IMPORTANT: A framework to systematically analyze the Impact of Mobility on Performance of RouTing protocols for Adhoc NeTworks

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***Abstract*— A Mobile Ad hoc Network (MANET) is a collection of wireless mobile nodes forming a temporary network without using any existing infrastructure. Since not many MANETs are currently deployed, research in this area is mostly simulation based. Random Waypoint is the commonly used mobility model in these simulations. Random Waypoint is a simple model that may be applicable to some scenarios. However, we believe that it is not sufficient to capture some important mobility characteristics of scenarios in which MANETs may be deployed. Our framework aims to evaluate the impact of different mobility models on the performance of MANET routing protocols. We propose various protocol independent metrics to capture interesting mobility characteristics, including spatial and temporal dependence and geographic restrictions. In addition, a rich set of parameterized mobility models is introduced including Random Waypoint, Group Mobility, Freeway and Manhattan models. Based on these models several 'test-suite' scenarios are chosen carefully to span the metric space. We demonstrate the utility of our test-suite by evaluating various MANET routing protocols, including DSR, AODV and DSDV. Our results show that the protocol performance may vary drastically across mobility models and performance rankings of protocols may vary with the mobility models used. This effect can be explained by the interaction of the mobility characteristics with the connectivity graph properties. Finally, we attempt to decompose the routing protocols into mechanistic "building blocks" to gain a deeper insight into the performance variations across protocols in the face of mobility.**

I. INTRODUCTION

A Mobile Ad hoc NETwork (MANET) is a collection of wireless nodes communicating with each other in the absence of any infrastructure. Classrooms, battlefields and disaster relief activities are a few scenarios where MANETs can be used. MANET research is gaining ground due to the ubiquity of small, inexpensive wireless communicating devices. Since, not many MANETs have been deployed, most of this research is simulation based. These simulations have several parameters including the mobility model and the communicating traffic pattern. In this paper, we focus on the impact of mobility models on the performance of MANET routing protocols. We acknowledge that the communicating traffic pattern also has a significant impact on the routing protocol performance and merits a study on its own. However, as in most studies in this area, in order to isolate the effect of mobility, we fix the communicating traffic pattern to consist of randomly chosen source-destination pairs with long enough session times.

Mobility pattern, in many previous works was assumed to be Random Waypoint. In the current network simulator *(ns-2)* distribution, the implementation of this mobility model is as follows: at every instant, a node randomly chooses a destination and moves towards it with a velocity chosen uniformly randomly from $[0, V_{max}]$, where V_{max} is the maximum allowable velocity for every mobile node [1]. Most of the simulations using the Random Waypoint model are based on this standard implementation. For the rest of the paper, we refer to this basic implementation as the Random Waypoint model.

In the future, MANETs are expected to be deployed in myriads of scenarios having complex node mobility and connectivity dynamics. For example, in a MANET on a battlefield, the movement of the soldiers will be influenced by the commander. In a city-wide MANET, the node movement is restricted by obstacles or maps. The node mobility characteristics are very application specific. Widely varying mobility characteristics are expected to have a significant impact on the performance of the routing protocols like DSR [2], DSDV [3] and AODV [4]. Random Waypoint is a well designed model but it is insufficient to capture the following characteristics:

1) Spatial dependence of movement among nodes.
2) Temporal Dependence of movement of a node over time.
3) Existence of barriers or obstacles constraining mobility.

In this study, we focus on the impact of the above mentioned mobility characteristics on protocol performance. While doing so, we propose a generic framework to systematically analyze the impact of mobility on the performance of routing protocols for MANETs. This analysis attempts to answer the following questions:

1) Whether mobility affects routing protocol performance?
2) If the answer to 1 is yes, why?
3) If the answer to 1 is yes, how?

To answer *Whether*, the framework evaluates the perfor-

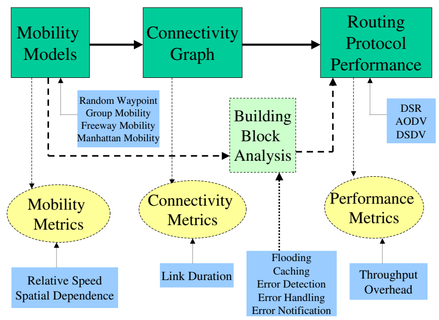

Fig. 1. IMPORTANT Framework

mance of these routing protocols over different mobility patterns that capture some of the characteristics listed above. The mobility models used in our study include the Random Waypoint, Group Mobility [5], Freeway and Manhattan. To answer *Why*, we propose some protocol independent metrics such as mobility metrics and connectivity graph metrics. Mobility metrics aim to capture some of the aforementioned mobility characteristics. Connectivity graph metrics aim to study the effect of different mobility patterns on the connectivity graph of the mobile nodes. It has also been observed in previous works that under a given mobility pattern, routing protocols like DSR, DSDV and AODV perform differently [6] [7] [8]. This is possibly because each protocol differs in the basic mechanisms or "building blocks" it uses. For example, DSR uses route discovery, while DSDV uses periodic updates. To answer *How*, we want to investigate the effect of mobility on some of these "building blocks" and how they impact the protocol performance as a "whole".

In order to conduct our research and answer the above questions systematically, we propose a framework for analyzing the Impact of Mobility on the Performance Of RouTing protocols in Adhoc NeTworks (IMPORTANT). Through this framework we illustrate how modeling mobility is important in affecting routing performance and understanding the mechanism of ad hoc routing protocols. As shown in Fig.1, our framework focuses on the following aspects: mobility models, the metrics for mobility and connectivity graph characteristics, the potential relationship between mobility and routing performance and the analysis of impact of mobility on building blocks of ad hoc routing protocols.

The rest of this paper is organized as follows. Section II gives a brief description of the related work and elaborates our contribution. Section III discusses some limitations of the Random Waypoint model and motivates part of our framework. Section IV presents our proposed metrics to capture characteristics of mobility and the connectivity graph between the mobile nodes. Section V describes the mobility models used and introduces two new models, the Freeway mobility model and the Manhattan mobility model. Results of our simulation experiments are presented and discussed in Section VI. The analysis of the impact of mobility on protocol building blocks is discussed in Section VII. Finally, our conclusions from this study and planned future work are listed in section VIII.

II. Related Work

Extensive research has been done in modeling mobility for MANETs. In this section, we mainly focus on experimental research in this area. This research can be broadly classified as follows based on the methodology used:

A. Random Waypoint Based Performance Comparisons

Much of the initial research was based on using Random Waypoint as the underlying mobility model and CBR traffic consisting of randomly chosen source destination pairs as the traffic pattern. Routing protocols like DSR [2], DSDV [3], AODV [4] and TORA [9] were mainly evaluated based on the following metrics: packet delivery ratio (ratio of the number of packets received to the number of packets sent) and routing overhead (number of routing control packets sent). [6] concluded that on-demand protocols such as DSR and AODV performed better than table driven ones such as DSDV at high mobility rates, while DSDV performed quite well at low mobility rates. [7] performed a comparison study of the two on-demand routing protocols: DSR and AODV, using the performance metrics of packet delivery ratio and end to end delay. It observed that DSR outperforms AODV in less demanding situations, while AODV outperforms DSR at heavy traffic load and high mobility. However, the routing overhead of DSR was found to be lesser than that of AODV. In the above works, focus was given on performance evaluation, while parameters investigated in the mobility model were change of maximum velocity and pause time. In our work, however, we design our test suites very carefully to pick scenarios that span a much larger set of mobility characteristics. Not only do we use Random Waypoint but also other mobility models such as RPGM [5], Freeway and Manhattan in our evaluation of the performance of routing protocols.

B. Scenario Based Performance Comparisons

Random Waypoint is a simple model that is easy to analyze and implement. This has probably been the main reason for the widespread use of this model for simulations. Realizing that Random Waypoint is too general a model, recent research has started focusing on alternative mobility models and protocol independent metrics to characterize them. [10] conducted a scenario based performance analysis of the MANET protocols. It proposed models for a few "realistic" scenarios such as a conference, event coverage and disaster relief. To differentiate between scenarios used, the study introduced the relative motion of the mobile nodes as a mobility metric. Their conclusions about the performance of proactive and reactive protocols were similar to [6]. [8] used a mobility model in which each node computes its next position based on a probability distribution. This model does not allow significant changes in direction between successive instants. It concluded that proactive protocols perform better than reactive ones in terms of packet delivery ratio and end-to-end delay. However, reactive protocols were seen to incur a lower routing overhead. [5] introduced the Reference Point Group Mobility (RPGM) model, which is one of the mobility models used in this study. Rate of link changes was used to characterize a few group mobility patterns as well as Random Waypoint. It observed that the rate of link change for Random Waypoint was higher than that for RPGM. From experiments, it observed that protocols like AODV, DSDV and HSR [11] perform worse with Random Waypoint than with RPGM. Thus, it concluded that mobility models do matter and it is not sufficient to simulate protocols with only the "random walk" like models. [12] proposed a mobility framework that consisted of a Mobility Vector Model which can be used to generate "realistic" movement patterns used in several varied applications. It proposed the Displacement Measure that is a normalization of the actual distance traveled by the geographic displacement as a metric to evaluate the different movement patterns including those generated by Random Waypoint, Random Walk, RPGM and Mobility Vector models. By experiments, it observed that Random Waypoint and Random Walk produced higher Displacement Measure as compared to the Mobility Vector model. It studied the effect of transmission range on throughput across different mobility models and concluded that as the transmission range is increased, the rate of link changes decreased and the throughput for all protocols increased. However, the link change rate does not seem to vary greatly across the different mobility models. As far as routing overhead was concerned, Mobility Vector was seen to produce a worse overhead than Random Waypoint. Our study is also framework based. However, we do not aim to provide a generic mobility model from which all "realistic" mobility patterns can be derived. Rather, our framework aims at systematically studying the effect of mobility per se on performance of MANET routing protocols. The contributions of our proposed framework are three fold:

1) Focus on mobility characteristics such as spatial dependence, geographic restrictions and temporal dependence. Define mobility metrics that capture these characteristics. Choose mobility models that span the metric space and use them to evaluate the performance of routing protocols.
2) Define connectivity graph metrics. Study the interaction of mobility metrics and connectivity graph metrics and its effect on protocol performance.
3) Analyze the reasons for the differences in protocol performance as a "whole" by investigating the effect of mobility on "parts" that build the protocol.

III. Limitations of Random Waypoint

Random Waypoint model was introduced in [6] and is among the most commonly used mobility models in the MANET research community. In this model, at every instant, each mobile node chooses a random destination and moves towards it with a speed uniformly distributed in $[0, V_{max}]$, where V_{max} is the maximum allowable speed for a node. After reaching the destination, the node stops for a duration defined by the "pause time" parameter. After this duration, it again chooses a random destination and repeats the whole process again until the simulation ends.

The Random Waypoint model is widely accepted mainly due to its simplicity of implementation and analysis. However, we observe that the basic Random Waypoint model as used in most of the simulations is insufficient to capture the following mobility characteristics:

1) **Temporal dependency:** Due to physical constraints of the mobile entity itself, the velocity of mobile node will change continuously and gently instead of abruptly, i.e. the current velocity is dependent on the previous velocity. However, the velocities at two different time slots are independent in the Random Waypoint model.
2) **Spatial dependency:** The movement pattern of a mobile node may be influenced by and correlated with nodes in its neighborhood. In Random Waypoint, each mobile node moves independently of others.
3) **Geographic restrictions:** In many cases, the movement of a mobile node may be restricted along the street or a freeway. A geographic map may define these boundaries.

In our study, we focus on the above-mentioned characteristics. In the next section, we formally define metrics to capture some of these characteristics.

IV. Metrics

To quantitatively and qualitatively analyze the impact of mobility on routing protocol performance, we make use of several protocol independent metrics and protocol performance metrics. The protocol independent metrics attempt to extract the characteristics of mobility and the connectivity graph between the mobile nodes. These metrics are then used to explain the impact of mobility on the protocol performance metrics. The metrics we use can be broadly classified as:

1) Protocol Independent Metrics.
2) Protocol Performance Metrics.

A. Terminology

Before formally defining the metrics, we introduce some basic terminology that will be used later in the paper:

1) $\vec{V_i}(t)$: Velocity vector of node i at time t.
2) $|\vec{V_i}(t)|$: Speed of node i at time t.
3) $\theta_i(t)$: Angle made by $\vec{V_i}(t)$ at time t with the X-axis.
4) $\vec{a_i}(t)$: Acceleration vector of node i at time t.
5) $x_i(t)$: X co-ordinate of node i at time t.
6) $y_i(t)$: Y co-ordinate of node i at time t.
7) $D_{i,j}(t)$: Euclidean Distance between nodes i and j at time t.
8) $RD(\vec{a}(t), \vec{b}(t'))$: Relative Direction(RD) (or cosine of the angle) between the two vectors $\vec{a}(t), \vec{b}(t')$ is given by $\frac{\vec{a}(t)\cdot\vec{b}(t')}{|\vec{a}(t)|*|\vec{b}(t')|}$.
9) $SR(\vec{a}(t), \vec{b}(t'))$: Speed Ratio(SR) between the two vectors $\vec{a}(t), \vec{b}(t')$ is given by $\frac{\min|\vec{a}(t)|,|\vec{b}(t')|}{\max|\vec{a}(t)|,|\vec{b}(t')|}$.
10) R: Transmission range of a mobile node.
11) N: Number of mobile nodes.
12) T: Simulation time.
13) $random()$: returns a value uniformly distributed in the interval $[-1, 1]$.

B. Protocol Independent Metrics

Mobility Metrics: We propose these metrics to differentiate the various mobility patterns used in our study. The basis of differentiation is the extent to which a given mobility pattern captures the characteristics of spatial dependence, temporal dependence and geographic restrictions. In addition to these metrics, we also use the Relative Speed metric that differentiates mobility patterns based on relative motion. This metric was proposed in [10].

1) **Degree of Spatial Dependence:** It is extent of similarity of the velocities of two nodes that are not too far apart. Formally,

$$D_{spatial}(i,j,t) = RD(\vec{v_i}(t), \vec{v_j}(t)) * SR(\vec{v_i}(t), \vec{v_j}(t))$$

The value of $D_{spatial}(i,j,t)$ is high when the nodes i and j travel in more or less the same direction and at almost similar speeds. However, $D_{spatial}(i,j,t)$ decreases if the Relative Direction or the Speed Ratio decreases.

As it is rare for a node's motion to be spatially dependent on a far off node, we add the condition that

$$D_{i,j}(t) > c_1 * R \Rightarrow D_{spatial}(i,j,t) = 0$$

where $c_1 > 0$ is a constant which will be determined during our experiments in VI.

Average Degree of Spatial Dependence: It is the value of $D_{spatial}(i,j,t)$ averaged over node pairs and time instants satisfying certain condition. Formally,

$$\bar{D}_{spatial} = \frac{\sum_{t=1}^{T}\sum_{i=1}^{N}\sum_{j=i+1}^{N} D_{spatial}(i,j,t)}{P}$$

where P is the number of tuples (i,j,t) such that $D_{spatial}(i,j,t) \neq 0$. Thus, if mobile nodes move independently of one another, then the mobility pattern is expected to have a smaller value for $\bar{D}_{spatial}$. On the other hand, if the node movement is co-ordinated by a central entity, or influenced by nodes in its neighborhood, such that they move in similar directions and at similar speeds, then the mobility pattern is expected to have a higher value for $\bar{D}_{spatial}$.

2) **Degree of Temporal Dependence:** It is the extent of similarity of the velocities of a node at two time slots that are not too far apart. It is a function of the acceleration of the mobile node and the geographic restrictions. Formally,

$$D_{temporal}(i,t,t') = RD(\vec{v_i}(t), \vec{v_i}(t')) * SR(\vec{v_i}(t), \vec{v_i}(t'))$$

The value of $D_{temporal}(i,t,t')$ is high when the node travels in more or less the same direction and almost at the same speed over a certain time interval that can be defined. However, $D_{temporal}(i,t,t')$ decreases if the Relative Direction or the Speed Ratio decreases.

Arguing in a way similar to that for $D_{spatial}(i,j,t)$, we have the following condition

$$|t - t'| > c_2 \Rightarrow D_{temporal}(i,t,t') = 0$$

where $c_2 > 0$ is a constant which will be determined during our experiments in section VI.

Average Degree of Temporal Dependence: It is the value of $D_{temporal}(i,t,t')$ averaged over nodes and time instants satisfying certain condition. Formally,

$$\bar{D}_{temporal} = \frac{\sum_{i=1}^{N}\sum_{t=1}^{T}\sum_{t'=1}^{T} D_{temporal}(i,t,t')}{P}$$

where P is the number of tuples (i,t,t') such that $D_{temporal}(i,t,t') \neq 0$ Thus, if the current velocity of a node is completely independent of its velocity at some previous time step, then the mobility pattern is expected to have a smaller value for $\bar{D}_{temporal}$. However, if the current velocity is strongly dependent on the velocity at some previous time step, then the mobility pattern is expected to have a higher value for $\bar{D}_{temporal}$.

3) **Relative Speed (RS):** We use the standard definition from physics i.e.

$$\mathrm{RS}(i,j,t) = |\vec{V_i}(t) - \vec{V_j}(t)|$$

As in the case of $D_{spatial}(i,j,t)$, we add the following condition

$$D_{i,j}(t) > c_3 * R \Rightarrow \mathrm{RS}(i,j,t) = 0$$

where $c_3 > 0$ is a constant which will be determined during our experiments in VI.

Average Relative Speed: It is the value of $\mathrm{RS}(i,j,t)$ averaged over node pairs and time instants satisfying certain condition. Formally,

$$\bar{\mathrm{RS}} = \frac{\sum_{i=1}^{N}\sum_{j=1}^{N}\sum_{t=1}^{T} \mathrm{RS}(i,j,t)}{P}$$

where P is the number of tuples (i,j,t) such that $\mathrm{RS}(i,j,t) \neq 0$.

4) **Geographic Restrictions:** We developed the notion of degree of freedom of points on a map. Degree of freedom of a point is the number of directions a node can go after reaching that point[1]. We do not quantitatively define the Geographic Restrictions, but we qualitatively include it in our study as will be seen in Section V.

Connectivity Graph Metrics: Since routing protocol performance is in general affected by the network topology dynamics, we feel that it is useful to have metrics to analyze the effect of mobility on the connectivity graph between the mobile nodes. The connectivity graph metrics aim to study this effect. These metrics might also help in relating mobility metrics with protocol performance, which will be shown in Section VI.

The connectivity graph is the graph $G = (V, E)$, such that $|V| = N$ and at time t, a link $(i,j) \in E$ iff $D_{i,j}(t) \leq R$. Let $X(i,j,t)$ be an indicator random variable which has a value 1 iff there is a link between nodes i and j at time t. $X(i,j) = \max_{t=1}^{T} X(i,j,t)$ be an indicator random variable

[1]Currently we do not have a good way of quantitatively aggregating this definition for the whole map. This is part of our on going and future work.

which is 1 if a link existed between nodes i and j at any time during the simulation, 0 otherwise.

1) **Number of Link Changes:** Number of link changes for a pair of nodes i and j is the number of times the link between them transitions from "down" to "up". Formally,

$$\text{LC}(i,j) = \sum_{t=1}^{T} C(i,j,t)$$

where $C(i,j,t)$ is an indicator random variable such that $C(i,j,t) = 1$ iff $X(i,j,t-1) = 0$ and $X(i,j,t) = 1$ i.e. if the link between nodes i and j is down at time $t-1$, but comes up at time t.

Average Number of Link Changes: It is the value of LC(i,j) averaged over node pairs satisfying certain condition. Formally,

$$\bar{\text{LC}} = \frac{\sum_{i=1}^{N}\sum_{j=i+1}^{N} \text{LC}(i,j)}{P}$$

where P is the number of pairs i,j such that $X(i,j) \neq 0$.

2) **Link Duration:** It is the average duration of the link existing between two nodes i and j. It is a measure of stability of the link between these nodes. Formally,

$$\text{LD}(i,j) = \begin{cases} \frac{\sum_{t=1}^{T} X(i,j,t)}{\text{LC}(i,j)} & \text{if } \text{LC}(i,j) \neq 0 \\ \sum_{t=1}^{T} X(i,j,t) & \text{otherwise} \end{cases} \quad (1)$$

Average Link Duration: It is the value of LD(i,j) averaged over node pairs satisfying certain condition. Formally,

$$\bar{\text{LD}} = \frac{\sum_{i=1}^{N}\sum_{j=i+1}^{N} \text{LD}(i,j)}{P}$$

where P is the number of pairs i,j such that $X(i,j) \neq 0$.

3) **Path Availability:** It is the fraction of time during which a path is available between two nodes i and j. The node pairs of interest are the ones that have communication traffic between them. Formally,

$$\text{PA}(i,j) = \begin{cases} \frac{\sum_{t=\text{start}(i,j)}^{T} A(i,j,t)}{T-\text{start}(i,j)} & \text{if } T - \text{start}(i,j) > 0 \\ 0 & \text{otherwise} \end{cases} \quad (2)$$

where $A(i,j,t)$ is an indicator random variable which has a value 1 if a path is available from node i to node j at time t, and has a value 0 otherwise. start(i,j) is the time at which the communication traffic between nodes i and j starts.

Average Path Availability: It is the value of PA(i,j) averaged over node pairs satisfying certain condition. Formally,

$$\bar{\text{PA}} = \frac{\sum_{i=1}^{N}\sum_{j=i+1}^{N} \text{PA}(i,j)}{P}$$

where P is the number of pairs i,j such that $T -$ start$(i,j) > 0$.

C. *Protocol Performance Metrics:*

We evaluate the performance of the MANET routing protocols using the metrics of throughput (ratio of the number of packets delivered to the number of packets sent) and routing overhead (number of routing control packets sent) as done in several previous studies in this area of research.

V. Mobility Models

As mentioned in Section I, Random Waypoint does not seem to capture the mobility characteristics of spatial dependence, temporal dependence and geographic restrictions. In the previous section, we defined Mobility metrics that either qualitatively or quantitatively define these characteristics. To thoroughly study the effect of mobility on MANET protocol performance, we seek to evaluate the protocols over a rich set of mobility models that span the design space of the Mobility metrics. Thus, apart from Random Waypoint, we use the following mobility models:

1) Reference Point Group Mobility (RPGM) Model
2) Freeway Mobility Model
3) Manhattan Mobility Model

Each of the above models has certain characteristics that are different from Random Waypoint, which will be shown by our metrics and simulations.

1) **RPGM Model:** [5] introduced this model. Here, each group has a logical center (group leader) that determines the group's motion behavior. Initially, each member of the group is uniformly distributed in the neighborhood of the group leader. Subsequently, at each instant, every node has a speed and direction that is derived by randomly deviating from that of the group leader.

Applications: Group mobility can be used in military battlefield communications where the commander and soldiers form a logical group. More applications are mentioned in [5].

Important Characteristics: Each node deviates its velocity (both speed and direction) randomly from that of the leader. The movement in group mobility can be characterized as follows:

a) $\left|\vec{V}_{member}(t)\right| = \left|\vec{V}_{leader}(t)\right| + random() * SDR * max\_speed$

b) $\theta_{member}(t) = \theta_{leader}(t) + random() * ADR * max\_angle$

where $0 \leq SDR, ADR \leq 1$. SDR is the Speed Deviation Ratio and ADR is the Angle Deviation Ratio. SDR and ADR are used to control the deviation of the velocity (magnitude and direction) of group members from that of the leader. max_speed and max_angle are used to specify the maximum deviation a group member can take. In our simulation, we set maximum speed for the group leader as the max_speed and set 180° as the max angle. Since the group leader mainly decides the mobility of group members, group mobility pattern is expected to have high spatial dependence for small values of SDR and ADR.

2) **Freeway Mobility Model:** We propose this new model to emulate the motion behavior of mobile nodes on a freeway. The freeway map used in our study is shown in Fig.2.
Applications: It can be used in exchanging traffic status or tracking a vehicle on a freeway.
Important Characteristics: In this model we use maps. There are several freeways on the map and each freeway has lanes in both directions. The differences between Random Waypoint and Freeway are the following:
   a) Each mobile node is restricted to its lane on the freeway.
   b) The velocity of mobile node is temporally dependent on its previous velocity.
   c) If two mobile nodes on the same freeway lane are within the Safety Distance (SD), the velocity of the following node cannot exceed the velocity of preceding node.

The inter-node and intra-node relationships involved are:
   a) $\left|\vec{V_i}(t+1)\right| = \left|\vec{V_i}(t)\right| + random() * |\vec{a_i}(t)|$
   b) $\forall i, \forall j, \forall t \quad D_{i,j}(t) \leq SD \Rightarrow |\vec{V_i}(t)| \leq |\vec{V_j}(t)|$, if j is ahead of i in its lane.

Due to the above relationships, the Freeway mobility pattern is expected to have spatial dependence and high temporal dependence. It also imposes strict geographic restrictions on the node movement by not allowing a node to change its lane.

3) **Manhattan Mobility Model:** We introduce the Manhattan model to emulate the movement pattern of mobile nodes on streets defined by maps. The Manhattan map used in our study is shown in Fig.3.
Applications: It can be useful in modeling movement in an urban area where a pervasive computing service between portable devices is provided.
Important Characteristics: Maps are used in this model too. The map is composed of a number of horizontal and vertical streets. Each street has two lanes for each direction (North and South direction for vertical streets, East and West for horizontal streets). The mobile node is allowed to move along the grid of horizontal and vertical streets on the map. At an intersection of a horizontal and a vertical street, the mobile node can turn left, right or go straight. This choice is probabilistic: the probability of moving on the same street is 0.5, the probability of turning left is 0.25 and the probability of turning right is 0.25.
The velocity of a mobile node at a time slot is dependent on its velocity at the previous time slot. Also, a node's velocity is restricted by the velocity of the node preceding it on the same lane of the street. The inter-node and intra-node relationships involved are the same as in the Freeway model.
Thus, the Manhattan mobility model is also expected to have high spatial dependence and high temporal dependence. It too imposes geographic restrictions on node mobility. However, it differs from the Freeway model in giving a node some freedom to change its direction.

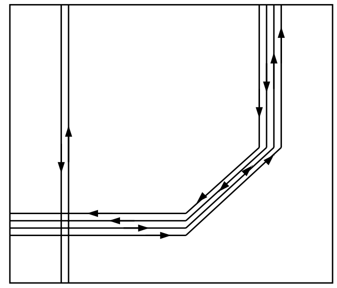

Fig. 2. Map used in Freeway Mobility Model

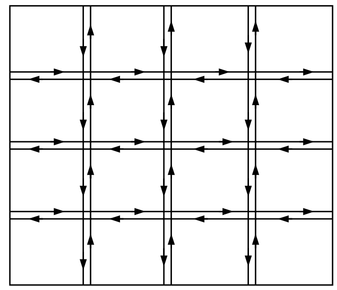

Fig. 3. Map used in Manhattan Mobility Model

Most of the mobility models mentioned above are parameterized. E.g. SDR and ADR are some of the parameters used in RPGM, while maps are important parameters in the Freeway and Manhattan models. Although we did not quantitatively define Geographic Restrictions in Section IV, we qualitatively include them in our study by using the Freeway and Manhattan models. Using a parameterized approach, we aim to get a good coverage of design space of the proposed mobility metrics by producing a rich set of mobility patterns that can be used as a "test-suite" for further research.

VI. Experiments

As a first step, we wanted to validate if our proposed metrics differentiate the mobility models. Once this was done, we focused on answering the following questions: *Whether* mobility affects protocol performance?, if yes, we attempt to answer the questions *Why*? and *How*? mentioned in Section I.

A. Validating the Mobility Metrics

Our mobility scenario generator produced the different mobility patterns following the RPGM, Freeway and Manhattan models according to the format required by *ns-2*. In all these patterns, 40 mobile nodes moved in an area of 1000m x 1000m for a period of 900 seconds. Random Waypoint mobility pattern was generated using the *setdest* tool which is a part of the *ns-2* distribution. For RPGM, we used 2 different mobility scenarios: single group of 40 nodes and 4 groups of 10 nodes each moving independently of each other and in an overlapping fashion. Both Speed Deviation Ratio (SDR) and

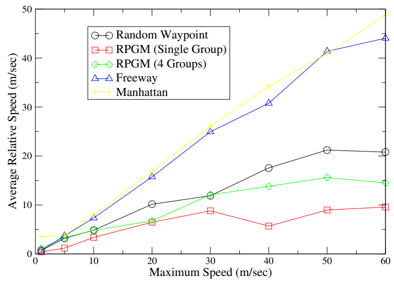

Fig. 4. Average Relative Speed

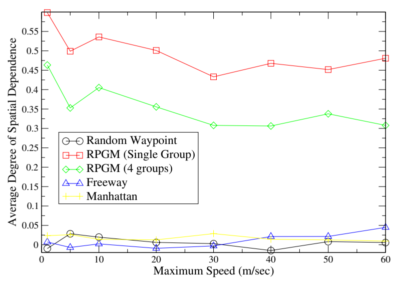

Fig. 5. Average Degree of Spatial Dependence

Angle Deviation Ratio (ADR) were set to 0.1. For the Freeway and Manhattan models, the nodes were placed on the freeway lanes or local streets randomly in both directions initially. Their movement was controlled as per the specifications of the models. If a node moves beyond the boundary of the area it is re-inserted at the beginning position in a randomly chosen lane in the area. The maximum speed V_{max} was set to 1, 5, 10, 20, 30, 40, 50 and 60 m/sec to generate different movement patterns for the same mobility model. On evaluating these patterns with our mobility metrics, we observed that some of the metrics were able to differentiate between the mobility patterns based on the characteristics we focused on, while the others failed.

Average Relative Speed ($\bar{RS}$): We experimented with different values of the constant c_3 mentioned in Section IV. For the value of $c_3 = 2$, $\bar{RS}$ could differentiate between the different mobility patterns very clearly. As seen in Fig.4, $\bar{RS}$ has the lowest value for RPGM (single group and multiple group mobility) as the nodes move together in a co-ordinated fashion with little deviation, while it has a medium value for Random Waypoint. Its value for the Freeway and Manhattan mobility patterns is the highest and almost twice that for Random Waypoint. This high value is because of the movement in opposite direction for both Freeway and Manhattan mobility patterns.

Average Degree of Spatial Dependence ($\bar{D}_{spatial}$): We experimented with different values of the constant c_1 mentioned in Section IV. For the value of $c_1 = 2$, $\bar{D}_{spatial}$ could differentiate between the different mobility patterns very clearly. As seen in Fig.5, $\bar{D}_{spatial}$ has a higher value for single group mobility (around 0.5) than that of multiple group mobility (about 0.35). However, for the Random Waypoint, Manhattan and Freeway, its value is almost 0. Intuitively, in RPGM, the group leader controls the movement of the mobile node and thus the mobility pattern has a high spatial dependence. Initially, we expected the Freeway and Manhattan mobility patterns to have a high spatial dependence as a node's movement is influenced by nodes before it in the lane. Due to the use of lanes in opposite directions in the map, the positive Degree of Spatial Dependence of a node with nodes in the same direction cancels the negative Degree of Spatial Dependence of the node with nodes traveling in the opposite direction.

Average Degree of Temporal Dependence ($\bar{D}_{temporal}$): This metric could not differentiate between the various mobility patterns used in our study. The usefulness of this metric is still under investigation.

In summary, $\bar{RS}$ and $\bar{D}_{spatial}$ are found to be useful mobility metrics in our study. Fig.4 and 5 show that for each of these metrics, we had scenarios with relatively low values, medium values and relatively high values. Similarly, for Geographic Restrictions, the Freeway does not allow a node to change directions as freely as the Manhattan model. So, we believe that our "test-suite" has given a reasonably good coverage of the mobility metric space.

B. Validating the Connectivity Graph Metrics

To study the effect of mobility on the Connectivity Graph, we evaluated the connectivity graphs resulting from the mobility patterns used in Section VI-A. We had the following observations about the Connectivity Graph metrics:

Average Link Duration ($\bar{LD}$): As seen in Fig.6, $\bar{LD}$ has a higher value for single group and multiple groups than Random Waypoint. For the Freeway and Manhattan its value is similar to Random Waypoint or even worse. Since nodes in a group move at velocities that are deviated by a small fraction from the group leader, an already existing link between two nodes is expected to have a higher duration. The low value for the Freeway and Manhattan may be because of the opposite direction of motion and high relative speeds.

Average Number of Link Changes($\bar{LC}$): This metric was not able to differentiate between the several mobility patterns used in our study.

Average Path Availability($\bar{PA}$): We use the *Breadth First Search* algorithm on the snapshots of the network to calculate

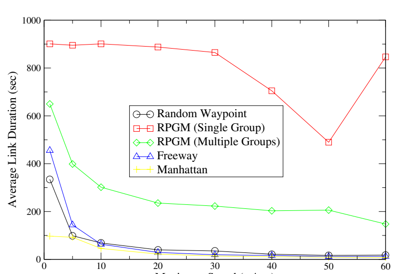

Fig. 6. Average Link Duration

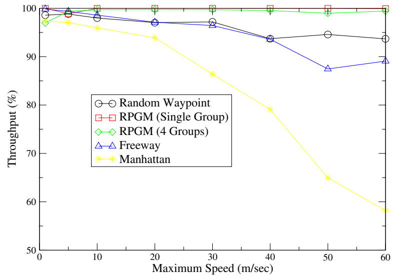

Fig. 7. DSR Throughput

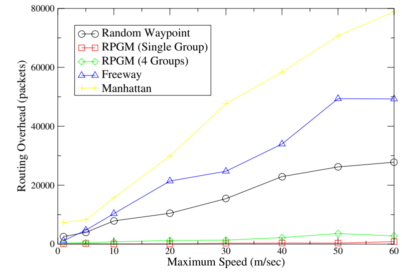

Fig. 8. DSR Routing Overhead

whether a path between a specific source destination pair exists [15]. For RPGM (single group), RPGM (mutiple group), Random Waypoint, Freeway and Manhattan models, $\overline{PA}$ is found to be around 100%, 92%, 97%, 99% and 95% respectively. In most cases, a path is available at least 95% of the time. Thus, the difference across the models was too small to be of any help.

In summary, $\overline{LD}$ is found to be a useful metric to differentiate the connectivity graph arising from the different mobility patterns used in our study.

To evaluate the effect of mobility on the performance of protocols, we carried out simulations in the network simulator (*ns-2*) environment with the CMU Wireless Ad Hoc networking extension. The transmission range of the nodes was 250m. The mobility patterns used were the same as those used to Section VI-A. The traffic pattern was generated by the *cbrgen* tool that is part of *ns-2* distribution. The traffic consisted of 20 Constant Bit Rate (CBR) sources and 30 connections. The source-destination pairs were chosen at random. The data rate used was 4 packets/sec and the packet size was 64 bytes.

To remove any effects due to randomness of the traffic pattern, we used different random seeds to generate 3 different traffic patterns having the same number of sources and connections. The results for each model (for a given V_{max}) are averaged over simulation runs using these 3 different traffic patterns.

C. Whether *mobility affects protocol performance?*

We evaluated the performance of DSR, AODV and DSDV across this rich set of mobility models and observed that the mobility models may drastically affect protocol performance. We use DSR as an illustrative example. DSR shows a difference of almost 40% in throughput from Manhattan to the RPGM (Single Group) model as seen from Fig.7. Also, there is an order of magnitude difference in the routing overhead of DSR across the various models as shown by Fig.8. Similar performance differences were observed for other protocols used in our study. We observed that DSR, DSDV and AODV achieve the highest throughput and the least overhead with RPGM and incur high overhead and low throughput with both Freeway and Manhattan models. This is consistent with the observations made in [5] which evaluated the protocols using Random Waypoint and several other group mobility applications. However, we take a step further and attempt to analyze the reason for this performance difference in Section VI-D.

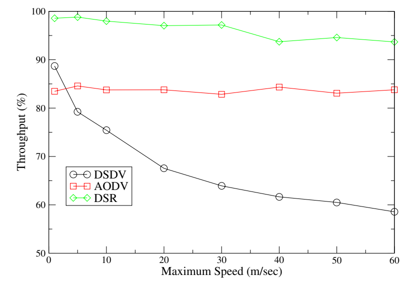

Fig. 9. Random Waypoint: Throughput

Relative Performance of Protocols Across Mobility Models: In this part, we investigated the effect of mobility on relative rankings of protocol performance. As shown in Fig.9, 10, 11, 12 and 13, DSR seems to produce the highest throughput in most cases, while AODV seems to outperform DSR (by almost 11%) in the Manhattan model. As seen from Fig.10 and 13, the relative ranking of AODV and DSDV in terms of throughput seems to depend on the underlying mobility model.

Also, DSR incurs the least routing overhead in most cases, while DSDV has a lower overhead than DSR in the Freeway and Manhattan models as shown in Fig.17 and 18. The relative ranking of DSR and DSDV in terms of routing overhead seems to depend on the underlying mobility model as shown in Fig.14, 15, 16, 17 and 18.

Thus, we conclude that relative rankings of protocols may vary with the mobility model used. We also observe that DSDV achieves a higher throughput than AODV (by around 10%) in RPGM. Thus, in general it is not always true that

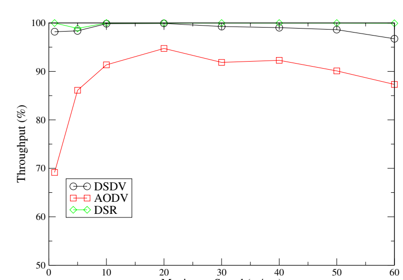

Fig. 10. RPGM (Single Group): Throughput

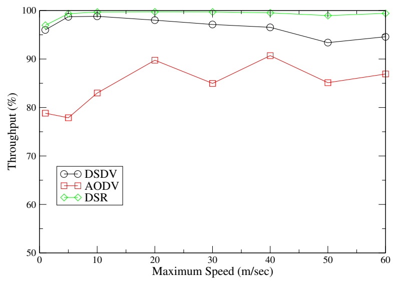

Fig. 11. RPGM (4 Groups): Throughput

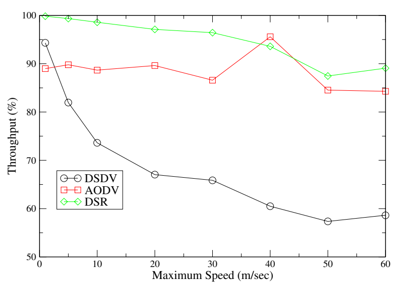

Fig. 12. Freeway: Throughput

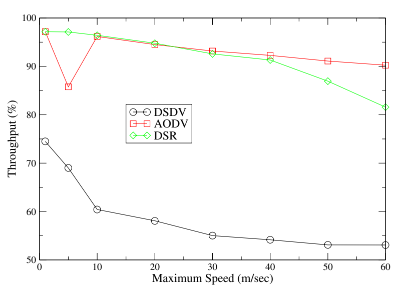

Fig. 13. Manhattan: Throughput

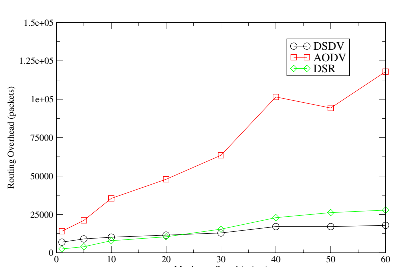

Fig. 14. Random Waypoint: Routing Overhead

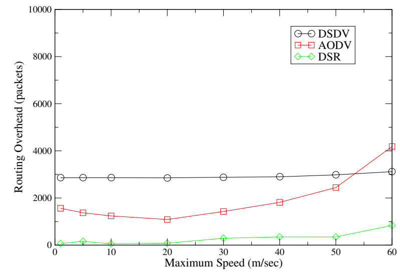

Fig. 15. RPGM (Single Group): Routing Overhead

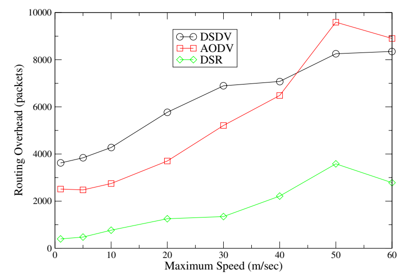

Fig. 16. RPGM (4 Groups): Routing Overhead

on demand protocols perform better than table driven ones in terms of throughput. Also, a protocol with the least overhead does not always produce the highest throughput. E.g. in the Freeway model, DSDV seems to have the least throughput and the least overhead.

Although, these results were somewhat expected, the quantitative analysis helped us gain a lot of insight to answer the next question.

D. Why *mobility affects protocol performance?*

First, the relationship between the mobility metrics and the performance metrics was unclear. But after introducing the connectivity graph metrics, we were able to observe a very clear correlation between Average Degree of Spatial Dependence, Average Relative Speed, Average Link Duration and protocol performance metrics. *The mobility pattern influences the connectivity graph which in turn influences the protocol performance.*

In general, it was observed that DSR, DSDV and AODV had a higher throughput and lower overhead for the group

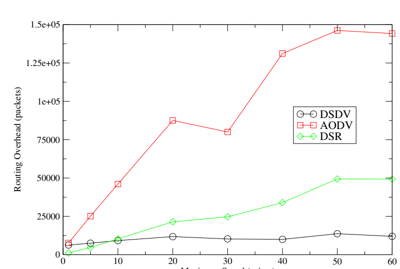

Fig. 17. Freeway: Routing Overhead

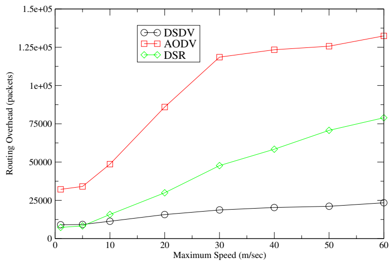

Fig. 18. Manhattan: Routing Overhead

mobility models than for the Random Waypoint model. At the same time, all the protocols had a higher throughput and lower overhead for Random Waypoint than the Freeway and Manhattan models. One plausible reason for this observation can be as follows:

1) With similar relative speed, between Random Waypoint and RPGM, high degree of spatial dependence (for RPGM) means higher link duration, which in turn will result in higher throughput and lower routing overhead.
2) With the same degree of spatial dependency, between Freeway/Manhattan and Random Waypoint, high relative speed (for Freeway/Manhattan) means lower link duration, which will result in lower throughput and higher overhead.

The above reasoning can be explained as follows: For a given relative speed, if a mobility pattern has a high degree of spatial dependence, an already existing link between two nodes is expected to remain stable for a longer period of time as the nodes are likely to move together. Thus fewer packets will be dropped due to link breakage leading to higher throughput. At the same time, the control overhead is lower as little effort is needed to repair the seldom broken link. For a given spatial dependence, if a mobility pattern has a high relative speed, the nodes might move out of range more quickly. Thus an already existing link may remain stable for a relatively shorter duration. This may lead to more packets being dropped due to link breakage, resulting in lower throughput. Higher control overhead is needed to repair the more frequently broken link. We also note that the Freeway and Manhattan mobility patterns have high relative speed and low degree of spatial dependence leading to the worst performance of all the protocols while using these models.

VII. Analysis of Building Blocks

Unlike the conventional evaluation studies, we pursue our analysis beyond the “whole protocol” level and attempt to answer *How* mobility affects protocol performance by looking into the “parts” that constitute the MANET routing protocols. We propose an approach to systematically decompose a protocol into its functional mechanistic ”building blocks”. Each building block can be thought of as a parameterized ”black box”. The parameter settings define the behavior of each block, while the nature of interaction between the building blocks defines the behavior of the protocol as a ”whole”. We use the analysis of reactive protocols as an example to illustrate this approach. In this section, we carry out a preliminary analysis of the impact of mobility on two building blocks after identifying the basic building blocks of MANET routing protocols.

Basic Building Blocks: The mechanism of several MANET routing protocols is composed of two major phases:

1) **Route Setup Phase:** Route Discovery is the major mechanism in this phase. It is initiated if there is no cached route available to the destination. This mechanism consists of the following building blocks:
   Controlled Flooding: Flooding is mainly used for Route Discovery if the route to the destination does not exist in the cache. One of its parameter is the range of flooding, generally described by TTL field in IP header. Depending on the value of TTL, either a non-propagating direct-neighbor inquiry (DSR) or an expanding ring search (AODV) can be initiated before the global route discovery flooding.
   Caching: Caching is used in both Route Discovery and Route Maintenance (discussed next) to increase the possibility of finding a route without initiating the flooding. One of its parameters is number of allowed cache entries for a source destination pair. Only one entry is allowed for each source destination pair in AODV, while all possible routes can be cached in DSR. The other parameter is whether aggressive caching is allowed i.e. whether the mobile node can cache the route information it overhears? In DSR, aggressive caching is the default. Currently, AODV does not implement the above options for Caching.
2) **Route Maintenance Phase:** Route Maintenance phase takes the responsibility of detecting broken links and repairing the corresponding routes. This phase is made up of the following building blocks:
   Error Detection: It is used to monitor the status of the link with its immediate neighbors.
   Error Handling: It is in charge of finding alternative routes to replace an invalid route. One of the parameters to this block is whether localized recovery should be used? In a non-localized recovery, the node detecting the link breakage will ask the source to reinitiate the route discovery (AODV), while in a localized recovery, the node detecting the broken link will attempt to find an alternative route in its own cache before asking the source to reinitiate the route discovery (DSR packet salvaging).
   Error Notification: It is used to notify the nodes in the network about invalid routes. One of the parameters to this block is the recipient of error notification. Either only the source is notified (DSR) or the entire network is notified (AODV, due to the periodic routing updates).

Impact of Mobility on Building Blocks: We speculate that the optimal parameter settings of the building blocks are affected by mobility pattern. To validate our speculation, we analyze the effect of mobility on the following building blocks:

Caching: As most previous studies, we observe that DSR has a higher throughput than the other protocols under most mobility patterns with high or moderate link duration (like Random Waypoint model or RPGM). However, we observe that DSR performs worse than AODV (by about 11%) under the mobility patterns with extremely low link duration and weak route stability (like Manhattan) as shown in Fig.13. One possible explanation for this observation is that the price paid for eliminating the stale cached routes obtained by aggressive caching more than evens out the benefit gained from aggressive caching. Thus, whether aggressive caching should be adopted depends on the mobility scenarios the protocol will be deployed in.

Controlled Flooding: There is high possibility of finding cached route in a node's neighborhood under mobility scenarios with stable routes and high link duration while this possibility is low under the mobility scenarios with smaller link durations. Thus, whether Controlled Flooding should be used depends on the underlying mobility scenarios.

During the analysis, we noticed that DSR attempts to apply several optimizations and optimal parameter settings for most building blocks i.e. non-propagating direct-neighbor inquiry for Controlled Flooding, multiple cache entries and aggressive caching for Caching, local error recovery for Error Handling. In summary, DSR is a well-designed protocol whose parameters have been adjusted to achieve the optimal performance.

Our current study of classifying the building blocks and investigating its effect on the performance of various routing protocols is mainly based on intuitive analysis. To understand the functionality of building blocks and their contributions to the routing performance, we plan to conduct a quantitative analysis using the procedure profiling of the building blocks we mentioned. We are interested in how the contributions of these building blocks will change across mobility patterns, which will help us, better answer *How* mobility affects protocol performance.

VIII. Conclusions & Future Work

In this paper, we proposed a framework to analyze the impact of mobility pattern on routing performance of mobile ad hoc network in a systematic manner. In our study, we observe that the mobility pattern does influence the performance of MANET routing protocols. This conclusion is consistent with the observation of previous studies. But unlike previous studies that compared different ad hoc routing protocols, there is no clear winner among the protocols in our case, since different mobility patterns seem to give different performance rankings of the protocols. We hope that our "test-suite" of mobility models can be incorporated into the current scenarios used to test the MANET routing protocols.

Moreover, we observe that the mobility pattern influences the connectivity graph that in turn influences the protocol performance. In addition, we did a preliminary investigation of the common building blocks of MANET routing protocols, the effect of mobility on these building blocks and how they influence the protocol as a "whole".

In the future, we plan to study the impact of our "test-suite" on the performance of other ad hoc network protocols like multicast ad hoc, geographic routing protocols. This study would help us understand the impact of mobility more deeply and clearly. We believe that several parameters such as traffic patterns, node density and initial placement pattern of nodes may affect the routing performance and need to investigate them further. We are currently investigating the quantitative analysis of the building blocks.

IX. Acknowlegements

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