Chapter 2

# THE IMPORTANT FRAMEWORK

## *for Analyzing and Modeling the Impact of Mobility in Wireless Adhoc Networks*

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Abstract: To study the impact of mobility on performance of Mobile Ad Hoc Network (MANET) protocols in a systematic way, we propose the IMPORTANT framework. This framework aims to evaluate the effect of different mobility models on the performance of MANET routing protocols. We propose various protocol independent metrics to capture interesting mobility characteristics of the mobility space, including spatial and temporal dependence, relative speed, geographic restrictions, link duration and path duration. In addition, a rich set of parameterized mobility models is discussed including Random Waypoint, Group Mobility, Freeway and Manhattan models. Based on these models several 'test-suite' scenarios are chosen carefully to span the mobility 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 reactive routing protocols into mechanistic ``building blocks'' to gain a deeper insight into the performance variations across protocols in the face of mobility.

Key words: mobility; modeling and analysis; routing protocols; performance evaluation; building block.

# 1. INTRODUCTION

Mobility pattern of the Mobile Ad Hoc Network, in many previous studies, was assumed to be Random Waypoint because of its relatively simple implementation and analysis. However, in the future, MANETs are expected to be deployed in various different scenarios and applications 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[1], DSDV[2] and AODV[3]. As observed in the previous chapter, Random Waypoint model is a well-designed and commonly used mobility model, but we find it is insufficient to capture those characteristics including **Spatial Dependence** of movement among nodes, **Temporal Dependence** of movement of a node over time and the **Geographic Restriction**.

In our work, 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. What are the key characteristics of mobility space?
2. Whether and to what degree mobility affects routing protocol performance?
3. If the answer to 2 is yes, why?
4. If the answer to 2 is yes, how?

To answer *What*, based on the previous discussion, we define several key dimensions of the mobility space. We also propose and discuss different mobility patterns that capture the characteristics of those mobility dimensions, including the Random Waypoint, Group Mobility, Freeway and Manhattan model. To answer *Whether*, the framework evaluates the performance of MANET routing protocols over those models. To answer *Why*, we propose some protocol independent metrics such as mobility metrics and connectivity graph metrics, which could be used to explain the relationship between mobility and protocol performance. 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 our study[4] and previous studies[5] that under a given mobility pattern, routing protocols like DSR, DSDV and AODV perform differently. This is possibly because each protocol differs in the basic mechanisms or ``building blocks'' it uses. 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.2-1, our framework focuses on the following aspects: (1) the characteristics of mobility space and the set of mobility models to cover the mobility space; (2) the metrics for mobility and connectivity graph characteristics; (3) the potential relationship between mobility, connectivity graph and routing performance; (4) the analysis of building blocks of ad hoc routing protocols.

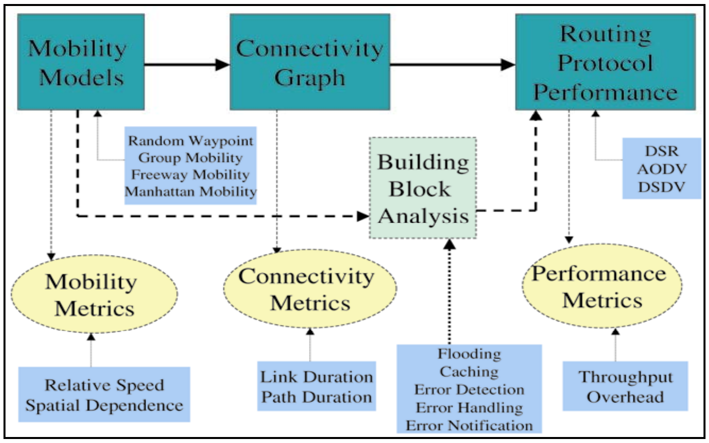

*Figure 2-1.* The IMPORTANT Framework for Mobility Modeling and Analysis

The rest of this chapter is organized as follows. Section 2 describes the dimensions of mobility space we aim to explore. We also propose several metrics to capture characteristics of mobility and the connectivity graph between the mobile nodes. Section 3 describes the mobility models used in our study and introduces two new models, the Freeway mobility model and the Manhattan mobility model. Characteristics of those mobility models are examined in Section 4. Results of evaluating the protocols over those models are presented and the possible explanation is discussed in Section 5. The analysis of the impact of mobility on protocol building blocks is discussed in Section 6. After we summarize this study in Section 7, we briefly discuss some future research directions in Section 8.

# 2. MOBILITY SPACE AND CONNECTIVITY GRAPH

## 2.1 Dimensions of the Mobility Space

In most previous works, the Random Waypoint model was widely accepted as the de facto standard mainly due to simplicity of its implementation and analysis. The key parameters of the Random Waypoint model are the maximum node velocity $V_{\max}$ and pause time. By adjusting these parameters, users are able to compare the performance of routing protocols under various mobility scenarios. However, we find that the node velocity and pause time cover only one dimension of the mobility space. Other important dimensions of mobility space and their effect on MANET protocol performance should also be studied systematically. In our framework, we aim to define the dimensions of the mobility space and explore the key characteristics of those dimensions.

Through the discussion in the previous chapter, we observe that the mobility space may include the following dimensions:

1. **Relative Velocity**: The movement of nodes is determined by the relative speed between those nodes. In Random Waypoint model, parameter $V_{\max}$ is indirectly used to adjust the relative speed.
2. **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 more or less dependent on the previous velocity, according to certain parameter.
3. **Spatial Dependency**: The movement pattern of a mobile node may be more or less influenced by and correlated with nodes in its neighborhood, according to certain parameter.
4. **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.

Obviously, by adjusting the $V_{\max}$ parameter, the Random Waypoint model is only able to generate various mobility scenarios with different level of node speeds. However, it is insufficient to capture many of the mobility characteristics mentioned above. That is to say, a simple random-based mobility model like Random Waypoint model may not be suitable to cover all the dimensions of mobility space. In our study, we focus on the above-mentioned dimensions of the mobility space[1] and analyze their characteristics in the following sections.

To quantitatively and qualitatively analyze the characteristics of mobility models and their impact on routing protocol performance, in the next section, we propose several protocol independent metrics to extract the characteristics of mobility and the connectivity graph between the mobile nodes. These metrics are also used to explain the impact of mobility on the protocol performance metrics.

## 2.2 Mobility Metrics

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

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, relative velocity and geographic restrictions.

1. **Degree of Spatial Dependence** ($D_{spatial}(i,j,t)$): It is a measure of the extent of similarity of the velocities of two nodes that are not too far apart. Formally,
   $$D_{spatial}(i,j,t) = RD(\vec{V}_i(t),\vec{V}_j(t)) * SR(\vec{V}_i(t),\vec{V}_j(t)) \qquad (1)$$
   The value of $D_{spatial}$ is high when the nodes *i* and *j* travel in more or less the same direction and at almost similar speeds. Through

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[1] We acknowledge that the mobility space may have even more dimensions than what we discussed here. However, in our experience, the four dimensions proposed do capture many important characteristics of mobility that affect the performance of MANET protocols. Further investigation of mobility dimensions is an interesting direction for future research.

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

$$D_{i,j}(t) \geq 2R \Rightarrow D_{spatial}(i,j,t) = 0 \qquad (2)$$

**Average Degree of Spatial Dependence** ($\overline{D}_{spatial}$): It is the value of $D_{spatial}(i,j,t)$ averaged over node pairs and time instants satisfying certain condition. Thus, if mobile nodes move independently of one another, then the mobility pattern is expected to have a smaller value for $\overline{D}_{spatial}$. On the other hand, if the node movement is coordinated 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 $\overline{D}_{spatial}$. This metric is used to characterize the 'Spatial Dependency' dimension of mobility space.

2. **Degree of Temporal Dependence** ($D_{temporal}(i,t,t')$): It is a measure of the extent of similarity of the velocities of a node at two time slots, t and t', that are not too far apart. It is a function of the acceleration of the mobile node and the geographic restrictions. Formally,

$$D_{temporal}(i,t,t') = RD(\vec{V}_i(t),\vec{V}_i(t')) * SR(\vec{V}_i(t),\vec{V}_i(t')) \qquad (3)$$

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. Arguing in a way similar to that for $\overline{D}_{spatial}$, we have the following condition

$$|t-t'| \geq 30\sec \Rightarrow D_{temporal}(i,t,t') = 0 \qquad (4)$$

**Average Degree of Temporal Dependence** ($\overline{D}_{temporal}$): It is the value of $D_{temporal}(i,t,t')$ averaged over nodes and time instants satisfying certain conditions. Thus, if the current velocity of a node is completely independent of its velocity at some previous time slot, then the mobility pattern is expected to have a smaller value for $\overline{D}_{temporal}$. However, if the current velocity is strongly dependent on the velocity at some previous time slot, then the mobility pattern is expected to have a higher value for $\overline{D}_{temporal}$. This metric is used to characterize the 'Temporal Dependency' dimension of mobility space.

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

$$RS(i,j,t) = |\vec{V}_i(t) - \vec{V}_j(t)| \qquad (5)$$

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

$$D_{i,j}(t) \geq 2R \Rightarrow RS(i,j,t) = 0 \qquad (6)$$

**Average Relative Speed**($\overline{RS}$): It is the value of $RS(i,j,t)$ averaged over node pairs and time instants satisfying certain condition. The metric of relative speed aims to quantitatively represent the 'Relative Velocity' dimension of mobility space.

4. **Geographic Restrictions**: For this metric, we develop 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, but currently we do not have a good way of quantitatively aggregating this definition for the whole map. Thus, we do not quantitatively define the Geographic Restrictions, but we qualitatively include it in our study as will be seen in Section 4.2.

## 2.3 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 5.

The connectivity graph is the graph *G=(V,E)*, such that $|V| = N$ and at time *t*, a link (i,j) $\in E$ iff $D_{i,j}(t) \le R$. 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*.

1. **Link Duration** ($LD(i,j,t_1)$): For two nodes *i* and *j*, at time $t_1$, duration of the link *(i,j)* is the length of the longest time interval $[t_1, t_2]$ during which the two nodes are within the transmission range of each other. Moreover these two nodes are not within the transmission range at time $t_1 - \varepsilon$ and time $t_2 + \varepsilon$ for $\varepsilon > 0$. Formally,

   $$LD(i,j,t_1) = t_2 - t_1 \quad (7)$$

   iff $\forall t \; t_1 \le t \le t_2, \varepsilon > 0$: $X(i,j,t) = 1$ and $X(i,j,t_1 - \varepsilon) = 0$ and $X(i,j,t_2 + \varepsilon) = 0$. Otherwise, $LD(i,j,t_1) = 0$.

   **Average Link Duration** ($\overline{LD}$): It is the value of $LD(i,j)$ averaged over all existing links for node pairs satisfying certain condition.

2. **Path Duration** ($PD(n_1, n_k, t_1)$): For a path $P = \{n_1, n_2, \cdots, n_k\}$, consisting of *k* nodes , at time $t_1$, path duration is the length of the longest time interval $[t_1, t_2]$, during which each of the *k*-1 links between the nodes exist. Moreover, at time $t_1 - \varepsilon$ and time $t_2 + \varepsilon$, $\varepsilon > 0$, at least one of the *k* links does not exist. Thus, path duration is limited by the duration of the links along its path. Specifically, at time $t_1$, path duration is the minimum of the durations of the *k-1* links $(n_1, n_2), (n_2, n_3), \cdots (n_{k-1}, n_k)$ at time $t_1$. Formally,

   $$PD(n_1, n_k, t_1) = \min_{1 \le z \le k-1} LD(n_z, n_{z+1}, t_1) \quad (8)$$

   That is, $PD(n_1, n_k, t_1)$ is the shortest path duration between node $n_1$ and node $n_k$ at time $t_1$.

   **Average Path Duration** ($\overline{PD}$): It is the value of $PD(n_1, n_k, t_1)$ averaged over all existing paths for node pairs satisfying certain condition.

## 3. MOBILITY MODELS

As mentioned in the Section 2, Random Waypoint does not seem to capture the mobility characteristics of spatial dependence, temporal dependence and geographic restrictions. 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. The set of mobility models[2] include Random Waypoint model(RW), Reference Point Group Mobility model(RPGM), Freeway mobility model(FW) and Manhattan mobility model(MH). Each of the above models is designed to represent a class of mobility models with certain mobility properties. As validated by the simulations in section 4, the mobility characteristics and connectivity graph properties of RPGM, FW and MH models are shown to be different from Random Waypoint model. Also, we validate that these proposed models are able to cover the proposed mobility space.

1. **Random Waypoint Model**:

The Random Waypoint model is most used mobility model in research community. 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[6]. 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. In our framework, the RW model acts as the 'baseline' mobility model to evaluate the protocols in Ad Hoc Network.

2. **RPGM Model**:

Group mobility[7] can be used to model military battlefield communication, among other applications. 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.

*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) $|V_{member}(t)| = |V_{leader}(t)| + random() * SDR * \max\_speed$ (9)

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[2] We develop a mobility generator tool listed in the *ns-2 contribution code* webpage. The code and the user manual of this tool can be found in our IMPORTANT framework webpage http://nile.usc.edu/IMPORTANT/

(b) $\theta_{member}(t) = \theta_{leader}(t) + random() * ADR * \max\_angle$ (10)
where $0 < SDR, ADR < 1$. 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. 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.

3. **Freeway Mobility Model**:

We propose this new model to emulate the motion behavior of mobile nodes on a freeway. 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. Formally,

$$| \vec{V}_i(t+1) | = | \vec{V}_i(t) | + random() * | \vec{a}_i(t) | \quad (11)$$

(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. Formally,

$$\forall i, \forall j, \forall t, D_{i,j}(t) < SD \Rightarrow | \vec{V}_i(t) | < | \vec{V}_j(t) | \quad (12)$$

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.

4. **Manhattan Mobility Model**:

We introduce the Manhattan model to emulate the movement pattern of mobile nodes on streets defined by maps. 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. However, the map is composed of a number of horizontal and vertical 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 with certain probability. Except the above difference, the inter-node and intra-node relationships involved in the Manhattan model 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.

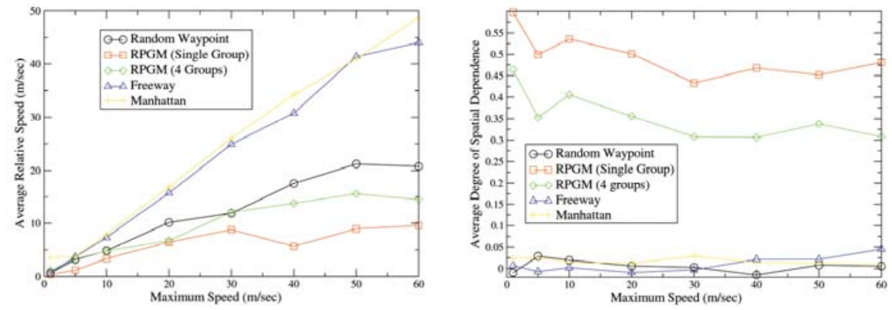
## 4. CHARACTERISTICS OF MOBILITY MODELS

As a first step, we want to validate if our proposed mobility models can cover the mobility design space.

Our mobility scenario generator produces the different mobility patterns following the RPGM, Freeway and Manhattan models. The output mobility trace is integrated into the network simulator (*ns-2*). In all these patterns, 40 mobile nodes moved in an area of 1000m x 1000m for a period of 900 seconds. For RPGM, we use 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 Angle Deviation Ratio (ADR) were set to 0.1. In the Freeway and Manhattan models, the node movement is 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 observe that some of the metrics are able to differentiate between the mobility patterns based on the characteristics we focus on, while the others fail, as we shall explain next.

### 4.1 Validating the Mobility Metrics

*Average Relative Speed* ($\overline{RS}$): As seen in Fig.2-2(a), $\overline{RS}$ has the lowest value for RPGM (single group and multiple group mobility) as the nodes move together in a coordinated 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.



(a) Average Relative Speed (b) Average Degree of Spatial Dependence

*Figure 2-2.* Mobility Metrics

*Average Degree of Spatial Dependence* ($\overline{D}_{spatial}$): As seen in Fig.2-2(b), $\overline{D}_{spatial}$ 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. In Manhattan and Freeway model, 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* ($\overline{D}_{temporal}$): This metric could not differentiate between the various mobility patterns used in our study.

In summary, $\overline{RS}$ and $\overline{D}_{spatial}$ are found to be useful mobility metrics in our study.

## 4.2 Sensitivity Analysis of Mobility Models

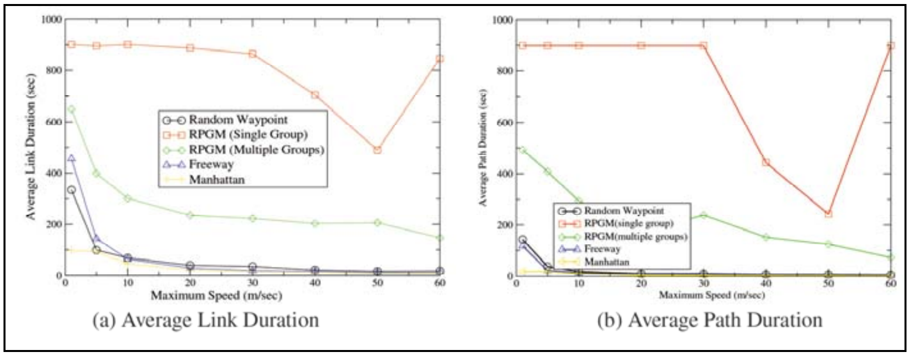
Through simulation, Fig.2-2(a) and Fig.2-2(b) show that for each of these metrics, we generate scenarios with relatively low values, medium values and relatively high values. Although we did not quantitatively define Geographic Restrictions in Section 2.2, we qualitatively include them in our study by using the Freeway and Manhattan models. Obviously, 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.

Moreover, most of the proposed 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. Using a parameterized approach, we aim to get a good coverage of the design space of the proposed mobility metrics by adjusting those parameters.

## 4.3 Validating the Connectivity Graph Metrics

After examining the mobility characteristics, in order to clearly study the effect of mobility on the Connectivity Graph, we evaluated the connectivity graphs resulting from the mobility patterns. We have the following observations about the Connectivity Graph metrics:

*Average Link Duration* ($\overline{LD}$): As seen in Fig.2-3(a), $\overline{LD}$ 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.



(a) Average Link Duration (b) Average Path Duration

*Figure 2-3.* Connectivity Graph Metrics

*Average Path Duration* ($\overline{PD}$): Similar to $\overline{LD}$, as shown in Fig.2-3(b), RPGM(single group and multiple groups) has a higher $\overline{PD}$ value than Random Waypoint. The $\overline{PD}$ values for Manhattan and Freeway are similar to or slightly lower than Random Waypoint. Since each path is composed of several links, it is likely that the behavior of path duration will be determined by the behavior of link duration.

In summary, $\overline{LD}$ and $\overline{PD}$ are found to be useful metrics to differentiate the connectivity graph arising from the different mobility patterns used in our study.

## 4.4 Examining the PDF of Link Duration and Path Duration

In addition to investigating the average link and path duration, we also examine the detailed statistics of link and path duration across the ``test-suite'' of mobility models. This provides deeper understanding of the impact of mobility on the protocol performance[3].

1. PDFs of Link Duration

When $V_{\max}$ is small i.e. 1 or 5 m/sec, the link duration PDF has a multi-modal distribution for the FW and the RPGM model (with four groups). For example, as shown in Fig. 2-4, there is a big peak in the link duration PDF for the FW model (at around 100 sec). Through simulation, we identify that this peak accounts for the links between mobile nodes moving in the opposite directions. There are several small peaks centered at larger values of link duration (for example at around 250 sec). These peaks account for the links between mobile nodes moving in the same direction. However, the link duration PDFs for the RW, MH, FW and the RPGM (with 4 groups) do not exhibit the multi-modal behavior for $V_{\max} > 10 m / \sec$.

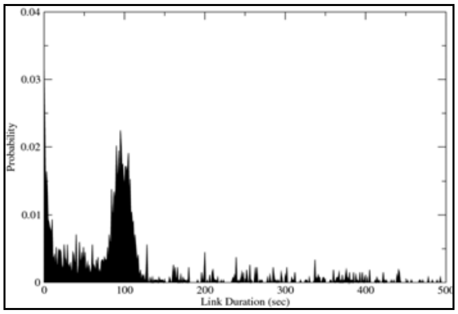


*Figure 2-4.* PDF of the Link Duration for the FW model. Here, Vmax = 5 m/s and R = 250 m

Having examined the link duration PDFs across the models used in our study, we then discuss the path duration PDFs.

2. PDFs of Path Duration

**We observe the multi-modal behavior for the FW model and the RPGM model (with 4 groups) when $V_{\max}$ is small i.e. around 1 or 5 m/sec and path length is short.** For example, as shown in Fig.2-5(a), two peaks exist in the path duration PDF for the FW model. The peak on the left (at around 75 sec) with large area seems to consist of paths containing nodes going in the opposite direction. The peak on the right (at around 400 sec)

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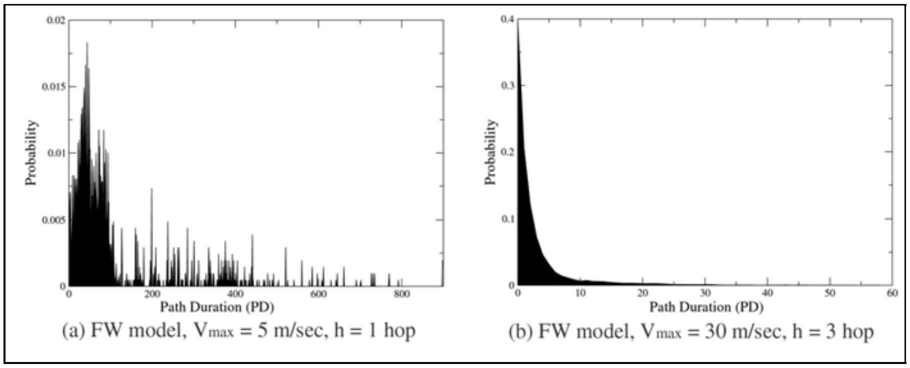
[3] Please refer to Ref.[8] for the utility of link and path duration statistics.

with a smaller area seems to consist of paths containing the nodes going in the same direction. On the other hand, the path duration PDF for the RW, FW, MH and RPGM models seems to be exponentially distributed when $V_{\max} > 10m/\sec$ and $h > 2$. For example, Fig.2-5(b) shows the path duration PDFs for the FW model. **Thus, from our analysis, we observe that if $V_{\max} > 10m/\sec$ and $h > 2$ then the path duration at connectivity graph level for the RW, MH, FW and RPGM can be approximated as an exponential distribution.**



(a) FW model, Vmax = 5 m/sec, h = 1 hop

(b) FW model, Vmax = 30 m/sec, h = 3 hop

*Figure 2-5.* PDF of Path Duration (at connectivity graph level)

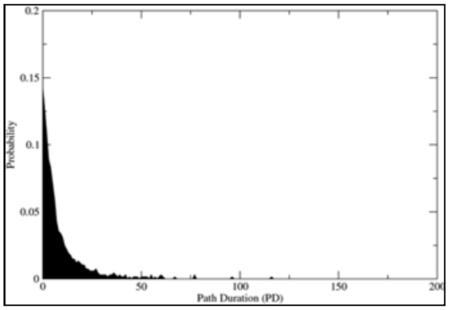


*Figure 2-6.* Path Duration PDF of DSR(at routing protocol level) for RW model. Here, Vmax=30m/sec and h=2hops

In addition to studying the path duration at connectivity graph level through analyzing the mobility trace file, we also examine the path duration of paths in the *ns-2* simulations using our packet tracer program. The results show that the path duration at the connectivity graph level is a reasonable approximation of path duration at routing protocol level. The conclusions made for path duration at connectivity graph level still hold for the path duration at routing protocol level. For both DSR and AODV in our *ns-2* simulations, we again observe the multi-modal distribution for FW and RPGM model (with 4 groups) if path length is short and $V_{\max}$ is small. As the velocity and path length increase; i.e., $V_{\max} > 10m/\sec$ and $h > 2$, we observe that the PDFs of path duration at routing protocol level seems to be exponentially distributed as well. As an example, Fig.2-6 shows the path duration PDFs of DSR for RW model.

## 4.5 Analytical Model for the Path Duration PDF

Under certain conditions, we observe that the probability distribution of path duration is exponential distribution with parameter $\lambda_{path}$ for most of used mobility models. Now, we try to characterize this distribution for each mobility model i.e. develop a model for this distribution. Intuitively, $\lambda_{path}$ has the following properties:

1. The greater the number of hops *h* in the path, the more likely a path is to break, thus the average path duration decreases (i.e. $\lambda_{path}$ increases). Hence, $\lambda_{path} \propto h$.
2. As the average relative speed *V* increases, link duration decreases and hence the average path duration decreases (i.e. $\lambda_{path}$ increases). Hence, $\lambda_{path} \propto V$.
3. As the transmission range *R* increases, link duration increases, the average path duration increases (i.e., $\lambda_{path}$ decreases). Hence, $\lambda_{path} \propto \frac{1}{R}$.

Thus,

$$\lambda_{path} = \lambda_0 \frac{hV}{R} \qquad (13)$$

where $\lambda_0$ is the constant of proportionality. The constant $\lambda_0$ is independent of *V*, *h* and *R*.

The above model for $\lambda_{path}$ is verified by our simulations in [10]. We find that the average path duration estimated from the statistical analysis decreases with increase in *h*, increase in $V_{\max}$ and decrease in *R*.

The constant factor $\lambda_0$ is determined by the map layout, node density and other detailed parameters of mobility scenarios. Under the same mobility model, $\lambda_0$ remains same for various *V, h* and *R* values. However, $\lambda_0$ is different for different mobility models; $\lambda_0$ is even different for the same mobility models with different map layout, node density or other parameters. In Appendix A of Ref.[8], we show the values of $\lambda_0$ for some of our simulations. From these values, we observe that, in most cases, $\lambda_0$ remains almost constant for a given mobility model across different values of *V, h* and *R*. The average $\lambda_0$ is 0.508, 0.464, 1.349 and 1.202 for RW, RPGM, FW and MH models used in our study.

Thus, the Probability Density Function (PDF) of the path duration across most of the mobility models used in our study can be approximated as an exponential distribution[4]:

$$f(x) = \frac{\lambda_0 hv}{R} e^{-\frac{\lambda_0 hv}{R}x} \qquad (14)$$

The Cumulative Density Function (CDF) of the path duration across the mobility models used in our study can be approximated as follows:

$$F(x) = 1 - e^{-\frac{\lambda_0 hv}{R}x} \qquad (15)$$

# 5. EVALUATION OF MANET ROUTING PROTOCOLS

After the mobility characteristics and connectivity graph properties of the proposed four mobility models have been carefully studied, we then focus on answering the following questions: *Whether* mobility affects protocol performance?, if yes, we attempt to answer the questions *Why?* and *How?* in this section and in the next section.

## 5.1 *Whether* mobility affects protocol performance?

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 4. 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

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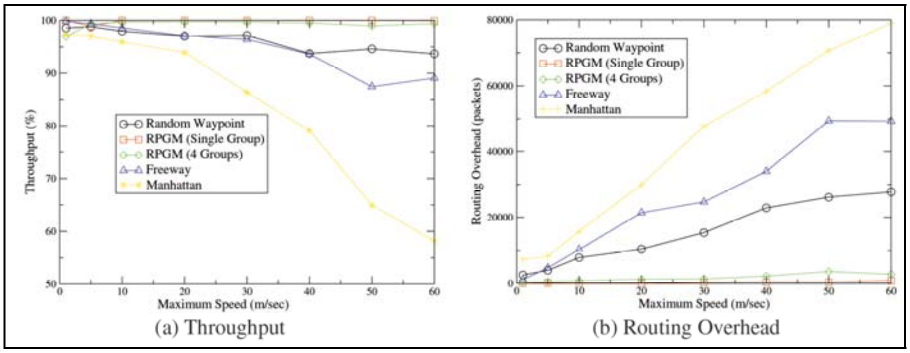
[4] We conducted the Kolmogorov Smirnov test on these PDFs. The D-statistic for the PDFs shows that the exponential distribution is a reasonable approximation for the path duration PDF[8].

given $V_{\max}$ ) are averaged over simulation runs using these 3 different traffic patterns.



(a) Throughput (b) Routing Overhead

*Figure 2-7.* DSR Protocol Performance across Mobility Models

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.2-7(a). Also, there is an order of magnitude difference in the routing overhead of DSR across the various models as shown by Fig.2-7(b). 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.

*Relative Performance of Protocols Across Mobility Models:* In this part, we investigated the effect of mobility on relative rankings of protocol performance. Due to the limited space, we only give the protocol performance for RW, RPGM(4 groups) and MH model in Fig.2-8, Fig.2-9 and Fig.2-10[5]. DSR seems to produce the highest throughput in most cases, while AODV seems to outperform DSR (by almost 31%) in the Manhattan model. As seen from Fig.2-8(a), Fig.2-9(a) and Fig.2-10(a), 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 Manhattan model (as shown in Fig.2-10(b)) and Freeway model. The relative ranking of DSR and DSDV in terms of routing overhead seems to depend on the

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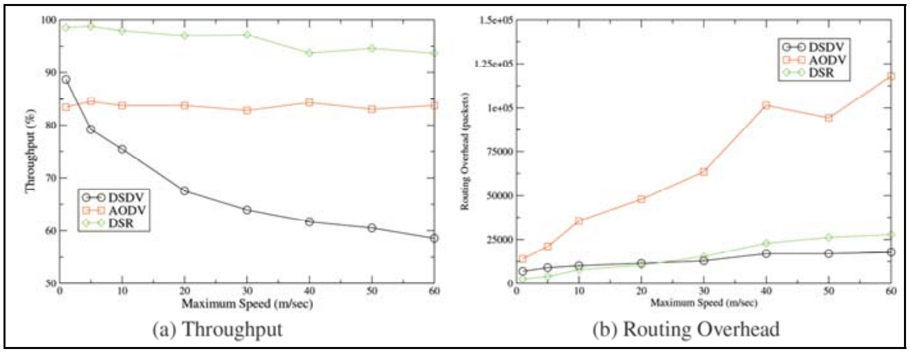
[5] For the full set of simulation result, please refer to Ref.[9].

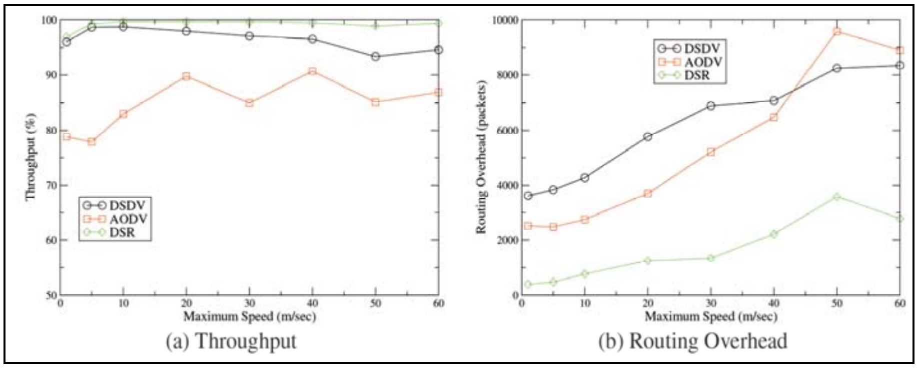
underlying mobility model as shown in Fig.2-8(b), Fig.2-9(b) and Fig.2-10(b).



(a) Throughput (b) Routing Overhead

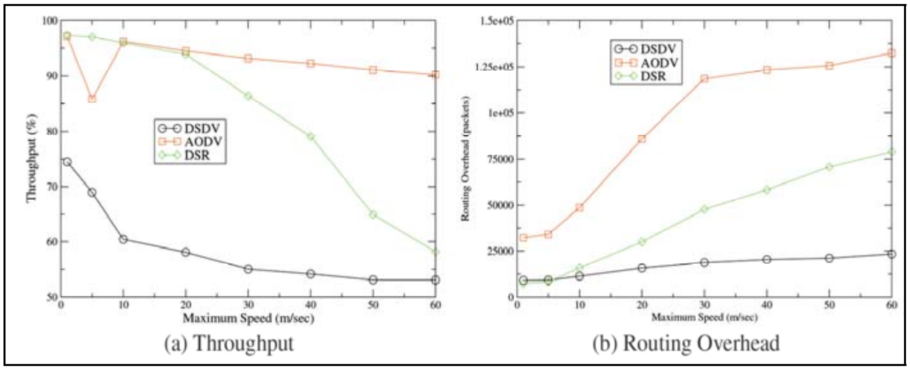
*Figure 2-8.* Protocol Performance for Random Waypoint Model

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 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[4].



(a) Throughput (b) Routing Overhead

*Figure 2-9.* Protocol Performance for RPGM(4 groups) Model



(a) Throughput (b) Routing Overhead

*Figure 2-10.* Protocol Performance for Manhattan Model

## 5.2 *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, Average Path Duration and protocol performance metrics: **The mobility pattern influences the connectivity graph which in turn influences the protocol performance.** The relationship is identified in Fig.2-1.

In general, it was observed that DSR, DSDV and AODV had a higher throughput and lower overhead for the group 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 and correspondingly higher path duration. It means that the path between source and destination is relatively stable. Thus, fewer packets will be dropped due to path breakage leading to higher throughput. At the same time, the control overhead is lower as little effort is needed to repair the seldom broken path.
2. With the same degree of spatial dependency, between Freeway/Manhattan and Random Waypoint, high relative speed (for Freeway/Manhattan) means lower link duration and correspondingly lower path duration. This may lead to more packets being dropped due to path breakage, resulting in lower throughput. Higher control overhead is needed to repair the more frequently broken path.

## 5.3 A Simple Analytical Model to Relate Path Duration with Performance of Reactive Protocols

In the previous subsection, by carefully studying the path duration as the key to *bridge* the causal relationship between mobility and performance, we qualitatively and intuitively study the reason why mobility could significantly affect protocol performance in Ad Hoc network. In this section, for the reactive MANET routing protocols, we take a further step and develop a simple first order model that shows that the throughput and overhead are in a strong linear relationship with the reciprocal of the average path duration. We use the case study of DSR[6]. Here, we propose the simple first order model as follows[7].

**Throughput:**

$$Throughput = (1 - \frac{t_{repair}}{PD}) * r \qquad (16)$$

where $t_{repair}$ is the time spent to repair a broken path each time and PD is the average path duration.

**Overhead:**

$$Overhead = \frac{T}{PD}(1(p) + N(p-1)) \qquad (17)$$

where p is non propagating cache hit ratio.

From the two above equations, we make an interesting observation: **There exists a linear relationship between the reciprocal of the path duration and the performance in terms of both throughput and routing overhead**. The correlation is positive between the reciprocal of average path duration and overhead while the correlation is negative between the reciprocal of the average path duration and throughput. Intuitively, higher path duration results in a higher throughput and lower overhead.

In order to validate the above models, we measure the Pearson coefficient of correlation between reciprocal of the average path duration and throughput we recorded in the experiments, we find that the coefficient between DSR throughput and the reciprocal of path duration for the same set of mobility patterns is -0.9165, -0.9597 and -0.9132 for RW, FW and MH mobility models respectively. Similarly, we also find that the coefficient between DSR overhead and the reciprocal of the path duration for the same set of mobility patterns is 0.9753, 0.9812 and 0.9978 for RW, FW and MH mobility models respectively. The above facts indicate a strong correlation

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[6] We derive the following models based on DSR, but we believe these models can be applied to other reactive protocol like AODV with appropriate modifications.

[7] Please refer to Ref.[10] for the detailed derivation.

between the reciprocal of path duration and DSR routing performance protocol. Thus, the two simple analytical models we propose are consistent with our experiment results.

## 6. ANALYSIS OF BUILDING BLOCKS

Unlike conventional approaches to performance evaluation, 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 behavior of building blocks and the nature of interaction between the building blocks defines the behavior of the protocol as a "whole". As an example, in this section, we carry out a preliminary analysis of the impact of mobility on two reactive routing protocols after identifying the basic building blocks of MANET reactive routing protocols and their parameter setting. Thus we can extract the relative merits of different parameter settings and achieve a better understanding of various building blocks of MANET routing protocols, which will serve as a solid cornerstone for development of more efficient MANET routing protocols[8].

The part(a) and part(b) of Fig.2-11 show the building block architecture for DSR and AODV respectively, the part(c) of Fig.2-11 shows a generalized building block architecture for reactive MANET protocols.

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[8] Please refer to Ref.[11] for the details of this building block approach.

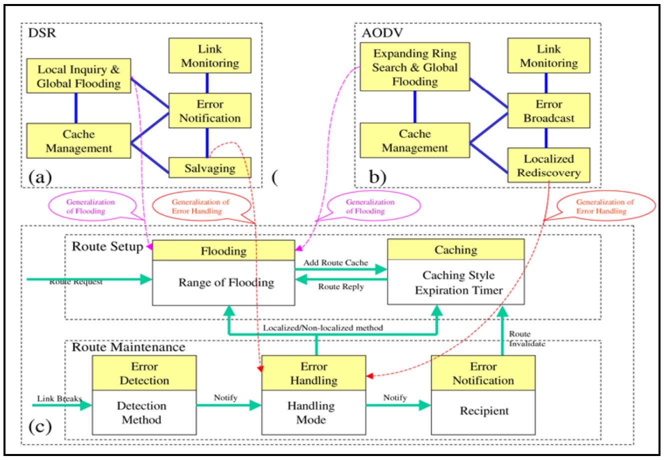


*Figure 2-11.* Diagram of Building Block Framework for Reactive Protocols

## 6.1 Design Choices of Building Blocks for DSR and AODV

First we discuss the design choices (parameter settings) of the identified building blocks of reactive MANET routing protocols and specific parameter settings for DSR and AODV. We pose some questions about the utility of the various design choices made by these protocols. In section 6.2, we attempt to answer these questions. The mechanism of reactive MANET routing protocols such as DSR and AODV is composed of two major phases: *Route discovery* phase and *Route maintenance* phase.

Route Discovery is initiated if there is no cached route available to the destination. This mechanism consists of the following building blocks:

**Flooding building block**: The flooding building block takes responsibility to distribute the route request messages within the network. Here, the key parameter is *the range of flooding*, generally described by TTL field in the IP header. For the *range of flooding*, DSR conducts a non-propagating direct-neighborhood inquiry(TTL=1) before the global flooding(TTL=D, D is network diameter). Similarly, AODV uses the expanding ring search(TTL=1,3,5,7) before the global flooding is initiated. Here, we want to answer the following question: *How useful are non-propagating route requests?*

**Caching building block**: The caching building block helps to efficiently and promptly provide the route to the destination without referring to the destination every time. One key parameter of this block is *whether aggressive caching is allowed*, i.e. whether multiple cache entries are allowed for the same destination and whether a node can cache the route information it overhears? As we know, DSR uses *aggressive caching*, while AODV does not. For caching, we are interested in the following questions: *How useful is caching? and Is aggressive caching better than non-aggressive caching?*

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 building block:** It is used to monitor the status of the link of a node with its immediate neighbors. Here, the parameter is *the mode of error detection used*. Since both DSR and AODV can use similar choice, we do not investigate this building block in our analysis.

**Error Handling building block:** It finds alternative routes to replace an invalid route after a broken link is detected. One of the parameters to this block is *what recovery scheme should be used*. In DSR, on detecting a broken link, the upstream node will first search its cache to replace the invalid route(this scheme is called salvaging), although the found alternative route may also be invalid in some scenarios. While in AODV, the upstream node detecting the broken link will initiate a localized flooding to find the route to the destination. For this building block, we are interested in the following question: *Which is a better scheme for localized error handling: cache lookup or localized flooding?*

**Error Notification building block:** It is used to notify the nodes in the network about invalid routes. The key parameter to this building block is *the recipient of the error message*. Either only the source is notified or the entire network is notified. Since both DSR and AODV only notify the error to the source, so we do not investigate this building block in our analysis.

Besides these three questions about the design choices, we are also interested at the explanation for the observation we made in section 5: DSR outperforms AODV in most mobility scenarios except the Freeway and Manhattan model with high mobility.

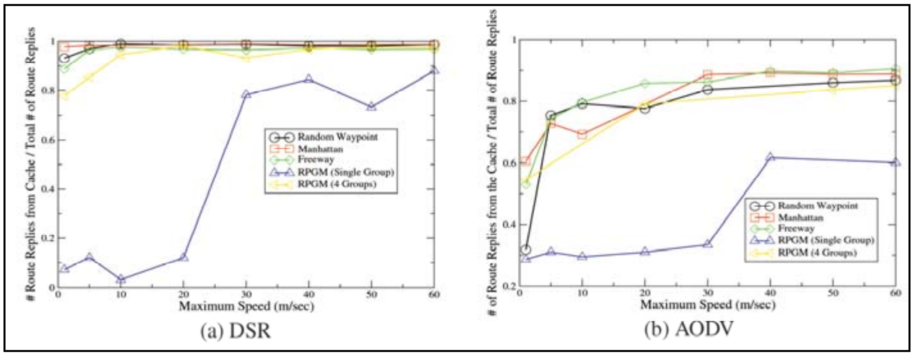
## 6.2 Experiments to Evaluate the Building Blocks

We identified parts of the network simulator (*ns-2*) code[6] which implement these building blocks and profiled them during our simulations. The simulation setting is exactly the same as section 5.

### 6.2.1 Flooding

We measure the likelihood of finding a route to the destination from the source's neighborhood. Through simulations, we find that non-propagating route request is frequently used (more than 30% for DSR and more than 10% for AODV in most scenarios). However, the ratio for DSR is almost twice as large as that for AODV across all mobility models. A possible reason for this comes from the fact that DSR uses aggressive caching as compared to AODV. When such a caching scheme is coupled with the mechanism of non propagating route requests, it translates to low routing overhead and high throughput as was shown in our study and several other comparative studies. Thus, it seems that caching has a significant impact on the performance of DSR and AODV. Hence we study it next.

### 6.2.2 Caching



(a) DSR (b) AODV

*Figure 2-12.* Ratio of the Number of Route Replies from the Cache to the Total Number of Route Replies

To measure the effectiveness of caching, we evaluate the *ratio of the number of route replies coming from the cache to the total number of route replies*. Fig.2-12(a) and Fig.2-12(b) show that this ratio is high for Random Waypoint, Manhattan and Freeway models, which implies that most of the route replies for these mobility models come from the cache(more than 80% in most mobility scenarios).

The difference in the ratio for DSR and AODV is greater than 20% for all mobility models. DSR uses aggressive caching as compared to AODV. Thus, the likelihood of a route reply coming from a cache is higher in DSR than in AODV. Therefore, fewer route requests will be needed and thus the routing overhead of DSR is lower than AODV as we observed in Section 5. Thus, aggressive caching seems to be a good design choice.

To completely evaluate the caching strategy, we also need to examine the validity of the cache entries. We evaluate the *ratio of invalid cache entries to the total number of cache entries* for DSR. In experiments, we find the invalid cache ratio increases from RPGM (around 10%) to Random Waypoint to Freeway (around 60%) to Manhattan (around 80%) mobility models. It means that caching may have adverse effects in mobility models with a high relative speed and it may lead to cache invalidation. Packets may be sent on invalid routes which might lead to packets being dropped and route request retries. This leads to a lower throughput and higher overhead for DSR for the Freeway and Manhattan models as was shown in our study.

On the other hand, in mobility models with very high relative speed like Manhattan and Freeway, AODV seems to achieve as good a throughput as DSR (and sometimes better). AODV does not use aggressive caching, thus the ratio of the number of route replies coming from the cache to the total number of route replies is lesser for AODV than DSR. Thus, the likelihood of getting invalid routes from the cache is lesser for AODV than for DSR. This may explain why AODV outperforms DSR in Freeway and Manhattan models with high mobility.

Moreover, at high relative speeds, the number of routes broken is greater. Thus, a protocol which has a better error handling mechanism at higher relative speeds might perform better in such situations. This line of reasoning leads us to evaluate the next building block of interest - Error Handling.

### 6.2.3 Error Handling

To study the effectiveness of error handling, we focus on localized error handling. We evaluate the *ratio of the number of localized error handling to the total number of route errors* for both DSR and AODV. For DSR, we notice that salvaging accounts for less than 2% of the total number of route errors. Moreover, if we take invalid cache entries into account, the effect of salvaging on the protocol performance is further lowered. On the other hand, in AODV, a route request is initiated by the upstream node that detects the broken link if it is closer to the destination. In AODV, the frequency of initiating localized flooding is between 40% and 50% for Freeway and Manhattan models. Moreover the routes obtained by this mechanism are more up to date than those from the cache salvaging in DSR. This is another factor that explains the better performance of AODV as compared to DSR in the Freeway and Manhattan models.

## 6.3 Discussion

The above study of the building blocks has given us greater insight into the design of the reactive routing protocols for MANETs. Decomposing a protocol into building blocks and evaluating these building blocks have shown us scenarios in which the chosen parameters can give a better performance. From the above study, we learnt the following principles of protocol design:

1. *Caching helps reduce the protocol overhead*. However, whether aggressive caching should be used depends on the scenarios in which the protocol will be deployed. For low mobility scenarios, aggressive caching might be useful, while for higher mobility scenarios, the more stale cache entries incurred by aggressive caching might affect the protocol throughput adversely.
2. *Non Propagating route requests, when combined with caching also reduce the protocol overhead*. If caching is widely done in the network, it may be more advantageous to do non propagating route requests (or expanding ring search) than globally flooding the route request. In DSR, due to aggressive caching, it may be more useful to do expanding ring search (from the source) on a route error than doing a global flooding (from the source).
3. *The nature of localized error handling also has a significant impact on protocol performance*. Re-initiating a route request from an intermediate node can be more advantageous than doing a local cache lookup in high mobility scenarios, while a cache lookup might be more advantageous for low mobility scenarios.

Thus, no particular parameter setting of these building blocks is the most optimal for all scenarios. This further strengthens our conclusion that there is no clear winner among the protocols across all mobility scenarios.

## 7. SUMMARY

In summary, we presented the IMPORTANT framework to analyze the impact of mobility patterns on the performance of routing protocols in mobile ad hoc networks in a systematic manner. In our study, we introduce and analyze a set of mobility models that cover our defined mobility space. Based on our analysis, we observe that mobility patterns do indeed influence the performance of MANET routing protocols. This conclusion is consistent with observations from 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 for the protocols.

Moreover, we observe that the mobility pattern influences the connectivity graph that in turn influences the protocol performance. We conducted a detailed study to investigate the path distributions under various mobility models and identified conditions under which the exponential distribution provides a good approximation for the path duration. In addition, we did an investigation of the common building blocks of reactive MANET routing protocols, the effect of mobility on these building blocks and how they influence the protocol as a ``whole".

## 8. DISCUSSION OF FUTURE RESEARCH DIRECTION

In this chapter and in[4][9], we proposed the concept of *mobility space* and *mobility dimensions* and presented a set of mobility models to represent several key characteristics of this mobility space, including relative speed, temporal and spatial dependency and geographic restriction. However, there may exist other useful dimensions of the mobility space that have neither been defined nor studied yet and their effects on MANET protocols remains unknown. Therefore, one potential research direction is to continue investigation of mobility characteristics to better define the mobility space and identify other important mobility dimensions. So far, in our discussions, we have considered synthetic mobility models that generate mobility traces based on pre-defined rules. Hence, another promising direction to pursue is to establish high quality trace-driven mobility models, where the mobility traces are collected from a real-life environment, such as vehicular mobility on highways, pedestrian mobility on campus, or robot mobility in sensor networks.

Most previous studies on mobility modeling and analysis considered protocol case studies for on-demand and table-driven ad hoc routing protocols. Many other MANET protocols (such as geographic routing) and services (such as resource discovery or location-based services) were not evaluated over a rich set of mobility models. There is a need to re-visit MANET protocols and service architectures and study their performance over various mobility models.

Recent case studies[12][13] considered mobility effects on geographic routing protocols. In Ref.[12] we conducted a study on the Grid location service[14] and observed that in addition to the interaction between mobility and the protocol building blocks, there is another interaction with the grid topology of the network. Such interaction is exacerbated when high spatial correlation exists (as in group mobility), which worsens the protocol's performance. This kind of interaction was not observed in the studies presented in this chapter.

Wireless sensor networks provide another class of networks that is very interesting to study. Some of the literature on sensor networks assumes that sensors are static. However, depending on the application, various types of mobility patterns may exist in sensor networks. Some patterns may be uncontrolled such as RF tags on animals or birds, while others may be controlled like robotic sensor nodes. In some situations the patterns appearing in sensor networks, due to the application-specific nature of these networks, may be different than those appearing in wireless ad hoc networks. New mobility models may be needed to capture mobility in sensor networks. Our initial work in [15][16] provides some expansion and contraction mobility models that may fit some sensor networks applications. However, this topic bears more future research.

Generally speaking, in most studies ([9][10][11], among many others), mobility has been considered as an evaluation parameter and is usually considered as an afterthought to the protocol design. Many of these studies show that the mobility may negatively affect the protocol performance. However, in recent works[15,17-19], mobility is integrated into the design of the protocol and is utilized to improve the performance the protocol by reducing the communication overhead. In these *mobility-assisted* protocols, mobility can play an important and positive role in improving MANET protocol performance. By virtue of depending on mobility, we expect performance of such protocols to be sensitive to the mobility pattern. Having an in-depth sensitivity analysis of mobility-assisted protocols over a rich set of mobility models would be an interesting future direction.

In addition, in some scenarios, movement of mobile nodes (i.e., robots) could be actively adjusted or even fully controlled by users, adding flexibility to the protocol design. Therefore, another research direction is to study how actively controlled mobility can possibly be utilized in mobile ad hoc and wireless sensor networks.

## 9. ACKNOWLEDGEMENT

The authors would like to acknowledge the contribution of Narayanan Sadagopan as a co-author on the IMPORTANT[4], PATHS[10] and BRICS[11] papers and Bhaskar Krishnamachari as a co-author on the PATHS paper. We also would like to thank Dave Johnson, John Heidemann and Yih-Chun Hu for their valuable suggestions at the initial stage of this study. This study was made possible by a grant from NSF Career Award 0134650.

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