PATHS: Analysis of PATH Duration Statistics and their Impact on Reactive MANET Routing Protocols

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ABSTRACT

We develop a detailed approach to study how mobility impacts the performance of reactive MANET routing protocols. In particular we examine how the statistics of path durations including PDFs vary with the parameters such as the mobility model, relative speed, number of hops, and radio range. We find that at low speeds, certain mobility models may induce multi-modal distributions that reflect the characteristics of the spatial map, mobility constraints and the communicating traffic pattern. However, our study suggests that at moderate and high velocities the exponential distribution with appropriate parameterizations is a good approximation of the path duration distribution for a range of mobility models. The reciprocal of the average path duration is analytically shown to have a strong linear relationship with the throughput and overhead that is confirmed by the simulation results for DSR.

Categories and Subject Descriptors

C.2.2 [**Computer-Communication Networks**]: Network Protocols

General Terms

Design, Performance

Keywords

Mobile Ad Hoc Network, Performance, Mobility, Path Duration

1. INTRODUCTION

Availability of small, inexpensive wireless communicating devices has played an important role in moving ad hoc networks closer to reality. Consequently, Mobile Ad hoc NETworks (MANETs) are attracting a lot of attention from the research community. MANETs are advantageous because of their readily deployable nature as they do not need any centralized infrastructure. Since this field is still in its developing stage, not many MANETs have been deployed yet. Thus, most of the research in this area is simulation based. These simulations have several parameters such as the mobility model, traffic pattern, propagation model, etc to name a few. We acknowledge that these and other factors like channel characteristics, MAC effects, etc do impact the protocol performance and the study of the interplay of these factors is very complex. In this paper, we focus on developing a detailed approach to study the effect of mobility per se on the performance of reactive MANET routing protocols like DSR [2] and AODV [5].

This paper proposes a novel approach to understand the effect of mobility on protocol performance. It uses statistical analysis (of simulation data) to obtain detailed statistics of link and path duration including their Probability Density Functions (PDFs). Further, through simple analytical models, using the case study of DSR, it shows a strong correlation between the reciprocal of **average path duration** and the throughput and overhead of reactive protocols.

Recently, there has been a greater focus on a systematic study of the effect of mobility on the performance of routing protocols. [17] proposed the IMPORTANT framework to systematically analyze the effect of mobility on routing protocols. In this framework, the authors proposed to evaluate the MANET routing protocols using a "test-suite" of mobility models that span several mobility characteristics like spatial dependence, geographic restrictions, etc. These models included the Random Waypoint (RW), Reference Point Group Mobility (RPGM), Freeway (FW) and Manhattan (MH). They found that mobility significantly impacts the performance of the protocols, which is in agreement with several other studies. Moreover, they also proposed a reason for *Why* mobility impacts performance: Mobility impacts the connectivity graph (average link duration in particular) which in turn impacts the protocol performance.

To explain *How* mobility impacts the performance, [18] introduced BRICS methodology. It proposed that a protocol could be considered to be made up of **parameterized** "building blocks" or basic mechanisms. The effect of mobility on the entire protocol can be explained in terms of its effect on these "building blocks". Some of the "building blocks" proposed by BRICS for reactive protocols were flooding, caching, error detection, error notification and error recovery. Both DSR and AODV use these "building blocks" in their operation. However, they still behave dif-

MobiHoc'03, June 1–3, 2003, Annapolis, Maryland, USA.

ferently for a given mobility model. BRICS suggested that a possible reason for this difference might be the different parameter settings for the "building blocks" in AODV and DSR. This leads to different impacts of mobility on these mechanisms. A brief overview of the work done in [17] and [18] is given in the section 3.

In this paper, we develop an approach that combines statistical analysis of simulation data and analytical modeling to get a deeper understanding of the protocol performance in the presence of mobility. [17] concluded that **average** link duration is a useful metric for relating mobility with protocol performance. For a given pair of nodes, link duration is defined as the time during which the two nodes are within the transmission range of each other. At the same time, intuitively, the protocol performance depends on the duration of a path between the source and the destination, i.e. path duration. Both link and path duration are formally defined in section 4. Path duration is significantly related to link duration. It is actually the minimum link duration along a path. In general, longer the path duration, better the performance in terms of throughput and overhead. However, the relationship between the path duration and protocol performance (throughput and overhead) has not been categorized yet. In this paper, we examine the detailed statistics of link and path duration including PDFs across the "test-suite" of mobility models proposed in [17]. We then attempt to categorize the relationship between average path duration, performance of the caching mechanism (non-propagating cache hit ratio) and protocol performance (throughput and routing overhead) as either strongly (or weakly) linearly (or non-linearly) related. The contributions of this study are the following:

1. Characterizing the statistics of link and path durations including PDFs for the different mobility models used in our study using simple statistical analysis. This also leads to a characterization of link and path durations based on the communicating traffic pattern.

2. Investigating possible distributions to approximate the path duration PDF across the mobility models used. At moderate to high mobility, we suggest that an exponential distribution with an appropriate parameterization is a reasonable approximation to most of our studied models.

3. Establishing a linear relationship, through simple first order analytical models (that are validated by simulation results), between the reciprocal of the average path duration and protocol performance (throughput and routing overhead), that helps explain several performance trends under various mobility models.

The rest of the paper is organized as follows: Section 2 gives an overview of the related work. Section 3 sets our work in context with the recent work in this area. Link and path duration are formally defined in section 4. Section 5 discusses our simulation setup while the results of these simulations are discussed in section 6. Section 7 gives first order analytical models relating the average path duration, and the protocol performance of reactive protocols using the case study of DSR. Our conclusions and future work are listed in section 8.

2. RELATED WORK

In this paper, we study the detailed statistics of link and path duration including their PDFs across a rich set of mobility models. As mentioned in section 1, we believe such a study might help in formulating analytical models for protocol performance across these mobility models. However, such a thought was inspired by other pioneering work done in MANET research.

2.1 Mobility Models:

Mobility models for simulations have been one of the early topics of research in this field. One of the early contributions was made by Broch, Maltz, Johnson, et al where they evaluated DSR, AODV, DSDV [3] and TORA [16] using the RW model [1]. They concluded that mobility does impact the performance of routing protocols. To evaluate these protocols over a wider range of scenarios, Johansson, Larsson, Hedman, et al proposed the scenario based performance analysis [10]. In this study they proposed mobility models for disaster relief, event coverage and conferences. Hong, Gerla, Pei, et al proposed the Reference Point Group Mobility (RPGM) model in [8]. One of the main applications of this model is in battlefield communications. The authors give several other applications of RPGM in [8]. While defining their framework, [17] proposed to evaluate the protocols under a richer set of mobility models. Apart from using the RW and RPGM, they used two other mobility models i.e. the FW and the MH models. In this study, we use these four models for our simulations.

2.2 Protocol Independent Metrics:

Apart from analyzing the effect of mobility on protocol performance, it is useful to characterize mobility independent of the protocols. Hence, there have been several attempts to propose mobility metrics. Johansson, Larsson, Hedman, et al proposed the relative motion between mobile nodes to distinguish the different mobility models used for their scenario based study in [10]. [17] used the metrics of relative motion and average degree of spatial dependence to characterize the different mobility models used in their study. They also proposed the connectivity graph metrics as a "bridge" relating the mobility metrics to the protocol performance. They found that average link duration at the graph level could explain this relationship. Hong, Gerla, Pei and Chiang proposed the rate of link change as a metric to differentiate the various kinds of RPGM and RW models in [8]. We agree with [17] and [8] that the connectivity graph characteristics might help in relating mobility with protocol performance. As mentioned in section 1, we believe that the path duration can also be added to this set of connectivity graph metrics. Moreover, unlike other studies, we not only examine the averages, but also focus on the detailed statistics including the PDFs of link and path duration across several mobility models.

2.3 Reactive Protocols:

In this paper, we focus on evaluating the reactive MANET routing protocols like DSR and AODV. There have been several studies to compare both proactive and reactive routing protocols. [11], [13], [2], [12] and [4] give a very good exposition of this subject. Here, we discuss the work that focus completely on reactive protocols. Johnson, Maltz, Broch, et al proposed DSR in [2], while AODV was proposed by

Perkins in [5]. Maltz, Broch, Jetcheva and Johnson gave a very comprehensive analysis of DSR in terms of its basic mechanisms of route discovery and caching [4]. They proposed several optimizations for reducing the route discovery overhead. Most of these optimizations are now part of the DSR implementation in the network simulator (*ns-2*) [15]. Das, Perkins and Royer compared the performance of AODV and DSR in [12]. They observed that DSR outperformed AODV in less demanding situations, while AODV outperformed DSR at heavy traffic load and high mobility. To explain these differences, the BRICS methodology was proposed to decompose protocols into basic "mechanisms" [18]. It illustrated an approach for this decomposition by suggesting a common architecture that encompassed both AODV and DSR. Though both AODV and DSR consist of similar mechanisms or "building blocks" (that are parameterized), they behave differently in the presence of mobility. Some of these mechanisms are caching, flooding, etc. A detailed overview of BRICS is given in section 3. In this study, we propose a simple analytical model that relates the average path duration and the performance of the caching mechanism to the routing overhead of DSR (and reactive protocols in general). Both [4] and [18] consider this mechanism to play an important role in determining the routing overhead of DSR and other reactive protocols. Moreover, we also develop a simple intuitive model to show the relationship (linear or non-linear) between the average path duration and the reactive protocol throughput.

2.4 Analysis

Apart from simulation-based studies, the MANET research literature also contains analytical work on mobility and protocol performance modeling. One of the earliest analysis of mobility was done by Mc Donald and Znati in [6]. They used a RW like mobility model and derived expressions for the probability of path availability and link availability for different initial conditions. Stochastic properties of the RW model were studied recently in [21], [22] and [23]. Su, Lee and Gerla exploited the non-random movement of mobile nodes during intervals to predict its location in [9]. They proposed a model for link duration and evaluated it using the RW model. In this paper, we examine the detailed statistics of link and path duration including PDFs across several mobility models used in our study. Gruber and Li presented a very detailed analysis of link duration times for a two hop MANET in [24]. In this study, the distribution of the link duration appeared to be exponential. Their analysis assumed that the source and destination are fixed while the intermediate hop is moving using the RW model. The exponential distribution of link duration also comes up in the analysis of single path and multipath DSR by Nasipuri, Castaneda and Das in [20]. They assumed that the link durations are exponentially distributed independent random variables (i.i.d) and analytically derived the distributions for path duration, which turns out to be exponential as well. The underlying mobility model was not very clearly specified. Moreover, the exponential distribution assumption was not validated by simulation or real data. Inspired by these works, in this paper, we examine the detailed statistics of link and path duration including PDFs across the RW, RPGM, FW and MH models. We observe that under certain conditions the path duration PDFs can be approximated by exponential distributions for the models used in our study. We demonstrate the effect of the number of hops, the transmission range and the relative speed of the mobility model on the path duration PDF. Using the case study of DSR, we propose simple analytical models that relate the average path duration and the non-propagating cache hit ratio to the performance of reactive protocols (in terms of throughput and routing overhead).

3. BACKGROUND

Our approach of evaluating the protocols across mobility models was inspired by the IMPORTANT framework proposed in [17]. This framework made an attempt towards the systematic evaluation of the impact of mobility on MANET routing protocols. It defined protocol independent metrics like the average degree of spatial dependence ($\bar{D}_{spatial}$) and the average relative speed ($\bar{\text{RS}}$)to capture certain mobility characteristics. One of these characteristics was the extent to which the motion of a node is influenced by nodes in its neighborhood (which is captured by $\bar{D}_{spatial}$). Another characteristic was the presence of geographic restrictions on mobility. Once these metrics were defined, mobility models that spanned these mobility characteristics were chosen. These models were:

1. **Random Waypoint (RW):** At every time instant, a node randomly chooses a speed and destination, and moves towards it. Each node moves independently of other nodes.
2. **Reference Point Group Mobility (RPGM):** Nodes move in either single or multiple groups. The movement of a node in a group is strongly influenced by the leader of the group.
3. **Freeway (FW):** Each node moves in its lane on the freeway. Its movement is constrained by nodes moving ahead of it in the same lane.
4. **Manhattan (MH):** Nodes move on a grid. As in the FW model, each node is constrained by nodes moving ahead of it. However at the cross points of the grid, a node is free to change its direction unlike the FW model.

Different mobility patterns following the above mobility models were generated by varying the maximum speed of the mobile nodes. The mobility metrics of these mobility patterns were evaluated. Using these patterns, simulations were run in the network simulator (*ns-2* [15]) environment with the CMU Wireless Ad Hoc networking extension to evaluate the performance of DSR, AODV and DSDV in terms of throughput and routing overhead. To explain the relationship between the mobility metrics and the protocol performance, certain connectivity graph metrics were defined. Some of these metrics were the number of link changes, the path availability and the average link duration. For their study, the most useful of these graph metrics was the average link duration ($\bar{\text{LD}}$), which could help in relating the mobility metrics to the protocol performance metrics. The study observed that, given a communication traffic pattern, the underlying mobility pattern does have a significant impact on the performance of routing protocols. Moreover, it concluded that there is no clear performance based ranking of the protocols across these mobility models.

To explain *Why* mobility affects the protocol performance, [18] proposed the BRICS methodology to systematically decompose routing protocols into basic mechanisms or "building blocks". This methodology claimed that the difference in the protocol performance comes from the fact that the basic mechanisms (or "building blocks") of these protocols are different. For example, DSR and AODV are reactive while DSDV is proactive. However, although DSR and AODV belong to the class of reactive protocols, they behave differently for a given mobility model. To understand this difference better, BRICS proposed the following possible decomposition of the reactive routing protocols:

Reactive protocols consist of two major phases:

1. **Route Setup Phase:** In this phase, a route between the source and destination is setup on demand. The basic mechanisms (and their parameters) used in this phase are:
   (a) *Flooding:* It is responsible for distributing the source's route request in the network. Its parameter is the range of flooding, which is specified by the Time To Live (TTL) field in the IP header.
   (b) *Caching:* Caching is an optimization to reduce the overhead of flooding. If a node has a cached route to the destination, it will reply to the source's route request. Its parameter is whether aggressive caching should be used. i.e. should the nodes use all the overheard route replies and should they cache multiple routes to the destination.
2. **Route Maintenance Phase:** This phase is responsible for maintaining the path between the source and the destination. The basic mechanisms used in this phase are *Error Detection*, *Error Notification* and *Error Recovery.*

Both DSR and AODV make different choices for the parameters of the "building blocks" mentioned above. For example, in the caching "building block", DSR performs aggressive caching while AODV does not. In the flooding "building block", before flooding a route request in the network, DSR issues a route request with a TTL of 1 (non-propagating route request). On the other hand, AODV performs an expanding ring search (with TTL = 1, 3, 5 and 7) before initiating the flooding[1]. As in [18], we define the **non-propagating cache hit ratio** as the ratio of the route requests which are answered by the one hop neighbors to the total number of route requests. [18] observed that the "building blocks" are impacted differently by a given mobility model, depending on their choice for the parameters. Moreover the performance of the entire protocol is determined by the performance of these building blocks. For example, the overhead of the protocol is affected by the non-propagating cache hit ratio. Higher the ratio, lower will be the frequency of route request flooding. Since both AODV and DSR use different caching strategies, this non-propagating cache hit ratio for the two protocols might be different, which leads to different routing overheads for these protocols for a given mobility model.

In this paper, we attempt to develop a deeper understanding of the impact of mobility on the protocol performance. We take a step further in the analysis of the impact of mobility on the connectivity graph. We determine the detailed statistics (including PDFs) of link and path duration at the connectivity graph level across the "test-suite" of mobility models proposed by [17]. Our study suggests that for moderately high speeds and paths with more than two hops, the path duration PDF can be approximated as an exponential distribution for the mobility models used. The average path duration and the non-propagating cache hit ratio are related to the throughput and routing overhead of reactive protocols through simple first order analytical models (that are validated by simulation results), using DSR as a case study.

In the next section, we formally define the link and path duration metrics.

4. CONNECTIVITY GRAPH METRICS

One of the main challenges for routing in MANETs is to deal with the topology (connectivity graph) changes resulting from mobility. The performance of a protocol is greatly determined by its ability to adapt to these changes. Realizing this, researchers have proposed metrics to characterize the effect of mobility on the connectivity graph with an aim to explain the effects of mobility on protocol performance. We define the link duration and path duration metrics in this section.

First, we mention some commonly used symbols in this section. Let

1. N be the total number of nodes.
2. $D_{ij}(t)$ be the Euclidean distance between nodes i and j at time t.
3. R be the transmission range of the mobile nodes.

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

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. Otherwise, $X(i, j, t) = 0$.

1. **Link Duration:** 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 $t_1 - \epsilon$ and time $t_2 + \epsilon$ for $\epsilon > 0$. Formally,
   $$\mathrm{LD}(i, j, t_1) = t_2 - t_1$$
   iff $\forall t \; t_1 \leq t \leq t_2, \; \epsilon > 0 \; : \; X(i, j, t) = 1$ and $X(i, j, t_1 - \epsilon) = 0$ and $X(i, j, t_2 + \epsilon) = 0$. Otherwise, $\mathrm{LD}(i, j, t_1) = 0$.
2. **Path Duration:** For a path $P = \{n_1, n_2, ...n_k\}$, 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 $t_1 - \epsilon$ and time $t_2 + \epsilon$, $\epsilon > 0$, 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

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[1] Although, the initial design does not specify the expanding ring search, the *ns-2* implementation of AODV uses the expanding ring search.

durations of the $k-1$ links $(n_1, n_2), (n_2, n_3)...(n_{k-1}, n_k)$ at time t_1. Formally,

$$\text{PD}(P, t_1) = \min_{1 \leq z \leq k-1} \text{LD}(n_z, n_{z+1}, t_1)$$

Thus, both link and path durations are a function of time. Link duration has been studied before across the "test-suite" of mobility models in [17]. However, that study was based on average values. Here, we also examine the PDFs of the link and path duration across these mobility models. We believe that this approach might give a deeper understanding of the impact of mobility on the protocol performance. PDFs are estimated using simple statistical analysis of the simulation data. The simulation settings for estimating the PDFs are discussed in the next section.

5. SIMULATION SETTINGS

Having defined the metrics, as mentioned in 1, we focus our attention on obtaining the detailed statistics of the link and path duration across the different mobility models used in our study. We simulate the node movement according to the "test-suite" of mobility models proposed in [17]. For each mobility model, we collect the detailed statistics of the link and path duration at the connectivity graph level. The details of the mobility models used are mentioned in section 5.1, while the collection of statistical data on link and path duration from these simulations is mentioned in section 5.2.

5.1 Mobility Patterns

The mobility patterns are obtained from the mobility scenario generator mentioned in [17]. This scenario generator produces the different mobility patterns following the RPGM, FW and MH models according to the format required by *ns-2*. In all these patterns, 40 mobile nodes move in an area of 1000m x 1000m for a period of 900 seconds. The values for the transmission range will be mentioned in section 5.2 when the link and path durations are measured. RW mobility pattern is generated using the *setdest* tool which is a part of the *ns-2* distribution. For RPGM, we use 2 different mobility scenarios: single group of 40 nodes and 4 groups of 10 nodes each moving independent of each other and in an overlapping fashion. Both Speed Deviation Ratio and Angle Deviation Ratio are set to 0.1[2]. For the FW and MH models, the nodes are placed on the freeway lanes or local streets randomly in both directions initially. Their movement is controlled as per the specifications of the respective models. The maximum speed V_{max} is set to 1, 5, 10, 20, 30, 40, 50 and 60 m/sec to generate different movement patterns for the same mobility model.

Once, the mobility patterns are obtained, we measure the link and path duration across them. Our procedure for doing this measurement in described in the next section.

5.2 Measuring Link Durations and Path Durations

For the purpose of measuring the link and path duration distributions, the transmission range R of the mobile nodes is set to 250 m. Then, the link and path durations at the connectivity graph level are measured using our trace analyzer program. Given a mobility trace file, this program analyzes the link and path durations. This analysis might get complicated due to node mobility. A common way to simplify the procedure is to take a series of "snapshots" of the network connectivity graph during the simulations. For each snapshot, the connectivity graph can be considered static and analyzed. Our mobility scenarios have a granularity of one second i.e. during the time interval [t,t+1], the connectivity graph does not change. Hence, we take a snapshot of the connectivity graph once every second. Once the snapshot of the network connectivity graph is taken, the link and path durations can be readily measured as follows:

1. **Link Durations:** The status of a link between every pair of nodes within the transmission range of each other is monitored during the simulation. The link duration is calculated as the interval between the time when the link is created and time when it breaks. This is done for every link that comes into existence during the simulation. The different link durations are then sorted into bins of 1 sec, 2 sec ... 900 sec (simulation time).

2. **Path Durations:** The status of a path between every source - destination pair in the network is monitored. The path duration is counted as the interval between the time when the path is set up and the time when the path is broken. However, there can be potentially exponential paths between any specific source - destination pair. Analyzing the duration of all these paths might not be feasible. As a reasonable approximation, we define the path duration as the duration of the shortest path[3]. The shortest path between the source and the destination is computed by the *Breadth First Search(BFS)* algorithm [25]. The path duration is measured for all source-destination pairs in the network. The different path durations thus obtained are then sorted into bins of 1 sec, 2 sec ... 900 sec (simulation time).

   PDF estimation: After having sorted the samples of link and path durations into bins as mentioned above, we plot a histogram of these durations for the mobility scenarios mentioned in section 5.1. For link durations, we plot the histograms for the different mobility models and different maximum velocities V_{max} for each model. For path durations, we plot the histograms vis-a-vis the number of hops h in the path for the various mobility models, various maximum velocities V_{max} for each model. Having collected a large set of samples for link and path durations, we use the relative frequency approach (from standard probability theory) to estimate the PDFs of the link and path duration across the different mobility models used in our study [26]. Once, the PDFs are determined, we compute the average link duration for the different mobility models and different values of V_{max}. For computing the average path duration, we also vary the transmission range R. The different values of R used are 50, 100, 150, 200 and 250 m. We compute the average path duration for

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[2] Speed Deviation Ratio and Angle Deviation Ratio are defined in [17]. They control the extent to which the group members can deviate from the leader in speed and direction.

[3] Thus, in general the one hop path duration is not the same as the link duration. If a path of more than one hop already exists between the source and the destination before they come within range of each other, we still monitor the original shortest path until it breaks.

the different mobility models, different values of V_{max}, different values of h and different values of R. This detailed statistical analysis of the path duration is used in section 7.

Our observations from these simulations and measurements are discussed in the following section.

6. OBSERVATIONS

The purpose of examining the detailed statistics of link and path duration across the "test-suite" of mobility models was to gain a deeper understanding of the impact of mobility on the protocol performance. We observe that for low V_{max}, some models like FW and RPGM (4 groups) have multi-modal distributions for both link duration and path duration. However, for moderate and high values of V_{max}, path durations can be approximated as exponential distributions for most of the models used in our study. Moreover, we also learn some lessons about the effect of traffic pattern on these distributions. We first discuss the link duration PDFs and follow it up with a discussion of the path duration PDFs.

6.1 Link Duration PDFs

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 the rest of the section we will refer to a "peak" as a cluster in the PDF. For example, as shown in figure 1 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. The peak on the left side dominates the PDF i.e. the area under the peak on the left side is much larger than the area under the peak on the right side. This is because the links between nodes traveling in opposite directions are frequently broken and the number of such instances is larger, compared to the links between nodes traveling in the same direction.

A similar phenomenon is also observed for RPGM (with 4 groups) at small velocities as shown in figure 2. However, in this case, we observe multiple peaks of almost similar size (for example at around 100 sec, 200 sec, 280 sec and 350 sec). The peak to the left of around 300 sec are slightly larger and are due to the links between the nodes from different groups, and the peaks to the right of 300 sec are due to the links between nodes within the same group. The area under the left peaks is more due to a larger number of inter-group links as compared to the intra-group links in our scenarios.

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. The link duration PDF for the RW model, RPGM (4 groups) and the FW model at $V_{max} = 30$ m/sec are shown in figures 3, 4 and 5 respectively.

Moreover, for the RPGM (single group) model, it is observed that most of the links have a duration of around 900 seconds (simulation time) i.e. most of the links last for the entire duration of the simulation. Since it does not convey any new information, we do not show the link duration PDF

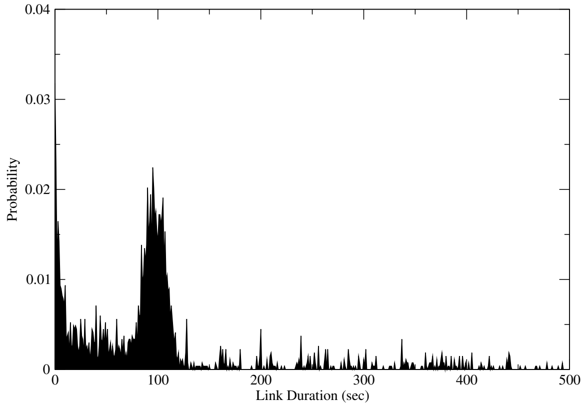

Figure 1: PDF of the Link Duration for the FW model. Here, Vmax = 5 m/s and R = 250 m

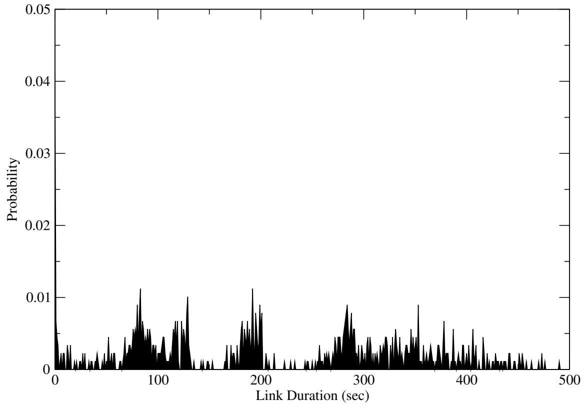

Figure 2: PDF of the Link Duration for the RPGM model with 4 Groups. Here, Vmax = 5 m/s and R = 250 m

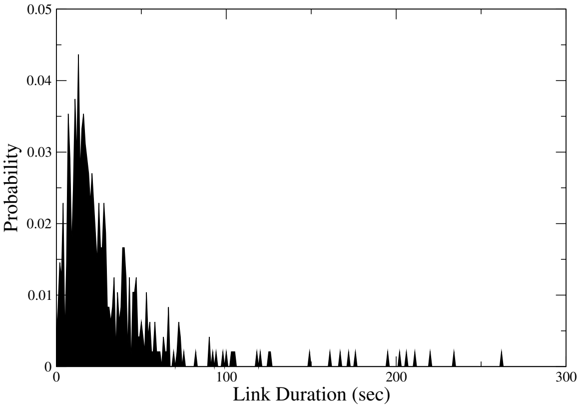

Figure 3: PDF of the Link Duration for RW model. Here, Vmax = 30 m/sec and R = 250m

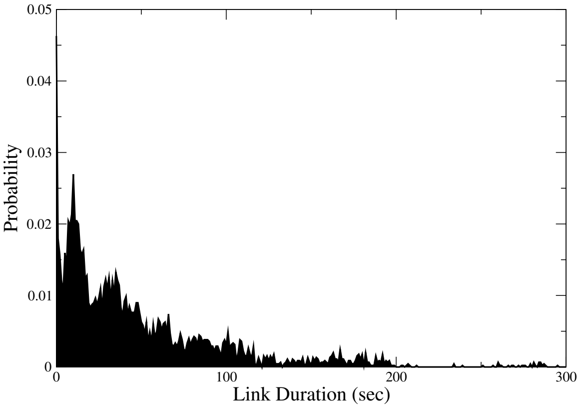

Figure 4: PDF of the Link Duration for RPGM (4 groups) model. Here, Vmax = 30 m/sec and R=250m

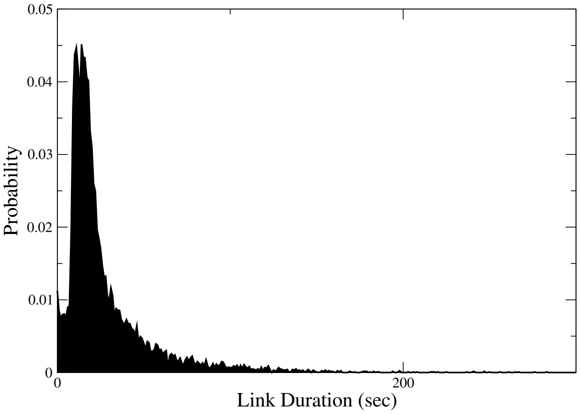

Figure 5: PDF of the Link Duration for FW model. Here, Vmax = 30 m/sec and R = 250m

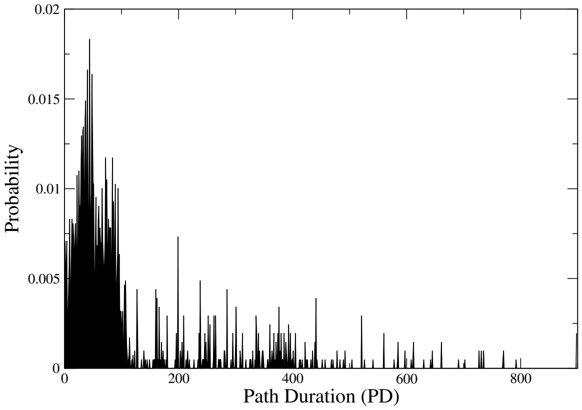

Figure 6: PDF of Path Duration for the FW model. Here, Vmax = 5m/sec and h = 1 hop

for the single group case.

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

6.2 Path Duration PDFs

We again 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 figure 6, 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) with a smaller area seems to consist of paths containing the nodes going in the same direction. We also notice a similar mutil-modal behavior for RPGM (with 4 groups) as shown in figure 7. The peak with larger area on the left (at around 30 sec) consists of paths having inter-group links, while the peak with smaller area on the right (at around 110 sec) is composed of paths containing intra-group links. Similar to the link duration PDF, the peak on the left dominates the PDF for both FW and RPGM (with 4 groups) models.

From the multi-modal PDFs for link and path duration for the FW and RPGM (with 4 groups) models at low speeds and small path lengths, we can learn some useful lessons about the effect of the traffic pattern on the protocol performance. At small speeds, if most of the communication traffic is between nodes on the same lane (for the FW model) or between nodes in the same group(for the RPGM model), greater will be the path duration for this traffic, which will also result in higher average path duration. Thus, intuitively the throughput will be higher. On the other hand, if most of the communication traffic is between nodes in opposite lanes (for the FW model) or between nodes in different groups (for the RPGM model), the path duration for this traffic will be lower, leading to a lower average path duration. This would result in lower throughput and higher routing overhead. Although, these explanations seem intuitive, we now have strong evidence (based on the peaks in

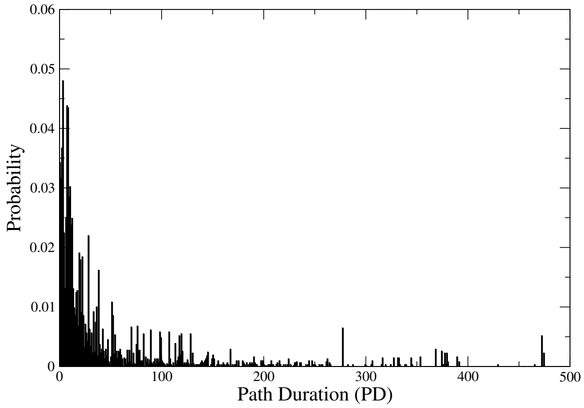

Figure 7: PDF of Path Duration for the RPGM model with 4 Groups. Here, Vmax = 5 m/sec and h = 2 hops

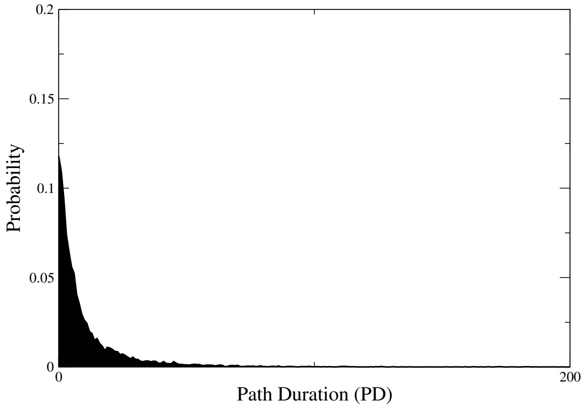

Figure 8: PDF of Path Duration for RW model. Here, h = 2 hops, Vmax = 30 m/sec and R = 250m

the path duration PDF) to back these intuitions.

The path duration PDF for the RW, FW, MH and RPGM models seems to be exponentially distributed when $V_{max} \geq 10$ m/sec and $h \geq 2$. Figures 8, 10 and 9 show the path duration PDFs for the RW, FW and RPGM (with 4 groups)

Thus, from our simulations, we observe that if $V_{max} \geq 10$ m/sec and $h \geq 2$, then the path duration for the RW, MH, FW and RPGM can be approximated as an exponential distribution. In section 7, we develop a simple analytical model to characterize the path duration PDF across these mobility models. We then relate the average path duration and the non-propagating cache hit ratio to the performance of reactive protocols by using the case study of DSR.

7. ANALYSIS

In this section, we demonstrate the utility of studying the link and path duration PDFs estimated statistically across the different mobility models used in our study. This is

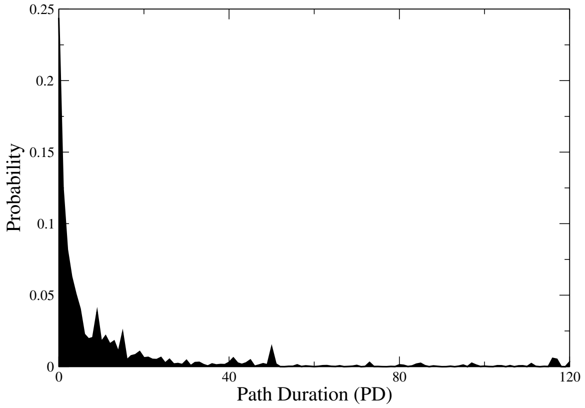

Figure 9: PDF of Path Duration for the RPGM model with 4 groups. Here, h = 4 hops, Vmax = 30 m/sec and R = 250m

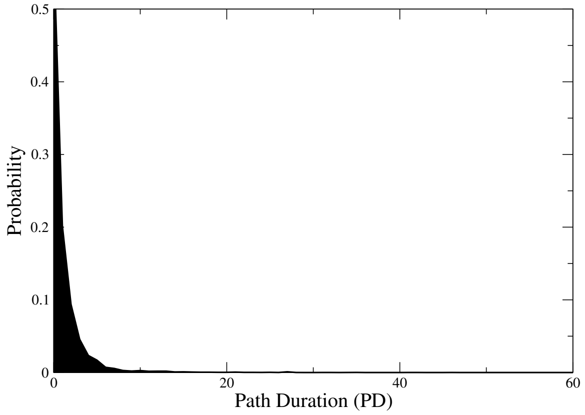

Figure 10: PDF of Path Duration for the FW model. Here, h = 4 hops, Vmax = 30 m/sec and R = 250m

done by first proposing an analytical model for path duration PDF in section 7.1, which is validated by our simulations done in section 5. The average path duration and the non-propogating cache hit ratio are related to protocol throughput and overhead in section 7.2. The analysis in this section can be used for those mobility scenarios where our approximation of the link and path duration PDFs as exponential distributions is valid (as mentioned at the end of section 6.2).

We also assume that the transmission range R is fixed. In general, R is a function of a several parameters including channel characteristics, physical layer capabilities like power control and ability to capture, smart antennas and so on. These factors would affect the connectivity graph considerably. However, in this section, we attempt to develop a simple intuitive first order model for the path duration PDF. Moreover, this model is validated by simulations in *ns-2*. In these simulations, the transmission range of the nodes is fixed (they do not use power control, smart antennas, etc). Moreover, these simulations do capture some of the channel and MAC effects.

7.1 Analytical model for path duration PDF

For our study, we assume that the path duration for the mobility models is exponentially distributed. However, this assumption is valid only under the conditions mentioned at the end of section 6.2. Now, we try to characterize this distribution for each mobility model i.e. develop a model for the parameter λ_{path} of this distribution. However, intuitively, λ_{path} has the following properties:

1. 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. λ_{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. λ_{path} increases). Hence, $\lambda_{path} \propto V$.
3. As the transmission range R increases, link duration increases, the average path duration increases (i.e λ_{path} decreases). Hence, $\lambda_{path} \propto \frac{1}{R}$.

Thus,

$$\lambda_{path} = \lambda_0 \frac{hV}{R} \qquad (1)$$

where λ_0 is the constant of proportionality. This constant factor is determined by the map layout, node density and other detailed parameters of mobility scenarios. This constant is independent of V, h and R.

The above model for λ_{path} is verified by our simulations in section 5. Figures 12, 13 and 14 show that the average path duration estimated from the statistical analysis in section 5.2 varies effect inversely as h, inversely as V_{max} and directly as R. In our analytical model, the average path duration is $\frac{1}{\lambda_{path}}$, since the path duration is assumed to be exponentially distributed with parameter λ_{path}. In figure 12, the curves for RPGM (4 groups) and FW appear to be truncated. This is because in our scenarios, the longest path for these models has 6 and 5 hops respectively, while the RW model has a longest path of 8 hops. Moreover, although we show the effect of V_{max} on the average path duration, the average relative speed and V_{max} are almost linearly related across all mobility models [17]. Hence, the relative speed will have a similar effect on the average path duration. The variation of average relative speed with V_{max} is shown in figure 11.

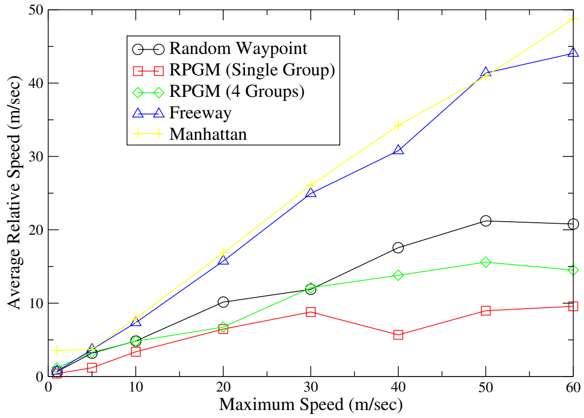

Figure 11: Average Relative Speed

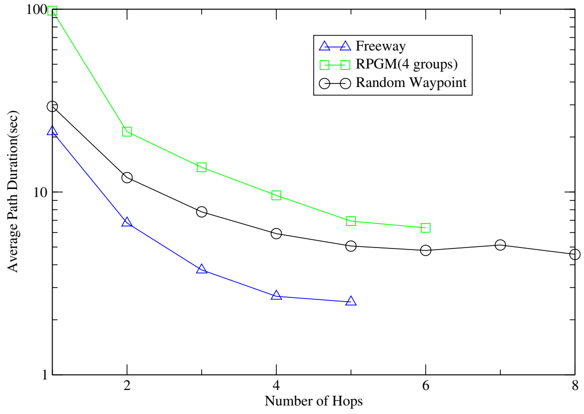

Figure 12: Effect of h on the average path duration for Vmax = 30 m/sec and R = 250m (inverse relationship)

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]:

$$f(x) = \frac{\lambda_0 hV}{R} e^{\frac{-\lambda_0 hV}{R} x} \qquad (2)$$

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

$$F(x) = 1 - e^{\frac{-\lambda_0 hV}{R} x} \qquad (3)$$

In the next section, we show the utility of average path

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[4] We conducted the Kolmogorov Smirnov test on these PDFs. The D-statistic for the PDFs shown in figures 8, 9 and 10 is 0.13, 0.17 and 0.19 respectively, which shows that the exponential distribution is a reasonable approximation for the path duration PDF [26].

duration by relating it to general trends in the performance of reactive MANET protocols.

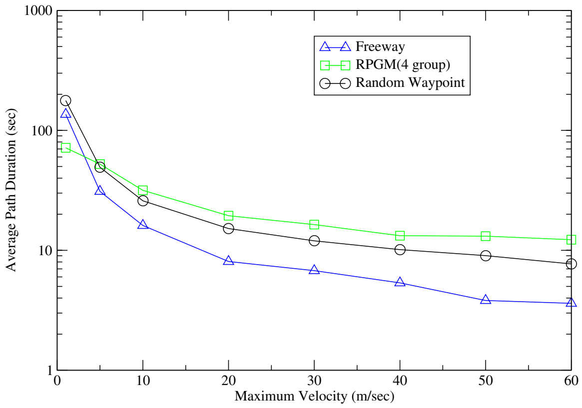

Figure 13: Effect of Vmax on the average path duration for h = 2 and R = 250m (inverse relationship)

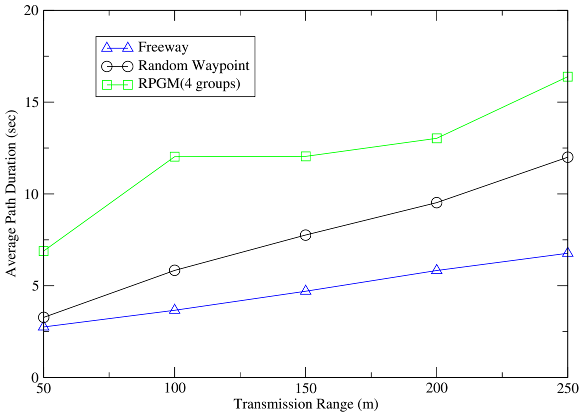

Figure 14: Effect of R on the average path duration for h = 2 and Vmax = 30 m/sec (linear relationship)

7.2 Relating the average path duration to performance of reactive protocols

As mentioned in section 1, one of the objectives of our study is to find whether the protocol performance is weakly (or strongly) linearly (or non linearly) related to the path duration. In this section, we give 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 again use the case study of DSR.

Before we derive the analytical model to study the relationship between path duration and protocol performance in terms of throughput and routing overhead, we first define the commonly used variables in this section. Let

1. N be the total number of nodes.
2. T be the total simulation time.
3. T_{flow} be the time during which actual data transfer place at maximum rate.
4. t_{repair} be the time spent to repair a broken path each time.
5. T_{repair} be the total time spent in repairing broken paths during the time T.
6. PD is the average path duration.
7. f is the frequency of path breaks, $f = \frac{1}{PD}$.
8. D is total data transferred during simulation.
9. r is the data rate, which is assumed to be constant [5]

Now, we propose a simple first order model relating the path duration with throughput and routing overhead respectively. 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.

Throughput:

The throughput analysis is done as follows:

For each source-destination pair, the time T is composed of two parts: the time used to transfer data and the time used to repair the broken path. Thus,

$$\begin{aligned} T &= T_{flow} + T_{repair} \\ &= T_{flow} + t_{repair} f T \end{aligned} \quad (4)$$

Since $PD = \frac{1}{f}$, then

$$\begin{aligned} T_{flow} &= (1 - \frac{t_{repair}}{PD})T \\ T &= \frac{T_{flow}}{1 - \frac{t_{repair}}{PD}} \end{aligned} \quad (5)$$

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[5] In genereal, the data rate might depend on MAC effects, channel characteristics, etc. However, the effect of these factors on protocol performance is beyond the scope of this work as we are mainly interested in the effect of mobility on protocol performance. However, as mentioned earlier, our simulations do capture some of these effects.

Now,

$$\begin{aligned} Throughput &= \frac{D}{T} \\ &= \frac{D}{\frac{T_{flow}}{1-\frac{t_{repair}}{PD}}} \\ &= (1 - \frac{t_{repair}}{PD})\frac{D}{T_{flow}} \\ &= (1 - \frac{t_{repair}}{PD})r \qquad (6) \end{aligned}$$

Overhead:
The overhead analysis is done as follows:
$\frac{T}{PD}$ gives the number of route requests issued by DSR in time T. A fraction p (the non propagating cache hit ratio) of these requests is replied by the first hop neighbors and thus needs only one route request transmission[6]. For the remaining fraction $(1-p)$, flooding of the route request will have to be done leading to N transmissions of the request. In general, the overhead of DSR (in terms of number of route request packets sent) can be given as follows:

$$Overhead = \frac{T}{PD}((p)1 + (1-p)N) \qquad (7)$$

From equations 6 and 7, we make an interesting observation: **There exists a linear relationship between the reciprocal of the average 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 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 between the reciprocal of path duration and DSR routing performance protocol. Thus, the two simple analytical models (which DO NOT capture MAC and physical layer effects) we propose are consistent with our experimental results (which DO capture MAC and physical layer effects). For the RPGM model, such a strong correlation between the average path duration and protocol performance does not seem to exist. One plausible reason is that number of path changes is relatively small in RPGM model and thus the accuracy of estimation is affected. Our simulations for DSR were run in the *ns-2* environment. 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. The mobility patterns generated in section 5.1 were used for these simulations.

Although the simple analytical models are derived based on DSR, we believe a similar approach can be extended to other reactive routing protocols such as AODV with appropriate modifications. For example, for AODV, we would have to take into account the cache hit probability at 1, 3, 5 and 7 hops rather than just at 1 hop.

In this section, we gave simple first order models relating the average path duration to the throughput and overhead of reactive protocols. However, from section 7.1, for our simulations, we observed that the average path duration is directly proportional to the transmission range R and inversely proportional to the number of hops h and average relative speed V. Thus, our first order models also relate the protocol throughput and overhead to several factors including the transmission range, the average number of hops in the path, the relative speed of the mobility model used. Thus, this entire approach has given us a greater understanding of the impact of mobility and other factors on protocol performance.

8. CONCLUSIONS & FUTURE WORK

We proposed an approach for a deeper understanding of the effect of mobility on MANET routing protocols. To begin with, this approach examined the detailed statistics (including PDFs) of link and path duration across a rich set of mobility models. For small velocities, these PDFs were observed to have a multi-modal distribution across some of the models used. This observation showed the impact of the traffic pattern on the path duration PDF. For moderate and high velocities, across the mobility models used in our study, it was observed that the path duration PDFs for paths of two or more hops can be approximated by an exponential distribution which is parameterized by the relative speed of the mobility model, the transmission range of the node and the number of hops in the path. We also proposed simple analytical models that show that the reciprocal of the average path duration is strongly correlated with the throughput and overhead of reactive routing protocols. Simulations for DSR seemed to confirm this relationship.

Thus, path duration seemed to be a good metric to predict the general trends in the performance of reactive routing protocols. At the same time, our analytical models showed the relationship between the path duration and other parameters like the average relative speed of the mobility model, the transmission range of the mobile nodes and the average number of hops in the path. These findings enabled us to relate the several parameters including mobility to the performance of reactive protocols using the detailed statistics of path duration.

As part of future work, one of our immediate goals would be to develop an analytical model for the non-propagating cache hit ratio for the mobility models used in our study. It would also be interesting to see how this ratio is affected by the communicating traffic pattern. As a longer-term goal, we seek to use richer analytical models to predict the performance trends of the reactive MANET routing protocols like DSR and AODV. We believe that by analyzing the basic mechanisms of these protocols, we can develop a comprehensive model for the "whole" protocol. Moreover, this analysis can be readily applied to other protocols that use similar mechanisms.

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[6] Under reasonable assumptions, it can be shown that p is independent of the relative velocity of the mobility model. For an simple analytical model, refer [19]

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