Recent Advances in Mobility Modeling for Mobile Ad Hoc Network Research

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ABSTRACT

In this paper, we survey recent advances in mobility modeling for mobile ad hoc network research. The advances include some new mobility models and analysis of older mobility models. First we classify mobility models into three categories according to the degree of randomness. We introduce newly proposed mobility models in each of these categories. Next we discuss analysis for existing mobility models. We describe the analysis work in three parts. The first part is the statistical properties of the most widely used Random Waypoint Model. The second part describes the mobility metrics that aim to capture the characteristics of different mobility patterns. The last part is the impact of mobility models on the performance of protocols. We also describe some possible future work.

Categories and Subject Descriptors

C.2.1 [**Computer Systems Organization**]: Computer Communication Networks—*Network Architecture and Design: Wireless Communication*

General Terms

Measurement, Performance, and Design

Keywords

Mobility Model, Mobility Metric, Statistical Property, Performance, Random Waypoint Model

1. INTRODUCTION

The wireless technology has made communication very convenient. Mobile ad hoc networking is among the recent advancements in wireless communication technology. Ad hoc networks make it possible for people to communicate using makeshift temporary networks built without any permanent infrastructure like routers, cell phone towers, landlinks etc. The mobile wireless end-hosts play the role of routers and forward data packets using peer-to-peer routing and forwarding. The quick deploy-ability of mobile ad-hoc networks makes them attractive for armies, emergency rescuers and many others.

The mobile ad hoc networks are different from Internet in two major ways. The first is that the hosts in this network are resource-constrained. They have only limited energy, computing power and memory. The second is that the hosts (and therefore the routers) of the network are mobile and the topology changes rapidly. These two features pose great challenges to the researchers working in the area. For example, we need to design new routing and transport-layer protocols to adapt to the changing topology, to keep the energy consumption low and to maintain high performance.

Many researchers performed valuable research in the area of energy-efficient routing and transport layer protocols. They use simulation to validate their algorithms and to evaluate the performance of their protocols. Popular simulators use mobility models to generate movement patterns for wireless-hosts. The mobility models, therefore, must imitate practical scenarios close enough for the simulators to provide realistic performance measurements.

Research in mobility modeling is performed in two directions. The first direction (primary research direction until 2000) is to design new models in order to mimic the real world scenarios better. The second direction (predominant afterwards) is to analyze these models. This includes finding the statistical properties of the mobility models, designing different mobility metrics and studying the influences of mobility models on routing protocols' performance. An earlier survey on mobility models can be found in [8]. The survey paper [8] covers the mobility models proposed until 2000 well and covers only sporadically after that. In this paper we present a survey of recent advancements in research on mobility models. While a brief survey on mobility models is also provided in the paper, our focuses are on statistical properties of mobility models, metrics and performance evaluation for mobile networks.

Many mobility models have been proposed in the literature [9, 10, 11, 12, 14, 16, 20, 24]. Also, detailed analysis for widely used models has been presented by different authors [1, 3, 4, 5, 23, 29, 30]. We differentiate our work from earlier work in that our survey includes a broader range of research topics that are related to mobility modeling. In [8], mobility models are classified in two categories. The first category is called entity mobility models, where all hosts in the system move independently with each other. The second category is called group mobility models, where sets of hosts move as groups. Important examples of entity mobility models include Random Walk Model, Random Waypoint Model [16] and Random Direction Model [24]. Example of group mobility model is the Reference Point Group Mobility(RPGM) Model [11].

In this paper, we use another classification criterion, viz., degree of randomness, to classify mobility models into three categories. This method of classification as well as other categorization methods can be found in [2]. The reason we choose this method is that it considers both hosts' movement patterns and their environments.

We further present current research on the statistical properties of Random Waypoint Model which shows the importance of mobility modeling [4, 3, 5, 23]. As an effort to quantify the influence of mobility, researchers recently focus more on mobility metrics. The paper will also list several important mobility metrics and discuss the influence of mobility models on performances of routing protocols.

The rest of the paper is organized in three subsequent sections. In section 2, we classify mobility models into three categories and discuss some recently proposed models. In section 3, we describe analysis of various models, including properties of Random Waypoint Model, its problems and remedies; and metrics used to represent network mobility and their influences on protocol performance. The last section concludes the paper with suggestions regarding future research directions.

2. MOBILITY MODELS

We classify various mobility models into three classes according to the degree of randomness after [2]. If models are built based on traces, then everything is deterministic and we call these models *trace based models*. If there is only partial randomness, the models are called *constrained topology based models*. Here hosts' movements are constrained by obstacles, pathways, etc., but speed and direction are still randomly chosen. Examples in this category include the City Section Mobility Model [9] which simulates people or vehicles moving along grid-like streets where different streets have different speed limits. If there is total randomness, we call these *statistical models*. Total randomness means that hosts can move anywhere in the area and the speed and direction are randomly chosen. Examples in this category include the Random Walk Model and the Random Waypoint Model.

2.1 Trace Based Models

If we can trace mobile hosts in their real world scenarios, we can gain valuable insight for actual mobility patterns and greatly enhance our mobility models. Some research has been done along this direction by researchers in wireless local-area networks and cellular networks [13, 17, 19, 26, 27]. However, since mobile ad hoc network is a new research area and no real working system is available yet, we are not able to get the trace data [8]. Even if we have real working system, it is still a very complicated task to trace the mobility pattern of the hosts [2]. To the best of our knowledge, no work has been done in collecting trace data. This will be a future work.

2.2 Constrained Topology Based Models

Constrained topology based mobility models simulate real-world scenarios, but still have some randomness to provide for variability. Models mimicking freeway scenarios [1] and city block scenarios [1, 9] belong to this category. Because they are very simple and intuitive, we will not cover such models in any more detail.

More complicated constrained topology based models are described below.

2.2.1 *Reference Point Group Mobility Model*

The Reference Point Group Mobility (RPGM) Model [11] mimics the behavior of a group of hosts that move as a single entity to perform some task. It is a very effective framework and may be adapted to model various scenarios, such as battlefield situation, disaster recovery and convention scenario. In this model, each group has a logical center and the trajectory of the group as a whole is represented by the locus of the center. Each host in this group has its own reference point. The reference points follow the group movement. The actual position of the host is determined by its reference point plus a random motion vector that denotes its offset from the reference point.

2.2.2 *Mobility Vector Model*

The Mobility Vector Model [12] is a more general framework. It can be used to describe a very large set of scenarios. It is especially useful in a heterogeneous environment where different types of hosts have different mobility patterns. In this model, the velocity of any host, the Mobility Vector, is composed of a Base Vector and a Deviation Vector: $\vec{M} = \vec{B} + \alpha\vec{V}$, where α is the acceleration factor. The Base Vector defines the primary velocity component and the Deviation Vector defines the deviation from the Base Vector. By changing $\vec{M}$, $\vec{V}$, or α, we can produce many different mobility patterns. For example, if we use Base Vector to represent the movement of the whole group and use Deviation Vector to represent the movement of individual hosts within the group, we get the RPGM model. One of the motivations behind the Mobility Vector Model is to make movement smooth. Some statistical models like Random Waypoint Model will produce unrealistic movements such as sudden stops and sharp turns. We can use the Mobility Vector Model to make it more realistic. For example, if we choose a negative α, we can mimic the deceleration of a host approaching its destination. The host slows down and stops at the destination, while in Random Waypoint Model it may suddenly stop at the destination.

2.2.3 *Obstacle Mobility Model*

The Obstacle Mobility Model [14] is based on the following real-life observations. First, people move towards specific destinations rather than randomly choosing some destinations. Second, there are obstacles in the real world. These obstacles, most commonly the buildings, block people's movements as well hinder signal-propagation. Third, people do not walk along random trajectories; they usually move along pathways and select shortest paths.

Take campus scenario as an example. Buildings are modeled by placing rectangles of random size at random locations; pathways are constructed by Voronoi diagram of the vertices of these rectangles; doorways are the intersections of these pathways with the buildings. A *Voronoi diagram* is a partitioning of a plane with n points into n convex polygons such that each polygon contains exactly one point and every point in a given polygon is closer to its central point than to any other [28]. A host randomly chooses a building as its destination, moves towards it, pauses sometime, and then moves on to another building. To reach a destination, the host can only move along pathways, although it may cross buildings through doorways. Among all these pathways, the host selects the shortest path. The model also considers the signal blocking problem. The communication of a host with other hosts will be totally blocked by buildings if the transmission is out of its Line-Of-Sight.

2.3 Statistical Models

In a statistical model, hosts can move to any destination and their velocities and directions are chosen randomly. The movements of hosts are described by some stochastic process. These models are basically idealistic rather than realistic, because in a real world, hosts will not move randomly without any destination. However, if we know nothing about the hosts' real mobility pattern or do not specify any specific scenario, a statistical model is the only choice. These models provide common test beds for comparing performances of different routing protocols. Examples of statistical models include Random Walk Model, Random Waypoint Model [16] and Random Direction Model [24].

2.3.1 Random Waypoint Model

Random Waypoint Model [16] is the most widely used and studied mobility model. In this model, a host randomly chooses a destination called *waypoint* and moves towards it in a straight line with a constant velocity which is selected randomly from some given range. After it reaches the waypoint, it pauses for some time and then repeats the procedure.

2.3.2 Random Direction Model

Another model, named Random Direction Model [24], is very similar to the Random Waypoint Model. In this model, a host randomly chooses a direction from $[0, 2\pi]$ and moves; after some random time it either changes direction or changes speed.

3. ANALYSIS OF MOBILITY MODELS

Different mobility models introduce different mobility patterns which in turn introduce different network topology changes. These topology changes greatly influence the performance of routing protocols. This section describes work aiming to capture these relationships. First, statistical properties of Random Waypoint Model are given. Second, different mobility metrics are introduced. The ability of the mobility metrics to differentiate between mobility models is also discussed. At the end of the section, we discuss the influence of mobility models on routing protocol performance.

3.1 Analysis of Random Waypoint Model

Much research on Random Waypoint Model has been done. These researchers not only give properties of Random Waypoint Model, they also find problems with this model and remedies are provided readily.

3.1.1 Statistical Properties

The Random Waypoint Model can be described by a discrete time stochastic process [3]. In any time period , a host moves from present waypoint to next waypoint $P(i)$, at a random speed $V(i)$. Its pause time at $P(i)$ is denoted by $T(i)$. Random Waypoint Model is represented by a three dimensional stochastic process $\{(P(i), V(i), T(i)), i = 1, 2, ...\}$. Statistical properties of Random Waypoint Model are developed in [3, 4, 23]. Here we describe results on distributions of transition length, transition time and host position.

Transition length is defined as the distance between two consecutive waypoints. Stochastically, transition length is the distance between two random points (uniformly distributed) chosen in a rectangular area. Denote transition length as random variable L and suppose the rectangle area is $a \times b$. Its probability density function is $f_L(l) = \frac{4l}{a^2b^2} f_0(l)$. The analytical form for $f_0(l)$ is given in [3, 4].

Transition time is the time a host takes to move between two consecutive waypoints. Suppose the probability density function of its speed is $f_V(v)$. If we denote the transition time as a random variable T, then $T = \frac{L}{V}$ and its probability density function is

$$f_T(t) = \begin{cases} \int_{v_{min}}^{v_{max}} v f_L(vt) f_V(v)\, dv & \text{if } t \in [0, l_{max}/l_{min}]; \\ 0 & \text{otherwise.} \end{cases}$$

An approximate formula for the distribution of *host position* can also be found [3, 4]. At any time, a host remains in one of the following three states: static(never move), pausing, or moving. Pausing and moving states are called dynamic states. Suppose the probability of a host being static is p_s; the probability of a dynamic host pausing is p_p, then the probability of a dynamic host moving is $1 - p_p$. The probability density function of the position of the host is

$$\begin{aligned} f(x, y) &= f_{initial}(x, y) p_s \\ &+ f_{pause}(x, y) p_p (1 - p_s) \\ &+ f_{move}(x, y)(1 - p_p)(1 - p_s) \end{aligned}$$

The derivation of this formula is given in [3, 4].

3.1.2 Un-uniformity and its Remedy

It can be shown from above formula that the distribution of host position is not uniform. Hosts are more likely to concentrate in the center than near the borders (this is called the *border effect*). Some earlier researchers assumed that the distribution of host position is uniform and performed simulation studies based on that assumption [21]. The results obtained from such simulations need to be revalidated. This demonstrates the importance of formal methods and modeling in network research.

[5] uses simulation to analyze the host position distributions of Random Waypoint Model and Brownian-motion. They found that Brownian-motion almost always produce uniform host position distribution. But for Random Waypoint Model, it approximates uniform host position distribution only when border effect is very weak. As the pause time increases or the probability of pause increases, the border effect becomes weaker and distribution becomes more uniform. Factors like maximum speed and number of hosts show little influence on host position distribution.

3.1.3 Speed Decay and Remedy

When simulation uses Random Waypoint Model, speed is usually chosen randomly from $[0, v_{max}]$ and the average host speed is taken as $v_{max}/2$. Further, it is assumed that the average host speed remains the same during the simulation period. Authors of [29] pointed that this is not the case.

They explained that while fast hosts reach their destinations quickly, slow hosts take a long time to reach their destination. As time passes by, more and more hosts get "trapped" in slow journeys and dominate the average host speed. The average host speed thus consistently decays before it converges to the *steady-state average speed* ($\overline{V}$). Their formal analysis shows that if $v_{min} < v_{max}$, then the steady-state average speed is strictly smaller than the initial average host speed, that is, $\overline{V} < \frac{v_{min}+v_{max}}{2}$. They also proved that if $v_{min} \to 0$, $\overline{V} \to 0$ .The smaller the v_{min} the longer is the decay period and hence it takes longer time for the system to stabilize. Because host mobility has great impact on protocol performance, the consistent speed decay suggests that the results of many previous simulations, where v_{min} is set to 0, are possibly misleading. A simple fix to this problem is to set a non-zero v_{min}. By doing this, hosts can converge to steady-state average speed.

The speed decay problem was studied further in [30]. The finding was that any statistical mobility model that chooses destination (or distance) independently of speed, suffers from the *speed decay problem*. The steady-state average speed is time averaged, i.e., it is weighted by trip time. To reach a given destination, a slower host travels for longer time and a faster host travels for shorter time. The steady-state average speed is thus influenced more by slower hosts. [30] also shows how we can eliminate speed decay and get a stationary mobility model. For each trip, the host will select a speed. We denote this speed as a random variable V, and its distribution as $f_V(x)$. The *steady-state speed* is denoted by random variable V_{SS}, its distribution is denoted by $f_{V_{SS}}(x)$. Borrowing from renewal theory the methods of constructing equilibrium renewal process, they proposed the following way to eliminate the speed decay: choose initial speeds from the intended steady-state speed distribution $f_{V_{SS}}(x)$ and choose subsequent trips' speeds from $f_V(x)$. The effectiveness of this method is validated by simulations.

3.1.4 Other Problems and Suggested Remedy

Another problem with the Random Waypoint Model is that it is memory-less. The movement (speed and direction are two parameters of movement) between the current waypoint and the next waypoint is independent of the movement between the previous waypoint and the current waypoint. This characteristic generates unrealistic movements such as sudden stops and sharp turns [12]. [2] proposed an improved Random Direction Model instead of Random Waypoint Model that is free from such unrealistic movement patterns.

3.2 Mobility Metrics

Different mobility models lead to different mobility patterns. But models themselves do not give clear images how mobility patterns are different with each others. We need some mobility metrics to describe these mobility patterns. Efforts to find appropriate mobility metrics have begun only recently. We classify mobility metrics in two categories, viz., direct mobility metrics and derived mobility metrics. The *direct mobility metrics*, like host speed or relative speed, are measurements with a clear physical meaning. The *derived mobility metrics*, like graph connectivity, are measurements derived from physical observations through mathematical modeling.

3.2.1 Direct Mobility Metrics

The *direct mobility metrics* measure host motion directly, e.g., average host speed or minimum/maximum speed. For Random Waypoint Model, pause time is also used to reflect host mobility [7, 22], namely, the longer the pause time, the smaller the mobility. Other metrics belonging to this category include average relative speed [15], average degree of spatial dependence and temporal dependence [1].

Average relative speed [15] is defined based on relative speed of all pairs of hosts in the network. Suppose $P(m,t)$ and $P(n,t)$ are the positions of hosts m and n at time t, respectively. The *relative velocity* between m and n is defined as

$$V(m,n,t) = \frac{d(P(m,t) - P(n,t))}{dt}$$

Averaging the absolute value of relative velocity over time,

$$M_{m,n} = \frac{1}{T}\int_{t_0}^{t_0+T} |V(m,n,t)|\, dt$$

we have average relative speed $M_{m,n}$ of hosts m and n. The average relative speed M thus is defined as $M_{m,n}$ averaged over all host pairs

$$M = \frac{1}{N(N-1)/2}\sum_{m,n} M_{m,n} = \frac{1}{N(N-1)/2}\sum_{m=1}^{N}\sum_{n=m+1}^{N} M_{m,n}$$

where N is the number of hosts.

Attempts has been made in [1] to characterize the temporal dependence of the movement of an individual host and the spatial dependence between different hosts. The *temporal dependence* indicates how an individual host changes its velocity over time, or say, whether its current velocity is dependent on the previous velocity. *Average degree of temporal dependence* is proposed to capture temporal dependence. It is an average over the temporal dependence of all the hosts. For each host, the *degree of temporal dependence* is defined as the product of relative direction and relative speed (relative to itself) at two different time. The *spatial dependence* indicates whether a host's movement is correlated with other hosts. *Degree of spatial dependence* between two hosts i and j is defined as $D(i,j) = RD(i,j)SR(i,j)$, where $RD(i,j) = \cos\theta$, θ is the angle between the velocity of hosts i and j; $SR(i,j) = \frac{min(v_i,v_j)}{max(v_i,v_j)}$ is the speed ratio of hosts i and j. The *average degree of spatial dependence* is the average of degree of spatial dependence over all host pairs.

The direct mobility metrics has been used to measure different mobility models. For example, average degree of spatial dependence differentiates different mobility models successfully [1]; average relative speed varies almost linearly with link change rate (see next subsection) under Random Waypoint Model. However, some metrics can not accurately capture different characteristics of the models. For example, average degree of temporal dependence fails to differentiate different mobility models [1]. Average or minimum/maximum speed has been used widely. Although it indicates the degree of mobility, it fails to reflect relative motions between hosts. The metric "pause time" is model dependent: it can only be used in the Random Waypoint Model. More important, direct mobility metrics often do not directly reflect topology changes, while the latter is believed to be more influential to network performance.

Take the Random Walk Model for example, high mobility speed doesn't necessarily generate large geographic displacement[12] to cause dramatic topology changes.

3.2.2 Derived Mobility Metrics

Mobility models impact the connectivity graph which in turn influence the protocol performance. It is thus helpful to study metrics that capture the properties of connectivity graph. The category of *derived mobility metrics* include metrics derived from graph theoretic models as well as other mathematical models. Metrics derived from graph-theoretic models include link change rate [11, 12], link duration [1, 6, 25] and path duration [25]. The mobility measure metric proposed in [18] is derived from probabilistic models.

Papers [11, 12] proposed *link change rate* as an indicator of topology change. If a link between two hosts is established/severed due to host movement we consider the state of the link between them up/down. Link change rate is the total number of link up/downs in unit time.

Metric *average link duration* [1, 6, 25] is defined as the average of link durations over the host pairs that are within each other's transmission range. The *link duration* is the time interval during which two hosts are within each other's transmission range.

Average path duration [25] averages the durations of all the paths linking every source-destination pairs. *Path duration* is the time interval during which all links on a path (from a source to a destination) exist. The average path duration $1/\lambda$ is related to the path length (hop count) h, average relative speed V and transmission range R by relation $\lambda \propto \frac{hV}{R}$.

Mobility measure [18] is derived from average relative speed. It is based on the observation that relative speed does not make much sense for two hosts that are far away, but makes much sense for two hosts that are near the transmission range of each other. A relation of *remoteness* between two hosts is defined as a function of the distance between two hosts; it increases from 0 to 1 monotonically. The derivative of remoteness is 0 at distance 0, increases as the distance increases, reaches its maxima at the communication boundary ; then decreases as distance increases further, and approaches 0 as the distance approaches infinite. The mobility measure is defined as the average of the derivative of remoteness over all host pairs.

Evaluations have been performed to investigate how the derived mobility metrics are related to direct mobility metrics, how well the derived metrics can differentiate different mobility models, and how well the metrics can quantify routing performance. Results from [12] show that link change rate increases as average host speed increases. But results also show that, for different mobility models, differences in link change rate are small, which means link change rate can not differentiate different mobility models effectively. More over, [6] pointed out that the drawback of the link change rate is that it only counts the number of link changes without taking into account the duration of a link which heavily influences protocol performance. To this extent, [6] argues that average link duration is a good metric that not only quantifies host movements but also indicates protocol performance accurately. Under Random Waypoint Model, when average link duration increases, throughput increases and end-to-end delay and protocol overhead decreases consistently. For average path duration, it is found that at a high speed, path duration always shows exponential distribution no matter what mobility model is in use; it is also found that there exists a linear relationship between the reciprocal of the average path duration and the routing protocol performance in terms of throughput and routing overhead [25]. For the mobility measure defined on remoteness, simulations show that it has a consistent linear relationship with the link change rate for various mobility models [18].

3.3 Influences of Mobility Models on Routing Protocols

Many applications of mobile ad hoc network are expected to operate in a highly dynamic environment with high host mobility. Network performance thus depends on how well routing protocols adapt to the topology dynamics. Researchers have studied the influence of mobility models on the performance of routing protocols with regard to some mobility metrics. Not surprisingly, similar conclusions [1, 8, 11, 12] have been reached by different groups. A specific model captures only one of the many possible mobility characteristics. To evaluate protocols, it is inadequate to use only one model. Various models that span across all different mobility characteristics are needed. When evaluating a single protocol, this protocol is run on various models to see how its performance changes on different models. It is found that the performance of a specific protocol varies if underlying mobility models are different. When evaluating a group of protocols, these protocols are run on a single model to see how these protocols rank with this modeled motion. It is found that the rank of protocols varies if underlying mobility models are different. In a word, routing protocols are influenced by different mobility models in different ways.

4. CONCLUSIONS AND FUTURE RESEARCH

In this paper we summarize recent advances in mobility modeling for mobile ad hoc networks. The main focus is on the analysis of mobility models, mobility influence on routing protocols and mobility metrics used to measure mobility patterns. These helps researchers obtain an in depth understanding of the mobility models and realize their importance in the research of mobile ad hoc networks. Some of the future work are identified below.

Most of the models proposed so far are not realistic enough for performance study. More realistic models that can flexibly reflect different real world scenarios are needed. In this sense, models based on real trace data are expected. So far, most of the study in literature is focused on models where hosts move independently, research on group mobility model, given the importance of group motion behavior in large scale mobile ad hoc networks, is largely insufficient. More research in this direction is desired. Also, formal methods in modeling mobility models other than Random Waypoint Model are needed to test the spatial distribution and temporal distribution (e.g.,for speed).

Although many metrics have been recently proposed attempting to quantify network connectivity, especially the derived mobility metrics, most researchers still use the simple average(or maximum) speed as the mobility measurement in their study. Thus, network performance evaluation using some of those better metrics (the ones that capture topological changes) are desired. On the other hand, more mobility metrics are needed to accurately characterize mobility patterns.

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