Towards Mobility-Rich Analysis in Ad Hoc Networks: Using Contraction, Expansion and Hybrid Models

Yenliang Lu, Huier Lin, Yajuan Gu, Ahmed Helmy
Department of Electrical Engineering
University of Southern California
Email: yenlianl, huierlin, ygu, helmy@ceng.usc.edu

Abstract - **A wireless ad hoc network is an infrastructure-less network where nodes are mobile. The evaluation of ad hoc networking protocols is very sensitive to mobility. As a result, exploring a set of rich mobility models in ad hoc networks is essential. The purpose of this paper is to introduce a classification of various mobility models, in addition to proposing the contraction, expansion, and hybrid mobility models. These proposed models cover scenarios in which nodes merge, scatter, or switch to different movement patterns over time. We also investigate a set of mobility metrics to capture characteristics of mobility. We implement our mobility models in the *IMPORTANT* framework in *NS*-2. We use our framework to evaluate the performance of ad hoc routing protocols. Our study shows that no one metric is sufficient to capture mobility, but average node degree and link duration are very useful in capturing mobility dynamics. We note a wide spectrum of performance outcomes with mobility. Also, we observe that in some scenarios (involving contraction) performance *improves* with added velocity.**

1. INTRODUCTION

Ad hoc networks have recently attracted a lot of research attention due to its ability to self-configure and to be rapidly deployed and the potential of its use in a variety of applications, ranging from reconnaissance and military missions to vehicular networks. An ad hoc wireless network is a multi-hop wireless configuration without fixed infrastructure or central administration, consisting of mobile nodes. Mobility creates a highly dynamic environment that poses some of the main challenges in such ad hoc networks. The relative movement between nodes creates or breaks wireless connections and changing the network topology. This in turn affects the performance of the network and also invokes protocol mechanisms to react to such dynamics. This chain of reasoning, validated in previous studies [1][2], creates a clear link between mobility and performance. Hence, mobility modeling becomes crucial to the evaluation and study of ad hoc networking protocols. The mobility model specifies the dynamic characteristics of node movement. Traditional mobility models, including, random walk, random waypoint (RWP), and random direction models, attempt to mimic the movements of mobile objects [12][5]. Such models are simple to implement and analyze. On the other hand, in all these randomized models, nodes choose their velocity and direction independently, with no restrictions. Hence, these models do not capture correlation between node movements. Also, they do not incorporate environmental geographical restrictions.

Recent work on mobility models attempts to identify common mobility movements. For example, group mobility may exist in battlefields, disaster relief, or crowd migration. Freeway mobility models apply to vehicular networks.

Due to the growing variety of mobility models we first introduce a systematic mechanism for the classification of mobility models. We identify mobility models as being *recurring* or *terminal*. Also, we differentiate between *single* and *hybrid* mobility models. This helps us identify some characteristics of mobility that are not well understood.

In addition, we use a set of meaningful mobility metrics that enable us to differentiate between the different mobility models. We measure average node degree, link duration, relative speed, and spatio-temporal correlation.

We use the above understanding to introduce the contraction, expansion, circling, and hybrid mobility models (RWP & Contraction and RWP & Manhattan). Contraction mobility attempts to model situations where network nodes (e.g., persons) merge onto attraction points or events. Expansion mobility attempts to model scenarios in which nodes move away from an event. These models may also be useful in mobile sensor networks. The hybrid mobility model combines several existing mobility models together.

We develop and implement these mobility models in *NS*-2 [14] using the *IMPORTANT* [1] tool and conduct extensive simulations to evaluate the performance of various routing protocols [18], including DSR, AODV and DSDV, in on-going work. One interesting feature for the expansion and contraction models is that performance varies widely over time, where for other, recurring, mobility models (e.g., RWP or Freeway) performance does not vary much over time.

Our study shows the wide spectrum of performance outcomes with mobility. Among our observations, no one metric is sufficient to capture mobility, but average node degree and link duration are very useful in capturing mobility characteristics. Also, we observe that in some scenarios (involving contraction) performance improves with added velocity.

The remainder of this paper is organized as follows. Section 2 discusses related work. Section 3 presents the classification of mobility models. We introduce our mobility models and metrics in Section 4. Section 5 describes out simulations setup and analyzes the results and observations. Concluding remarks are presented in Section 6.

2. RELATED WORK

In this section, we will discuss several, commonly used, mobility models. Also, we describe some important factors affecting the performance in current ad hoc networks.

Mobility Model: Random Way Point mobility model (RWP) [3][4] is a simple, widely-used, model in the many simulation studies of ad hoc routing protocols. In the RWP mobility model each node independently chooses its next destination randomly within the network boundaries, and moves with constant speed towards that direction. The speed is chosen based on the uniformly random distribution in [0, *Vmax*]. After a node reaches its destination it pauses for a specified *pause-time*, then it chooses another random destination and random speed. This process is repeated for the duration of the simulation. The RWP model, however, does not consider the mobility correlation between new time intervals and previous time intervals and does not consider correlation between different nodes. A study in [11] on RWP shows a "speed decay" problem. We use velocity range [1,*Vmax*-1] to avoid this problem. In Reference Point Group Mobility Model (RPGM) [5][1] the location, direction and speed of mobile nodes in the same group are related to the leader's motion. In earlier work, Helmy's group have developed the *IMPORTANT* mobility framework [1] that proposes the Freeway (*FWY*) and Manhattan (*MH*) mobility models based on the geographical information. The Freeway mobility model utilizes maps to design the blueprint of obstacles and restrictions within a network. Every node simulates the movement of a vehicle on the highway that is only allowed to move within its lane without passing other cars. Velocity of every vehicle is temporally dependent on its previous speed. The Manhattan mobility model emulates moving patterns of cars on streets. It is composed of vertical and horizontal streets in different directions. At intersections, nodes may move straight, turn left or right according to a certain probability. Also, each mobile node's speed is related to the its previous velocity and velocity of its neighboring nodes. Recent studies on mobility models focus on capturing mobility characteristics and metrics in order to build a framework for performance comparison. [5] uses the performance metrics including end to end throughput and control overhead to measure the efficiency of routing protocols. Moreover, [1] and [2] describe and analyze many useful protocol independent metrics in order to classify the variances among the existing mobility models. Spatial dependence, temporal dependence, and geographic restriction metrics are the fundamental elements used to distinguish the mobility features among different mobility models. We borrow from these existing works, and go beyond their contribution to introduce new systematic classification of mobility models, a set of new mobility models and metrics, and an extensive simulation study with a new set of observations pointing out differences with previous studies.

Evaluation of Ad Hoc Routing Protocols: Several studies evaluated different ad hoc routing protocols (e.g., DSDV [6], AODV [7], and DSR [8]). In [10] RWP was used to compare two reactive protocols; DSR and AODV. AODV caches limited routes with explicit cache expiration. DSR uses aggressive caching. With a large number of sources, for low mobility, DSR is more efficient, while AODV performs better for high mobility. Furthermore, during heavy traffic, AODV achieves higher throughput than DSR, whereas DSR incurs less overhead. For other mobility models, AODV has higher throughput if the transmissions happens within the restricted local scope [5], such as the RPGM mobility model; however, DSDV's performance degrades with group mobility. Considering the Freeway and Manhattan mobility model [1], DSR achieves the highest throughput and DSDV generates the lowest overhead In general, all previous studies concluded that performance degrades with increased velocity. In [18] we show that this is not necessarily that case for some of our proposed models (e.g., contraction and hybrid).

3. CLASSIFICATION of MOBILITY MODELS

Previous work on mobility models [12][1] surveyed several mobility models including random walk, RWP, Gauss-Markov, exponential correlated random, community, pursuit, RPGM, freeway and Manhattan mobility models. In this paper, we classify models based on their characteristics. Then we identify characteristics that are not captured by the above mobility models and propose several mobility models including contraction, expansion, circling, and hybrid mobility models. The reason for proposing hybrid mobility models is that in many practical scenarios multiple-models may exist within the same network, due to the potential heterogeneity of network nodes and users. A mobility model may be *recurring* or *terminal.* Also a mobility model may consist of one model or a hybrid of models.

Recurring Mobility Models: In recurring mobility models the same synthetic model (e.g., RWP) is repeated throughout the simulation without terminating or changing (in terms of parametrs). Hence performance of the protocols in such environment does not change drastically in the long run. Nodes may, however, pause temporarily but mobility will not be terminated at a specific time point. Most current mobility models fall under this category. Examples include RWP, RPGM, Freeway, and Manhattan [1].

Terminal Mobility Models: The second set of mobility models is called the *terminal* mobility models, where the rules of movement change over time (e.g., some nodes may stop). Hence, the time-related characteristics of the performance under such mobility models may change significantly. Example terminal mobility models include the Contraction and Expansion models.

Hybrid Mobility Models: In hybrid mobility models, the movements of a node may switch from one mobility model to another based on its location in the network or based on the simulation time. For instance, a node could follow the RWP model in one simulation area. When this node crosses over a demarcation line, its mobility form will change to the Manhattan mobility model. An example of a hybrid mobility model includes 'Contraction & RWP'.

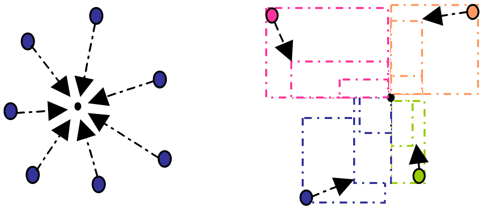
4. PROPOSED MOBILITY MODELS

This section introduces our mobility models and defines the metrics used to evaluate the characteristics of those models.

4.1 Proposed Mobility Models

Contraction Mobility Model

The contraction model emulates movement of mobile nodes toward a logical center from all directions (Fig 1).



.Fig 1. Contraction Mobility Model (left) and its Modified version (right)

At the beginning, all the mobile nodes are uniformly distributed in the area. During the whole movement period, the nodes move toward the center in a straight line. Every time interval (10sec), a node calculates a new speed randomly within [1,*Vmax*-1], and may pause for sometime (using pause probability and max pause time). When nodes reach the center they stop. Applications of this model include pursuit or students gathering for class.

Modified Contraction Mobility Model

Since in reality, humans usually will not walk along strict straight lines, we introduce the: Modified Contraction Model (fig 1). For each interval, a node selects the next destination randomly in the square defined by the current position point and the center point, randomly finds a speed within [1, *Vmax*-1]. The result is that the nodes move closer to the center in each interval, eventually reaching the center.

Expansion Mobility Model

This model has the opposite effect of movement pattern compared to the contraction model. Nodes in the area will move toward the edges away from the center in a line (fig 2).

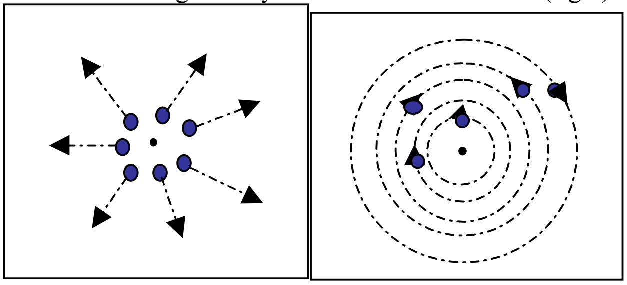


Fig 2. Expansion Mobility Model (left), Circling Mobility Model (right)

In simulation area, there is a logical center point. The nodes move away from the center to the edges. Initially, the nodes are uniformly distributed in the area (for some simulations, we constrain initial positions of the nodes to a small area around the center). For each interval, the nodes find the next destination and randomly find a speed within [1, *Vmax*-1]. Nodes pause with a probability for some time. Eventually, all the nodes reach the edges of the area and stay there. Applications of this model include people being evacuated from a dangerous place or students moving away from class.

Circling Mobility Model

The Circling Model (fig 2) emulates movement of mobile nodes circling around a center. Each node has its unique radius value and circles around the center in a specific direction. For each interval, the node picks the next destination position and speed within [1, *Vmax*-1]. Also, each node has a probability to pause for sometime when it reaches a destination. Nodes circle around the same center throughout the simulation. Application of this model includes circling around to park the car.

Hybrid Contraction & RWP Mobility Model

In reality, the simple mobility models with only one movement pattern can not capture all the characteristics of the movements. We introduce several hybrid models. The first is a hybrid model of contraction and RWP model (fig 3).

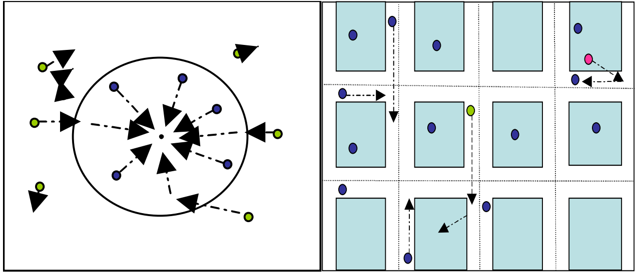


Fig 3. Hybrid RWP & Contraction (left), RWP and MH (right)

In this model, the simulation area is divided into two areas: a circle and the area outside of the circle. The mobile nodes distributed inside the circle have different movement pattern than those nodes outside the circle. At the beginning, the nodes are distributed uniformly in the whole area. If the nodes are inside the circle, they will move as nodes in the contraction model straight toward the center point and stop when reaching the center point. Nodes outside the circle move as in the RWP mobility model. The nodes outside the circle may move into the circle. Once nodes move inside of the circle, they change to the contraction model. The speed to the next destination is randomly selected within [1, *Vmax*-1]. Nodes have a probability to pause for sometime when they reach a destination. Applications of this model include on campus student mobility.

Hybrid Manhattan & RWP Mobility Model

This model mixes characteristics of the Manhattan model and RWP (fig 3). The area is a map with horizontal and vertical streets and blocks. Each street has two lanes for each direction. When the nodes are on the street, they move as in Manhattan mobility model as in [1]; when located in the blocks, nodes move as in RWP. Nodes inside blocks have a probability to go outside the blocks onto streets. Nodes getting on a street will move as Manhattan mobility model nodes. Nodes moving on a street have a probability to go inside a block whenever they reach a corner of a new block. Once a node goes inside a block, it will move as RWP. Applications of this model include movement in a city [13].

4.2 Protocol Independent Metrics

The following mobility metrics, link duration, relative speed, temporal dependence, and spatial dependence, largely borrowed from [1] are studied to differentiate the characteristics of proposed and existing mobility models. We also use Node Degrees as another metric.

Node Degree (ND) is defined as the number of neighbor nodes averaged over the amount of nodes and every time instant [1]. Note that two nodes are neighbors if they are in transmission range (*tr*). The node degree *ND* is given by:

$$ND = \frac{\sum_{t=1}^{T}\sum_{i=1}^{N} N(i,t)}{T.N}$$

Where, N is number of nodes, T is simulation time, and $N(i,t)$ is the number of neighbor nodes for node i at time t. Node degree is expect to change drastically especially with contraction and expansion models. For contraction, when all nodes move towards a center, *ND* should go up over time. On the other hand, *ND* for the expansion model may decrease since nodes move away from the center.

Link Duration (LD) is the average duration of the links between all node pairs. Let $d(i,j)$ be the distance between nodes i and j. We define link $LK(i,j,t)=1$ only if $d(i,j)$ is less than the transmission range (*tr*) at time t. Also, define link change $LC(i,j,t)=1$ if $LK(i,j,t\text{-}1)=1$, $LK(i,j,t)=0$ or if i and j are always within *tr*. Number of link changes during the simulation is given by $LC(i,j)=\sum_{t=1}^{T} LC(i,j,t)$. The average link duration between i and j during the simulation is given by $LD(i,j) = \frac{\sum_{t=1}^{T} LK(i,j,t)}{LC(i,j)}$. Finally, the link duration is *LD(i,j)* averaged over all node pairs over time $\overline{LD} = \frac{\sum_{i=1}^{N}\sum_{j=i+1}^{N} LD(i,j)}{P}$, where *P* is number of node pairs such that $LD(i,j) \neq 0$.

Relative Velocity or speed between two nodes is defined as: $RS(i,j,t) = |\overrightarrow{V_i}(t) - \overrightarrow{V_j}(t)|$, and $\overline{RS} = \frac{\sum_{i=1}^{N}\sum_{j=1}^{N}\sum_{t=1}^{T} RS(i,j,t)}{P}$, where *P* is the number of tuples for all *(i,j,t)*. Average Relative Speed $\overline{RS}$ is described as *RS(i,j,t)* averaged over nodes pairs over time, with *RS(i,j,t)=0* when $d(i,j) > 2tr$.

Spatial Dependence shows the similarity of two nodes' velocities within a certain distance range [1], and is given by:

$$D_{spatial}(i,j,t) = RD(\overrightarrow{V_i}(t), \overrightarrow{V_j}(t)) * SR(\overrightarrow{V_i}(t), \overrightarrow{V_j}(t))$$

where $RD(\overrightarrow{V_i}(t), \overrightarrow{V_j}(t))$ is the relative direction (or cosine the angle between the two vectors $\overrightarrow{V_i}(t)$ and $\overrightarrow{V_j}(t)$), and *SR* is speed ratio given by $SR(\overrightarrow{V_i}(t), \overrightarrow{V_j}(t)) = \frac{\min(|\overrightarrow{V_i}(t), \overrightarrow{V_j}(t)|)}{\max(|\overrightarrow{V_i}(t), \overrightarrow{V_j}(t)|)}$. The average spatial dependence $\overline{Dspatial} = \frac{\sum_{t=1}^{T}\sum_{i=1}^{N}\sum_{j=i+1}^{N} Dspatial(i,j,t)}{P}$, where *P* is the number of tuples (*i,j,t*). Average Spatial Dependence captures correlation between nodes' movement. If two nodes move the same direction at the same speed, the spatial dependence will reach its maximum value. Only nodes with distance less than 2*tr* are considered.

Temporal Dependence shows the similarity of node's velocities at different times [1], and is given by:

$$D_{temporal}(i,t,t') = RD(\overrightarrow{V_i}(t), \overrightarrow{V_i}(t')) * SR(\overrightarrow{V_i}(t), \overrightarrow{V_i}(t')) \cdot$$

Average temporal dependence $\overline{Dtemporal} = \frac{\sum_{i=1}^{N}\sum_{t=1}^{T}\sum_{t'=1}^{T} Dspatial(i,t,t')}{P}$, where *P* is the number of tuples (*i,t,t'*). Average Temporal Dependence expresses the correlation between two speed vectors of a node at different times. A node moving with the same speed and direction has high temporal dependence.

5. SIMULATION AND ANALYSIS

5.1 Mobility Metrics Analysis

To understand the characteristics of the previous six mobility models, detailed simulations have been conducted to measure the mobility metrics including node degree, link duration, relative speed, spatial dependence, and temporal dependence. A network of 50 nodes was used with maximum speed set to 5,10,15,20,25m/s, and areas of 4kmx4km and 1.5kmx1.5km. The transmission range of each node is 250m.

(1) Average Node Degree

Fig 4, 5 present the simulation results for the average node degree. For contraction, modified contraction, and RWP & contraction, nodes have similar behavior with time. These nodes merge together towards the center and have more neighbors over time leading the higher node degree. The same result occurs in Fig 10 when nodes are assigned a high speed. In sum, for contraction models an increase in node degree is observed with increase in node velocity and simulation time.

On the other hand, node degree of circling and RWP & Manhattan models remains almost constant over time and with the different speed. This is due to restrictions imposed by the map (e.g., streets) to restrict node deployment.

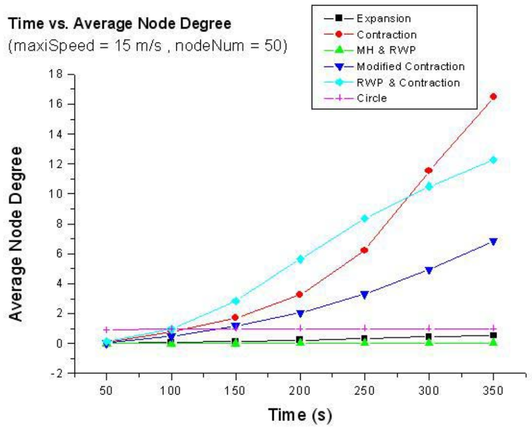


Fig 4 Average Node Degree vs. Simulation Time
(Initial positions are randomly deployed, area 4kmx4km)

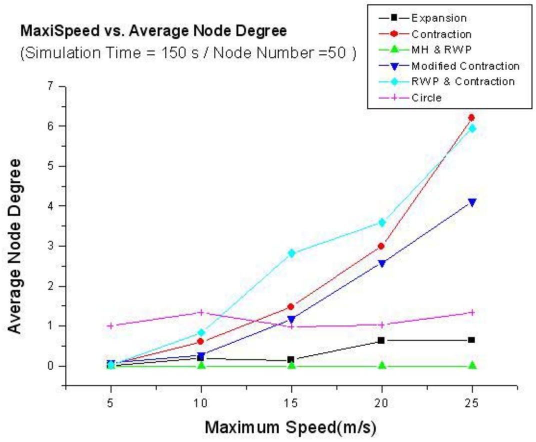


Fig 5 Average Node Degree vs. Mobility
(Initial positions are randomly deployed, area 4kmx4km)

For the expansion model, due to the sparse 4kmx4km network, node degree shows a low constant value from start to end. However, when the speed exceeds 20m/s some nodes reach the border and get into the radio range of other nodes. Due to this *border effect*, the node degree increases.

For smaller network area (1.5kmx1.5km) results are shown in Fig 6 and Fig 7. In this simulation, we limit the node's initial position for the expansion model to within 50m around the center. Note that node degree of this expansion model decreases over time and with the increasing speed.

(2) Average Link Duration

Two factors affect the dynamics of links between nodes. First, the distance between the nodes, and second is the relative speed between them. If two nodes are connected and moving away then the link between them will break. If they are not connected but moving closer a link will be created.

Fig 8 shows the decreasing link duration with increase of velocity almost consistently across all models. One exception is the MH&RWP as will be explained using relative velocity. Initially, we expected the contraction model to increase the link duration with increase in speed due to the merging effect. So we conducted another set of simulations with constant speed for the contraction and expansion models. Fig 9 compares results with random and constant speeds for extended (500s) simulation runs. For the contraction model, we see that as the speed increases so does the link duration. This is due to the movement pattern and merging of nodes towards the center, which leads to reduced link breaks and creation of new links. The reason is that nodes keep the same distance as they move toward the center. Then distance between node pairs will decrease because the moving nodes approach stopped nodes. With low random speed (5-10m/s), for the contraction model links tend to break due to relative speed. For expansion model, nodes always move away from the center, which breaks more links with increasing speed.

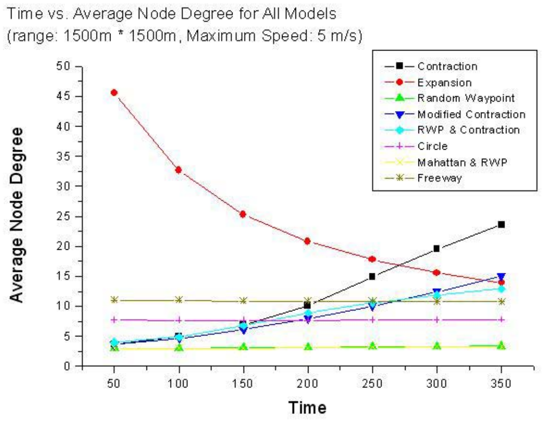


Fig 6. Node Degree vs. Simulation Time
(Restricted initial positions for the expansion model only)

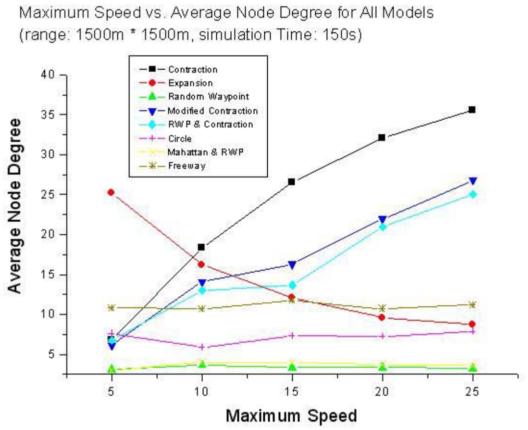


Fig 7. Node Degree vs. Mobility
(Restricted initial positions for the expansion model only)

(3) Average Relative Speed

Low relative speed indicates strong correlation between node movement, as in group mobility. In [1][2] it was shown that models with geographic constraints and bidirectional movement (e.g., FWY, MH models) have high relative speed. Movement in these models has less correlation between nodes, except neighboring nodes in the same lane. In our case, this resembles the circling model that exhibits high relative speed across various velocities (Fig 10). Terminal mobility models, including contraction, modified contraction, RWP & contraction, and expansion models, exhibit medium average relative speed, due to lack of bi-directionality. For these models, the relative speed increases with increasing velocity.

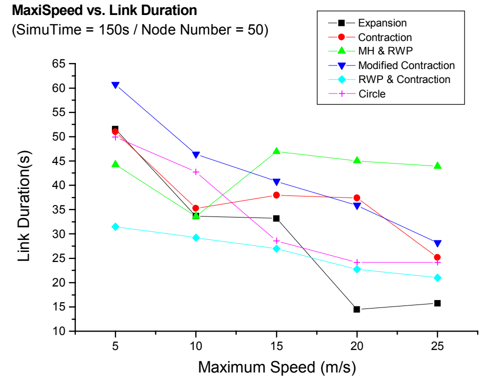


Fig 8 Link Duration vs. Mobility

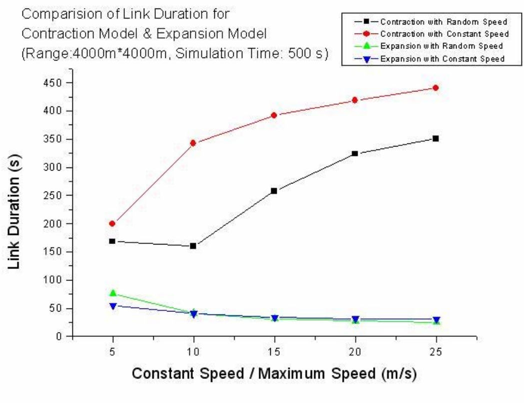


Fig 9. Link Duration (Constant Speed vs. Random Speed)

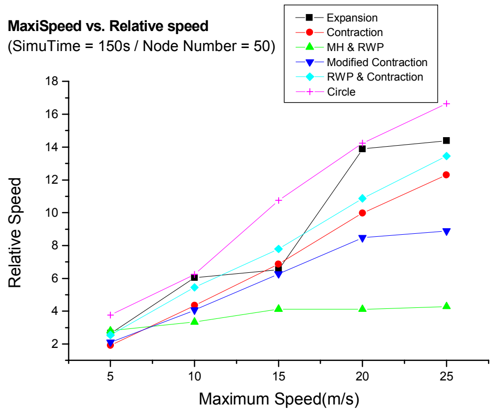


Fig 10. Relative Speed vs. Mobility

The MH&RWP hybrid model shows the lowest relative speed, because the RWP blocks area is much larger than that for MH (Fig 3). Hence, nodes within the RWP blocks decrease the relative speed. Relative speed, hence, is a meaningful metric to compare different mobility models.

(4) Average Degree of Spatial Dependence

Fig 11 shows the average spatial dependence. It is clear that this metric is able to clearly differentiate between the mobility models. For expansion and contraction we get high spatial dependence, while for hybrid and circular we get medium to low spatial dependence.

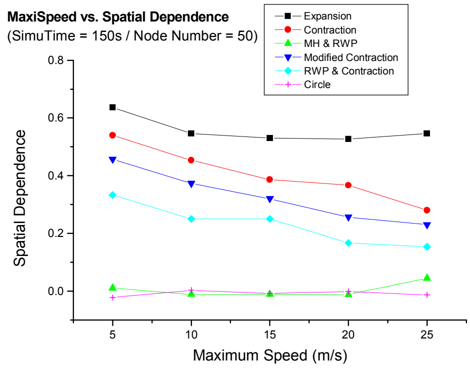


Fig 11. Spatial Dependence vs. Mobility

(5) Average Degree of Temporal Dependence

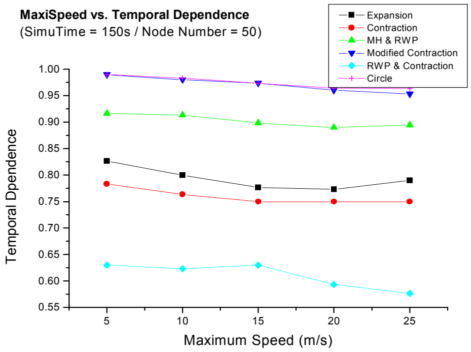


Fig 12. Temporal Dependence vs. Mobility

From Fig 12, expansion and contraction seem to exhibit medium temporal dependence. RWP&Contraction has the lowest temporal dependence while MH&RWP, circular and MH&RWP exhibit the strongest temporal correlation. This metric seems to differentiate between the proposed models.

We used the above mobility models to study ad hoc routing protocols in [18]. Details are omitted due to lack of space.

6. CONCLUSION

In this paper, we introduce several new mobility models including contraction, expansion, and hybrid models, and provide a classification for the mobility models. Our simulation indicates that no one metric is sufficient to understand mobility, but average node degree and link duration are useful to differentiate mobility characteristics and dynamics. Contraction-based models (contraction, modified contraction, and RWP & contraction), lead to an increase in average node degree and link duration with increase in velocity for non-sparse networks. This in turn leads to more throughput [18]. With constant speed, the performance steadily becomes better compared with random speed due to fewer broken links and a merging movement toward the center. The expansion model leads to reduced node degree and link duration with increased velocity. This leads to reduced throughput due to disconnections. When restricting the intial placement of nodes near the center, link duration and node degree reduce more drastically with velocity and the performance becomes worse. Circling model has the maximum relative speed, but does not incur as much disconnections as does expansion model.

Our on-going work [18] evaluates various routing protocols across these different mobility models to develop further insight as to which characteristics of mobility dominate the throughput and overhead performance of ad hoc routing protocols. We also plan to develop trace-based mobility models based on actual mobility traces collected from the USC campus.

REFERENCES[*][+]

[1] F. Bai, N. Sadagopan, A. Helmy, "*IMPORTANT*:A framework to systematically analyze the Impact of Mobility on Performance of RouTing protocols for Adhoc NeTworks", *IEEE INFOCOM*,April 2003

[2] N. Sadagopan, F. Bai, B. Krishnamachari, A. Helmy, "*PATHS*: analysis of PATH duration Statistics and their impact on reactive MANET routing protocols", *ACM MobiHoc*, June 2003.

[3] M. M. Zonoozi and P. Dassanayake. User mobility modeling and characterization of mobility patterns. *IEEE Journal on Selected Area in Communications*, 15(7):1239-1252. Sept 1997.

[4] M. Sanchez. Mobility models. http://www.disca.upv.es/misan/mobmodel.htm, 1998.

[5] X. Hong, M. Gerla, G. Pei, and C.-C. Chiang, "A group mobility model for ad hoc wireless networks," *ACM/IEEE MSWIM*, August 1999.

[6] C. E. Perkins and P. Bhagwat, "Highly dynamic destination sequenced distance vector routing (DSDV) for mobile computers," *ACM SIGCOMM*, 1994, pp. 234-244

[7] C. E. Perkins, E. M. Royer, "Ad-hoc On-Demand Distance Vector Routing", *2nd IEEE Workshop Mobile Comp* Sys&Aps. Feb. 1999, p 90-100.

[8] D. B. Johnson, D. A. Maltz, and J. Broch, "DSR: The dynamic source routing protocol for multi-hop wireless ad-hoc wireless networks", in Ad Hoc Networking, C. Perkins, Ed. Addison-Wesley, 2001, pp.139-172.

[10] Samir R. Das, Charles E. Perkins, and Elizabeth M. Royer "Performance Comparison of Two On-demand Routing Protocols for Ad Hoc Networks" in *INFOCOM*, March 2000.

[11] J. Yoon, M. Liu and B. Noble, "Random Waypoint Considered Harmful", in *IEEE INFOCOM*, April 2003, San Francisco, CA.

[12] Tracy Camp, Jeff Boleng, and Vanessa Davies: "A survey of Mobility Models for Ad Hoc Network research", April 12, 2002.

[13] P. Johansson, T. Larsson, N.Hedman, B. Mielczarek, and N. Degermark, "Scenario-based performance analysis of routing protocols for mobile ad-hoc networks," *ACM MobiCom'99)*,1999, pp.195-206.

[14] L. Breslau, D. Estrin, K. Fall, S. Floyd, J. Heidemann, A. Helmy, P. Huang, S. McCanne, K. Varadhan, Y. Xu, and H. Yu, " Advances in network simulation," *in IEEE Computer,* vol. 33, May 2000, pp.59-67

[15] J. Broch, D. A. Maltz, D. B. Johnson, Y.-C. Hu, and J. Jetcheva, „ A performance comparison of multihop wireless ad hoc network routing protocols,“ *ACM Mobicom*, October 1998.

[16] D. A. Maltz, J. Broch, J. Jetcheva, and D. B. Johnson, "The effects of on-demand behavior in routing protocols for multi-hop wireless ad hoc networks" *in IEEE Journal on Selected Areas in Communications special issue on mobile and wireless networks*, August 1999.

[17] X. Hong, T. Kwon, M. Gerla, D. Gu, and G. Pei, "A mobility framework for ad hoc wireless networks," *in ACM Second International Conference on Mobile Data Management (MDM)*, January 2001.

[18] Y. Lu, H. Lin, Y. Gu, A. Helmy, "Towards Mobility-Rich Performance Analysis of Routing Protocols in Ad Hoc Networks: Using Contraction, Expansion and Hybrid Models", USC Technical Report, March 2004.

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[*] A. Helmy was supported by NSF CAREER 0134650, Intel research grant and Pratt&Whitney Institute for Collaborative Engineering (PWICE).

[+] We acknowledge the excellent help of Fan Bai and Narayanan Sadagopan in using the *IMPORTANT* tool and defining the mobility metrics.