this model.

A. Model Description

Throughout this paper, we define one *movement* as an entire motion from the time that a node starts to travel to the time that the node first stops moving. Based on the physical law of a smooth motion, a movement in the smooth model contains three consecutive moving phases: Speed Up phase, Middle Smooth phase, and Slow Down phase. After each movement, a node may stay for a random pause time T_p. Each movement is quantized into $\mathcal{K}$ equidistant time steps, where $\mathcal{K} \in \mathbb{Z}$. The time interval between two consecutive time steps is denoted as Δt (sec). Since Δt is a constant unit time, for a simple representation, Δt is normalized to 1 in the rest of the paper.

1) Speed Up Phase (α–Phase): For every movement, an object needs to accelerate its speed before reaching a stable speed. Thus, the first phase of a movement is called *speed up* (α–phase), which lasts over time interval $[t_0, t_\alpha] = [t_0, t_0 + \alpha\Delta t]$. At initial time t_0 of a movement, the node randomly selects a *target speed* $v_\alpha \in [v_{\min}, v_{\max}]$, a *target direction* $\phi_\alpha \in [0, 2\pi]$, and the total number of *time steps* $\alpha \in [\alpha_{min}, \alpha_{\max}]$. These three random variables are independently uniformly distributed. In reality, an object typically accelerates the speed along a straight line. Thus, the direction ϕ_α does not change during this phase. To avoid sudden speed change, the node will evenly accelerate its speed along direction ϕ_α from starting speed $v(t_0) = 0$, to the target speed v_α, which is the ending speed of α–phase, i.e., $v(t_\alpha) = v_\alpha$. An example of speed change in α–phase is shown in Fig. 1, where the node speed increases evenly step by step and reaches the stable speed v_α of the movement by the end of this phase.

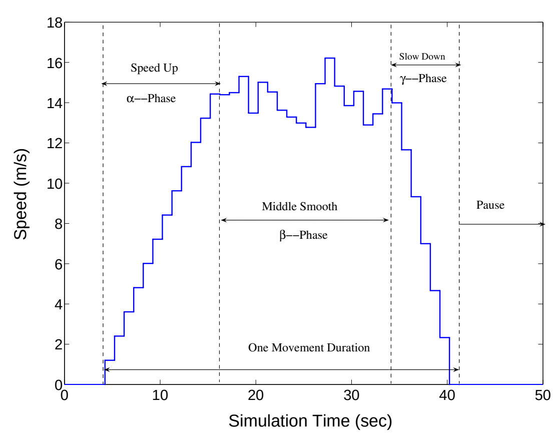


Fig. 1. An Example of Speed Transition in One Smooth Movement.

2) Middle Smooth Phase (β–Phase): In reality, after the speed acceleration, a moving object has a smooth motion according to its stable velocity. Correspondingly, once the node transits into β–phase at time t_α, it randomly selects β time steps, so that β–phase lasts over time interval: $(t_\alpha, t_\beta] = (t_\alpha, t_\alpha + \beta\Delta t]$. Where β is uniformly distributed over $[\beta_{min}, \beta_{\max}]$. Within the *middle smooth* (β–phase), the mobility pattern at each time step is similar to what is defined in GM model [10]. In detail, the initial value of speed v_0 and direction ϕ_0 in β phase are v_α and ϕ_α, respectively. Then, the following speed and direction of a smooth node at each time step fluctuate with respect to v_α and ϕ_α. Hence, we respectively substitute v_α for $\overline{V}$ and ϕ_α for $\overline{\phi}$, where $\overline{V}$ and $\overline{\phi}$ denote the asymptotic mean value of speed and direction, represented in equation (4) in [10]. The standard deviation σ_v and σ_ϕ are set as 1. This implies that the speed or direction difference between two consecutive time steps are less than 1 m/s or 1 rad within β–phase. We further assume that the memory level parameter $\zeta \in [0,1]$, used for adjusting the temporal correlation of node velocity, is constant for both speed and direction at each time step. Specifically, the speed and direction at the j^{th} time step for the node in β–phase are:

$$\begin{aligned} v_j &= \zeta v_{j-1} + (1-\zeta)v_\alpha + \sqrt{1-\zeta^2}\widetilde{V}_{j-1} \\ &= \zeta^j v_0 + (1-\zeta^j)v_\alpha + \sqrt{1-\zeta^2}\sum_{m=0}^{j-1}\zeta^{j-m-1}\widetilde{V}_m \\ &= v_\alpha + \sqrt{1-\zeta^2}\sum_{m=0}^{j-1}\zeta^{j-m-1}\widetilde{V}_m, \end{aligned} \quad (1)$$

and

$$\begin{aligned} \phi_j &= \zeta\phi_{j-1} + (1-\zeta)\phi_\alpha + \sqrt{1-\zeta^2}\widetilde{\phi}_{j-1} \\ &= \phi_\alpha + \sqrt{1-\zeta^2}\sum_{m=0}^{j-1}\zeta^{j-m-1}\widetilde{\phi}_m, \end{aligned} \quad (2)$$

where $\widetilde{V}_j$ and $\widetilde{\phi}_j$ are Gaussian random variables with zero mean and unit variance. As shown in Fig. 1, the node speed gently fluctuates around the target speed v_α within β–phase.

3) Slow Down Phase (γ–Phase): In real-life, every moving object needs to reduce its speed to zero before a full stop. Hence, to avoid the sudden stop event, the node experiences a *slow down* (γ–phase) to end one movement in the smooth model. In detail, once the node transits into γ–phase at time t_β, it randomly selects γ time steps and a direction $\phi_\gamma \in [0, 2\pi]$. Where γ is uniformly distributed over $[\gamma_{min}, \gamma_{\max}]$. In γ–phase, the node evenly decelerates its speed from v_β, the ending speed of β–phase, to $v_\gamma = 0$ during γ time steps. Fig. 1 shows the exact case of speed change in γ–phase. In reality, a moving object typically decelerates the speed along a straight line before a full stop. Thus, the direction ϕ_γ does not change during the γ–phase. Furthermore, in order to avoid the sharp turn event happening during the phase transition, ϕ_γ and ϕ_β are correlated. Specifically, ϕ_γ is obtained from (2), by substituting β for $j-1$. At the phase ending time $t_\gamma = t_\beta + \gamma\Delta t$, the node fully stops and finishes the current movement which lasts over time interval $[t_0, t_\gamma]$.

B. *Properties of Smooth Mobility Model*

To properly apply the smooth model for different kinds of study of MANETs, it is essential to deep understand the properties of the model. Next, we demonstrate the nice properties of the smooth model in terms of *smooth movement*, *stable average speed*, and *uniform node distribution* in sequence.

1) Smooth Movement: In the smooth model, we define the *distance* as the Euclidean distance between the current position and the starting position during one movement; and the *trace length* as the length of actual trajectory a node travels during one movement. Different from all random mobility models, because direction changes during one movement, the distance is no longer than the trace length. By observing distance evolution during one movement, people can indirectly tell the moving trajectory. Specifically, if the distance increases monotonously, it implies that the node travels forward with a smooth trace. In contrast, if the distance decreases at some time, it means that the node turns backward during the movement, that is, a sharp turn event occurs.

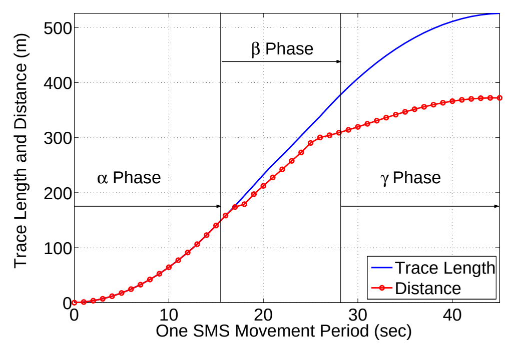


Fig. 2. Distance and Trace Length.

The simulation results of both *trace length* and *distance* evolution during one movement are shown in Fig. 2. We can see that both trace length and distance increase exponentially in α–phase as well γ–phase, because of the speed acceleration and deceleration, respectively. Furthermore, in α–phase, the trace length is equivalent to the distance, due to the constant direction ϕ_α in α–phase. In β–phase, the trace length increases linearly, whereas the uptrend of the distance fluctuates because of the change of direction at every time step. Since direction ϕ_γ dose not vary in γ–phase, both the trace length and the distance within γ–phase increase. And the difference between ϕ_α and ϕ_γ directly determines the difference between the trace length and distance in γ–phase. From Fig. 2, the distance monotonously increases during the entire movement period. Therefore, we conclude that *the mobility trace in smooth model is smooth without sharp turns.*

2) Stable Average Speed: According to the technique conclusion of the *sound* mobility model [11]: If the speed is independent of the travel time for every movement, the model will generate stable nodal movements without the average speed decay problem. Since the step speed and phase time are selected independently for each node in smooth model, the smooth model also has no average speed decay problem, which is a well-known problem of the RWP model [3]. Let $E\{v_{ini}\}$ denote the initial average speed and $E\{v_{ss}\}$ represent the average steady-state speed of the smooth model. We proved that *the smooth model always generates a stable nodal movement for an arbitrary targeting speed* in [12], given by:

$$E\{v_{ini}\} = E\{v_{ss}\} = \frac{\frac{1}{2}E\{v_\alpha\}(E\{\alpha\} + 2E\{\beta\} + E\{\gamma\})}{E\{T\} + E\{T_p\}}, \quad (3)$$

where $E\{T\}$ denotes the expected movement duration, such that $E\{T\} = E\{\alpha\} + E\{\beta\} + E\{\gamma\}$, and $E\{T_p\}$ represents the expected pause time.

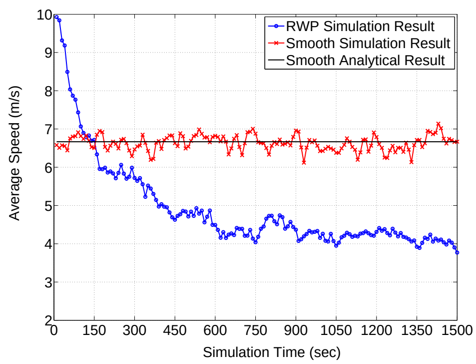
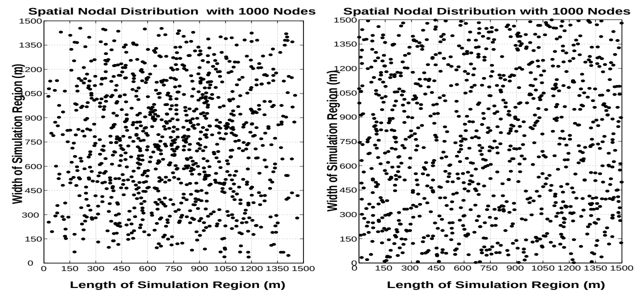


Fig. 3. Average Speed vs. Simulation Time.

To validate our theoretical result of (3), Fig. 3 illustrates the simulation results of average speed vs. 1500 seconds between the RWP and the smooth model. 1000 nodes move at the speed with the range $[0, 20]$ m/sec for both models with zero pause time. In smooth model, we set the range of each moving phase duration time as $[6, 30]$ seconds, that is, $E\{\alpha\} = E\{\beta\} = E\{\gamma\} = 18$ sec. From (3), the theoretical result of $E\{v_{ss}\}$ of the smooth model is obtained as: $E\{v_{ss}\} = \frac{2}{3}E\{v_\alpha\} = 6.7$ m/sec. In Fig. 3, we observe that the average speed of the smooth model is stable from the beginning of simulation at the value around 6.7 m/sec, which perfectly matches our theoretical result. Whereas, the average speed of RWP model keeps on decreasing as the simulation time progresses.

3) Uniform Node Distribution: Since each node in the smooth model selects direction, speed and phase time independently, the smooth model can be considered as an enhanced random direction (RD) model with memorial property on step speed and step direction. RD model was proved to maintain uniform node distribution in [13]. Accordingly, we show that the smooth model also *maintains uniform node distribution during the entire simulation period* in [12].

To verify this conclusion, Fig. 4 gives an illustration of the top view of two-dimensional spatial node position of the RWP and the smooth model. Where we distribute 1000 nodes uniformly in the simulation region at the initial time and later sample the node position at the 1000^{th} second for both models.



(a) RWP Model. (b) Smooth Model.

Fig. 4. Top-view of Node Distribution of the RWP and the Smooth Model with 1000 Nodes at the 1000^{th} sec, Respectively.

The result of RWP model in Fig. 4(a) shows that RWP model has non-uniform node distribution. The node density is the maximum at the center of the region, while it is almost zero near the network boundary, which agrees with the previous study [14]. In contrast, in Fig. 4(b), mobile nodes in the smooth model are evenly distributed in the simulation region.

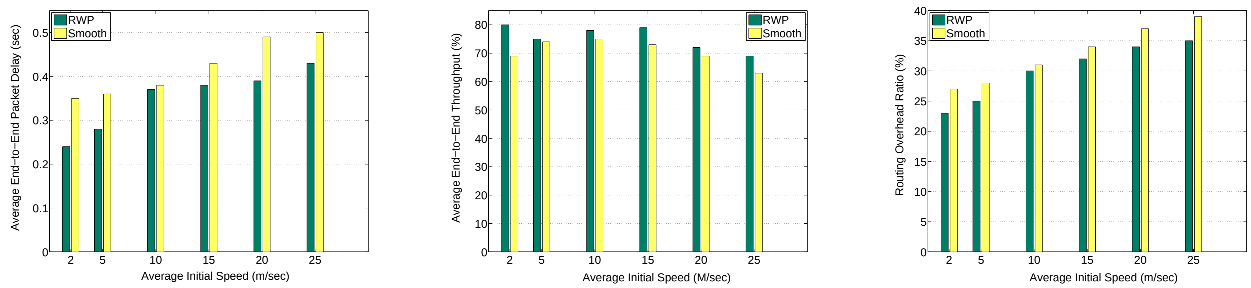
IV. Applications of Smooth Mobility Model

Our objective of designing the smooth model is to correctly indicate real-life network performance and effects of system parameters in diverse application scenarios of MANETs. Since the smooth model provides more realistic moving behaviors than current random mobility models, we apply the model to estimate the network performance based on routing and connectivity metrics. Meanwhile, we want to find out whether the evaluation results are different from random mobility models, for example the RWP model; and how different they are. Furthermore, in this section, we demonstrate how to apply the smooth model to support various applications, such as applications with group mobility and geographic restrictions.

A. Application in Routing Performance Evaluation

As the RWP model is the most widely used mobility model for MANETs in current simulation tools, we compare the routing performance of the AODV protocol [4] underlying the smooth and the RWP model through ns-2 simulator. The routing metrics includes: *average end-to-end packet delay*, *average end-to-end network throughput* defined as the percentage of packets transmitted by the sources that successfully reach their destinations, and *routing overhead* defined as the ratio of total size of network control packets to the total size of both network control packets and data packets initiated from the sources during the simulation.

In the simulation environment, 50 nodes move in an area of $1401m \times 1401m$ during a time period of 1000 seconds with zero pause time. To avoid biased simulation results, when a node reaches a boundary, it wraps around and reappears instantaneously at the opposite boundary in the same direction. Among these 50 nodes, the network traffics consist of 20 constant bit rate (CBR) sources and 30 connections. The

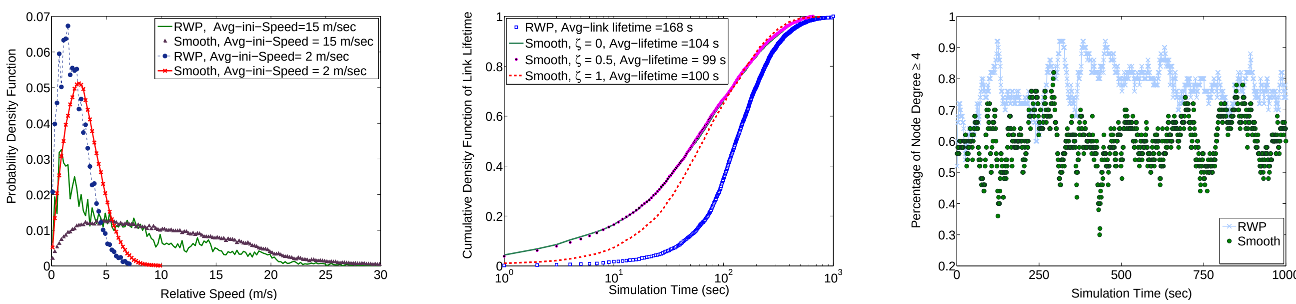


(a) Average End-to-End Packet Delay.

(b) End-to-End Network Throughput.

(c) Routing Overhead Ratio.

Fig. 5. Routing Performance Comparison between the RWP and the Smooth Model.



(a) PDF of Relative Speed.

(b) CDF of Link Lifetime.

(c) Node Degree.

Fig. 6. Network Connectivity Performance Comparison between the RWP and the Smooth Model.

source-destination pairs are chosen randomly through *cbrgen* tool of ns-2. Each source sends 1 packet/sec with the packet size 64 bytes. In smooth model, we set the time slot Δt of each step as 1 second, the memory parameter ζ as 0.5, and the range of each moving phase duration time as $[6, 30]$ seconds. Furthermore, we respectively set the initial average speed $E\{v_{ini}\}$ as $2, 5, 10, 15, 20,$ and 25 m/sec to generate different mobility levels for both models. For better demonstrations, we compare the routing performance metrics according to same average initial speed between these two models.

The simulation results are shown in Fig. 5. From Fig. 5, there exists an evident difference of simulation results for all routing metrics between the two models. Specifically, all three measured AODV routing performances of the RWP model outperform the smooth model, regardless of the average initial speed, which is mainly resulted from two reasons. One reason is that the decaying RWP speed keeps reducing the link change rate between two neighboring nodes. Hence, the lower frequency of link and path failures will dramatically reduce the routing overhead and packet delay, while increasing the network throughput. The other reason is that non-uniform RWP node distribution with maximum node density in the center region will increase the connectivity of the majority of nodes, which further “improves” the routing performance. Therefore, the lower mobility level and center concentrated node density of RWP model stresses AODV much less than the smooth model. Therefore, we claim that the routing protocols evaluation based on the RWP model is over optimistic.

B. Application in Network Connectivity Evaluation

Here, we apply the smooth model to evaluate the connectivity metrics in terms of probability density function (PDF) of relative speed, cumulative density function (CDF) of link lifetime and average node degree. The simulation results compared with the RWP model are shown in Fig. 6.

We evaluate the PDF of the relative speed of two models according to the initial average speed $E\{v_{ini}\}$ as 2 and 15 m/sec, respectively. For a pair of neighboring nodes (u, w), the relative speed $\overrightarrow{V^u}$ of node u according to the reference node w consists of two components in terms of X-axis and Y-axis of a Cartesian coordinate system centered at node w. Specifically, in the smooth model, the magnitude of n^{th} step relative speed of node u is: $|V_n^u| = \sqrt{(X_n - X_{n-1})^2 + (Y_n - Y_{n-1})^2}$, where X_{n-1}/X_n is the starting/ending coordinate of the n^{th} step of the relative trip in X-axis, so is Y_{n-1}/Y_n for Y-axis. Since $\Delta t = 1$ sec, $n >> 1$. Based on the central limit theorem (CLT) [15], when $n >> 1$, both i.i.d random variable $X_n - X_{n-1}$ and $Y_n - Y_{n-1}$ can be effectively approximated by an identical Gaussian distribution with zero mean. Furthermore, for any two independent Gaussian RVs, for example A and B, with zero mean and and equal variance, the RV $Z = \sqrt{A^2 + B^2}$ has a *Rayleigh density*. Hence, the relative speed V_n^u in the smooth model has an approximate Rayleigh distribution, which exactly matches the results shown in Fig. 6(a) of both scenarios with different $E\{v_{ini}\}$. Whereas, because of the speed decay and abrupt velocity change problems, the PDF of relative speed in the RWP model varies irregularly during the simulation and tends to have larger proportion in the region of small speed. This phenomenon shows more apparently when $E\{v_{ini}\}$ is large.

As the relative speed has a significant effect on the link lifetime, we further evaluate the CDF of link lifetime between these two models. Here, we specify $E\{v_{ini}\}$ as 2 m/sec. To investigate the effect of temporal correlation of node velocity in β–phase on link lifetime, we respectively set the memorial parameter ζ as 0, 0.5, and 1 in the smooth model. The simulation results are shown in Fig. 6(b). Given (2), when $\zeta = 1$, the node velocity has the strongest correlation, and the entire movement is a straight line according to the direction ϕ_α. In contrast, when $\zeta \neq 1$, the successive direction change in the β–phase increases the chance of link failures. Thus, from Fig. 6(b), in the region of short link lifetime, the corresponding CDF for $\zeta = 1$ is apparently less than that for $\zeta = 0$ and $\zeta = 0.5$. While based on (3), the smooth model generates stable average speed according to $E\{v_{ini}\}$, regardless of the value of ζ. Given $E\{v_{ini}\} = 2$ m/sec, we find that the expected link lifetime of the smooth model based on different ζ is almost same and around 100 second. In contrast, for the RWR model, because of the speed decay problem, the relative speed between RWP nodes is generally less than that in smooth model. Hence, the lower mobility level and lower topology change rate increase the link lifetime in the RWP model. From Fig. 6(b), we can see that the uptrend of CDF of link lifetime for the RWP model is dramatically less than that for the smooth model. Meanwhile, the expected link lifetime of the RWP model is 168 second, which is much longer than that of the smooth model.

Due to different spatial node distributions, mobility models with same node density (σ) would yield different average node degree during the simulation. As the default transmission range $R = 250$ m for mobile nodes in ns-2, in a square area of size 1401 m^2, the node density of each model is $\sigma = 5/(\pi R^2)$. Thus, on average each node would have 4 neighbors during the simulation. Fig. 6(c) illustrates the percentage of nodes whose node degree is no less than 4 during the simulation between these two models. We find that the result obtained in the RWP model is apparently larger than that of smooth model. This is because the majority of nodes move into the center region in the RWP model as time goes by [14]. Therefore, according to Fig. 6, we claim that the network connectivity evaluation based on the RWP model is over optimistic.

C. Application in Group Mobility

In reality, it is common that mobile users travel in a grouped manner. For example, to achieve the military missions (e.g., searching and attacking the enemies), soldiers move and collaborate together in a battlefield. In order to support MANET applications with group mobility, we provide a *flexible mobility framework* based on the smooth model. In the group mobility framework, we consider that each group has one leader and several group members. Initially, the leader lies in the center of the group, and other group members are uniformly distributed within the geographic scope of the group. The group leader dominates the moving behaviors of the entire group, including the node speed, direction and moving duration. Specifically, the velocity of a group member m at its n^{th} step is given by:

$$\begin{cases} V_n^m = V_n^{Leader} + (1-\rho)\cdot U \cdot \Delta V_{\max} \\ \phi_n^m = \phi_n^{Leader} + (1-\rho)\cdot U \cdot \Delta\phi_{\max}, \end{cases} \quad (4)$$

where U is a random variable with uniform distribution over $[-1, 1]$. $\Delta V_{\max}$ and $\Delta\phi_{\max}$ are the maximum speed and direction difference between a group member and the leader in one time step. $\rho \in [0, 1]$ is the spatial correlation parameter. When ρ approaches to 1, i.e., the spatial correlation between a group member and the leader becomes stronger, the deviation of the velocity of a group member from that of the leader is getting smaller. Therefore, by adjusting the parameter ρ, different smooth group mobility scenarios can be generated.

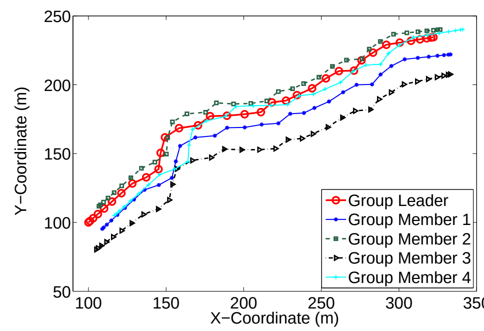


Fig. 7. Group Mobility based on the Smooth Model.

In this group mobility framework, the group leader follows the exact mobility patterns defined in the smooth model. The detailed moving behaviors of group members are described as follows. At the beginning of a movement, the group leader first selects the target speed v_α^{Leader}, target direction ϕ_α^{Leader}, and phase period α which is the same as all group members. Then, corresponding to v_α^{Leader} and ϕ_α^{Leader}, the target speed v_α^m and target direction ϕ_α^m of the group member m are selected from (4). For each time step in β–phase, the speed and direction of a group member are also obtained from (4) according to the reference velocity of the leader at that time step. When the leader transits into γ–phase, similarly, each group member selects its own values of v_β^m and ϕ_γ^m towards a stop. Thus, the entire group will stop after γ steps. By this means, every group member can evenly accelerate/decelerate the speed in α/γ–phase while keeping the similar mobility trajectory to the leader. Fig. 7 provides an illustration of 5 nodes traveling within one group movement duration. We set the parameters of (4) as: $\rho = 0.9$, $\Delta V_{\max} = 5$ m/sec, and $\Delta\phi_{\max} = \pi/3$.

It is observed that all trajectories of group members are in close proximity to that of the leader, as the spatial correlation (ρ) is strong. Based on the above demonstration, we conclude that the mobility framework based on the smooth model can be flexibly controlled to support diverse group mobility scenarios.

D. Application in Geographic Constrained Networks

In real world, the movement of nodes are often time under geographical constraints such as streets in a city or pathways of obstacles [1], [6]. Besides, vehicular ad hoc networking (VANET) designed for safety driving and commercial applications is a very important research branch of MANETs. To fully support study of MANET applications with geographical restrictions, next as an example shown in Fig. 8, we demonstrate how to apply the smooth model to mimic realistic moving behaviors of vehicles in a Manhattan-like city map.

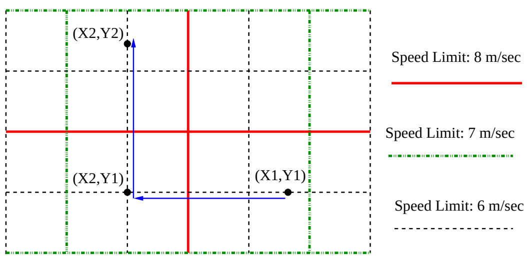


Fig. 8. Smooth Model Application in A Manhattan-Like City Map.

In Fig. 8, each line segment represents a bi-directional street of the city. The speed limit associated with each type of street is labeled on the right side of the map. In this model, the coordinate of intersection points between streets and the street speed limit are known for all nodes. Initially, mobile nodes are randomly deployed in the streets. For each movement, a node randomly chooses a destination and finds the shortest path using Dijkstra's algorithm. For example, in Fig. 8, the node located in (X_1, Y_1) will reach the destination (X_2, Y_2) through the intersection point (X_2, Y_1). Because mobile nodes are only allowed to move along the predefined streets in the map, the adapted smooth model describes a straight line movement without direction change for each trip. Thus, the moving behavior of every node along the street is pseudo-random [1]. For each straight line movement, the moving behaviors of mobile nodes comply the following rule:

$$\sqrt{(X_i - X_j)^2 + (Y_i - Y_j)^2} = \frac{V}{2}\alpha + V\beta + \frac{V}{2}\gamma, \qquad (5)$$

where V is the target speed and will not change during the β–phase. The selection of V is determined by the associated street speed limit V_{limit}, such that $V \in [V_{limit} - \epsilon, V_{limit}]$, where ϵ is a small positive value. Therefore, under this mobility framework, each nodal movement along the street is a typical movement with even speed acceleration and deceleration without speed decay problem. Furthermore, the node can properly stop at the target intersection point, such as (X_2, Y_1) in this example. By adjusting the geographic conditions of the map, the smooth model can be easily adapted to other applications, for example, a street battle. Thus, armored vehicles and tanks followed by the soldiers move along the streets according to the framework defined in (5). Moreover, mobile nodes can select different paths and moving speeds regarding to the dangerous status of the streets.

V. Conclusions

In this paper, on the purpose of providing correct performance evaluation and parameter analysis for MANETs having various application scenarios, we designed a smooth mobility model. Because the mobility patterns defined in the smooth model are based on the physical law of a smooth motion, the model provides more realistic node moving behaviors than the existing models, such as RWP model, in the simulation tools. Compared with the simulation results of the RWP model, we find that the smooth model, which generates stable speeds and maintains uniform node distribution, is more preferable for routing protocols evaluation and network connectivity study in MANETs. Finally, we provide a flexible mobility framework and demonstrate the easy adaptation of the smooth model for supporting MANET applications with group mobility and geographic constraints. The ns-2 code of our smooth model is available at $http://www4.ncsu.edu/\tilde{}mzhao2/research$.

References

[1] F. Bai and A. Helmy, "A survey of mobility models in wireless ad hoc networks, to appear on book wireless ad hoc and sensor networks." [Online]. Available: http://nile.usc.edu/~helmy/Modified-Chapter1-5-30-04.pdf

[2] C. Bettstetter, H. Hartenstein, and X. Perez-Costa, "Stochastic properties of the random waypoint mobility model," *ACM/Kluwer Wireless Networks, Special Issue on Modeling and Analysis of Mobile Networks*, vol. 10, no. 5, pp. 555–567, September 2004.

[3] J. Yoon, M. Liu, and B. Noble, "Random waypoint considered harmful," in *Proc. of IEEE INFOCOM*, 2003.

[4] C. Perkins, "Ad-hoc on-demand distance vector routing," in *Proc. IEEE MILCOM*, November 1997.

[5] D. B. Johnson and D. A. Maltz, "Dynamic source routing in ad hoc wireless networks," in *Mobile Computing*. Kluwer Academic Publishers, 1996, vol. 353.

[6] T. Camp, J. Boleng, and V. Davies, "A survey of mobility models for ad hoc networks research," *Wireless Communication and Mobile Computing (WCMC): Special issue on Mobile Ad Hoc Networking: Research, Trends and Applications*, vol. 2, no. 5, pp. 483–502, 2002.

[7] E. Royer, P. Melliar-Smith, and L. Moser, "An analysis of the optimum node density for ad hoc mobile networks," in *Proc. of IEEE International Conference on Communications (ICC)*, 2001.

[8] J.-Y. L. Boudec and M. Vojnovic, "Perfect simulation and stationarity of a class of mobility models," in *Proc. of IEEE INFOCOM*, March 2005.

[9] C. Bettstetter, "Smooth is better than sharp: A random mobility model for simulation of wireless networks," in *Proc. of ACM International Symposium on Modeling, Analysis and Simulation of Wireless and Mobile Systems (MSWiM)*, July 2001.

[10] B. Liang and Z. Haas, "Predictive distance-based mobility management for PCS networks," in *Proc. of IEEE INFOCOM*, April 1999.

[11] J. Yoon, M. Liu, and B. Noble, "Sound mobility models," in *Proc. of ACM MobiCom*, September 2003, pp. 205–216.

[12] M. Zhao and W. Wang, "Semi-Markov mobility model for mobile wireless networks," Technical Report TR01-NeTWIS-05, 2005.

[13] P. Nain, D. Towsley, B. Liu, and Z. Liu, "Properties of random direction models," in *Proc. of IEEE INFOCOM*, March 2005.

[14] C. Bettstetter, G. Resta, and P. Santi, "The node distribution of the random waypoint mobility model for wireless ad hoc networks," *IEEE Transactions on Mobile Computing*, vol. 2, no. 3, pp. 257–269, 2003.

[15] A. Papoulis, *Probability, Random Variables,and Stochastic Process*. McGraw-Hill, 1991.