IMPACT OF MOBILITY MODELS ON MULTI-PATH ROUTING IN MOBILE AD HOC NETWORKS

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ABSTRACT

The high-level contribution of this paper is a detailed simulation based analysis about the impact of mobility models on the performance of node-disjoint and link-disjoint multi-path routing algorithms for mobile ad hoc networks (MANETs). We consider the following MANET mobility models: Random Waypoint, Random Direction, Gauss-Markov, City Section and Manhattan mobility models. Simulations have been conducted for various network density and node mobility levels. The performance metrics studied include the lifetime per multi-path set, the multi-path set size and the average hop count per multi-path. For almost every simulation condition, we observe the Gauss-Markov mobility model to yield the least number of multi-paths, but the lifetime per multi-path set under this mobility model is the maximum. The Random Direction mobility model yields the smallest lifetime per multi-path set, even though it yields a relatively larger number of multi-paths.

KEYWORDS

Mobility Models, Multi-path Routing, Simulations, Mobile Ad hoc Networks

1. INTRODUCTION

A mobile ad hoc network (MANET) is a collection of mobile wireless devices or nodes that communicate with each other. The transmission range of a wireless node is the maximum distance within which the signals received from the node can be used to extract meaningful information. Two nodes within each other's transmission range can communicate directly. If two nodes are not within each other's transmission range, they have to communicate using a multi-hop route involving one or more intermediate nodes. Since wireless devices operate with limited battery power, they are often configured to work on a smaller transmission range. So, multi-hop routing is more common in MANETs.

The mobility of nodes makes fixed multi-hop routing unlikely in MANETs. In a dynamically changing environment, the position of the nodes changes over a period of time. As a result, a route determined between any pair of nodes breaks frequently and has to be re-discovered. Frequent route discoveries consume the battery charge at the nodes and also unnecessarily exhaust the network bandwidth that could be otherwise used for data transfer. Hence, routing solutions that maximize the time between route discoveries are of significant interest.

Several solutions to maximize the time between route discoveries have been proposed. One solution to the problem is multi-path routing. In a multi-path routing algorithm or protocol, a series of paths from the source node to the destination node are found at the same time. When a path gets broken, it is removed from the list of paths and the next path in the list is used. The process of going through the series of paths continues until the list becomes empty, after which another multi-path route discovery is performed. The relationship between the multi-path set size (the number of multi-paths learnt per route discovery) and the lifetime per multi-path set (the time taken between two successive multi-path route discoveries) is of significant importance to evaluate the efficiency of multi-path routing algorithms and this has not been yet thoroughly explored.

In this study, we explore the impact of the MANET mobility models on the performance of the link-disjoint and node-disjoint multi-path routing algorithms [1] that have been proposed for MANETs. The performance metrics of specific interest are the lifetime per multi-path set and the multi-path set size. The MANET mobility models considered are: Random Waypoint model [2], Random Direction model [3], Gauss-Markov model [4], City Section model [5] and the Manhattan model [6].

We model an ad hoc network as a unit disk graph where each node is a vertex of the graph and there exists an edge between two vertices if the physical distance between the two nodes is within the transmission range. In a set of link-disjoint paths between a source *s* and destination *d*, each edge in the graph can exist at most in one of the paths. In a set of node-disjoint *s-d* paths, each node (except *s* and *d*) in the network graph can exist in at most one of the paths. In [1], it has been observed that even though the multi-path set size identified by a link-disjoint path routing algorithm is more than that identified by a node-disjoint path routing algorithm, the lifetime per multi-path set for both link-disjoint and node-disjoint path routing are not that much different from each other. However, the simulations in [1] have been conducted only under the Random Waypoint mobility model. In this paper, we explore whether the above relationship between the multi-path set size and the lifetime per multi-path set remains the same for simulations under the different MANET mobility models. Another significant contribution of this paper is a ranking of the different mobility models with respect to the two performance metrics. Note that we use the terms 'path' and 'route', 'link' and 'edge' interchangeably. They mean the same.

The remainder of the paper is organized as follows: Section 2 reviews the different MANET mobility models studied. Section 3 outlines the link-disjoint and node-disjoint multi-path routing algorithms used. Section 4 describes the simulation environment and defines the performance metrics evaluated. Section 5 presents the performance results obtained for multi-path routing (link-disjoint and node-disjoint paths) and single-path routing under each of the mobility models and interprets them. Section 6 draws the conclusions of this research and also discusses future work.

2. REVIEW OF MOBILITY MODELS

A mobility model is used to capture the movement of a real-world object in simulation studies. In MANETs, a mobility model is used to define the movement of a mobile wireless node (shortly referred hereafter as MN). There are two types of MANET mobility models: single-entity and group. In single-entity models, each MN moves independently of all the other MNs within the network area. For simplicity, most of the mobility models are defined for a rectangular network area enclosed by (0, 0), (0, y_{max}), (x_{max}, y_{max}), and (x_{max}, 0). A characteristic feature of every mobility model is to ensure that a MN will not travel outside the network area. In group mobility models, nodes are assumed to be organized in groups and the mobility of a node is often reflective of the movement pattern of the entire group.

2.1 Random Waypoint Mobility Model

The Random Waypoint model [2] assumes each MN is initially placed on a uniform-randomly chosen coordinate within the network area. The node selects, uniformly and randomly, a target location within the network to move. The velocity to move to this location is also chosen uniformly and randomly from the range [v_{min}...v_{max}] where v_{min} and v_{max} represent the minimum and maximum possible node velocities. Once the MN moves to the chosen location, it waits at that location for a certain amount of time called the pause-time. The above process of choosing a random target location and random velocity to move is repeated until a predefined simulation time is reached.

2.2 Random Direction Model

The Random Direction model was introduced in [3] to overcome the density waves observed with the Random Waypoint model. Density waves are fluctuations in the average number of neighbors per MN over a period of time. In the Random Waypoint model, a MN tends to travel to the center of the graph before reaching its next stopping coordinate. This causes the MNs to cluster in the center and the average number of neighbors per MN to increase. MNs then disperse and the average number of neighbors per MN drops. The Random Direction model randomly places MNs in the network area. Each MN is assigned a uniform-random angle of movement (in the range [0...2π]) and a uniform-random velocity in the range [v_{min}...v_{max}]. A MN moves in a chosen direction and velocity until it reaches the network boundary. Once the MN reaches the network boundary, a new random angle of movement and velocity are assigned to the node and it continues to move accordingly. Random direction forces the mobile nodes to evenly occupy the network area over a period of time and reduce the density waves.

2.3 Gauss-Markov Model

The Gauss-Markov mobility model was originally used for network protocols proposed for wireless Personal Communications Systems [4]. The model works on a timeslot basis and each node uses its speed and direction in the previous timeslot to compute the speed and direction in the current timeslot. Each MN is assigned a uniform-random coordinate in the network area, a mean speed and a mean direction. The mean speed and mean direction represent the limit as time tends to ∞. The movement of a MN at a timeslot t is decided as follows (the formulae used are listed in Table 1): The speed s_t and direction θ_t are computed using formulae F1 and F2 respectively. The MN moves with the computed speed and direction to coordinate (x_t, y_t), determined using formulae F3 and F4. This process repeats until the simulation time is reached.

Table 1: Formulae for Gauss-Markov Mobility Model

$s_t = \alpha s_{t-1} + (1-\alpha)\bar{s} + \sqrt{1-\alpha^2}\, s_{x_{t-1}}$	(F1)
$d_t = \alpha d_{t-1} + (1-\alpha)\bar{d} + \sqrt{1-\alpha^2}\, d_{x_{t-1}}$	(F2)
$x_t = x_{t-1} + s_{t-1}\cos(d_{t-1})$	(F3)
$y_t = y_{t-1} + s_{t-1}\sin(d_{t-1})$	(F4)

In the above formulae, $s_{x_{t-1}}$ and $d_{x_{t-1}}$ are random variables over a Gaussian distribution with a mean of 0 and standard deviation of 1. The parameter α, where $0 \le \alpha \le 1$, is a tuning parameter used to vary the level of randomness. When α = 1, the MNs move in a linear motion, and when α = 0, the MNs move in a totally random fashion. If a MN is about to move outside the network area, its mean direction is adjusted and a new speed and direction are calculated using F1 and F2 respectively. New x and y values would be then calculated using F3 and F4 respectively.

2.4 City Section Model

The City Section mobility model [5] puts constraints on the movement of a node on a city street grid, constructed of horizontal and vertical streets. Each street on the grid is assigned a speed limit. A MN moves along the streets according to the speed limit set for that street. Initially, each MN is randomly placed on an intersection. A MN then moves to another randomly chosen intersection with at most one vertical and one horizontal motion. This movement is also the shortest path between the two street intersections. Each MN continues to move to randomly chosen street intersections until the simulation time is reached.

2.5 Manhattan Model

The Manhattan mobility model [6] is commonly used to model the movement of cars or people on a city street grid. Like the City Section model, each MN is initially placed on a random street intersection, but the Manhattan model utilizes a probabilistic approach for movement on the streets. The movement of a node is decided one street at a time. To start with, each node has equal chance (i.e., probability) of choosing any of the streets leading from its initial location. After a node begins to move in the chosen direction and reaches the next street intersection, the subsequent street in which the node will move is chosen probabilistically. If a node can continue to move in the same direction or can also change directions, then the node has 50% chance of continuing in the same direction, 25% chance of turning to the east/north and 25% chance of turning to the west/south, depending on the direction of the previous movement. If a node has only two options, then the node has an equal (50%) chance of exploring either of the two options. If a node has only one option to move (this occurs when the node reaches any of the four corners of the network), then the node has no other choice except to explore that option.

3. MULTI-PATH ROUTING ALGORITHMS

This section briefly reviews the algorithms [1] used to determine the sequence of link-disjoint (pseudo code in Figure 1) and node-disjoint multi-paths (pseudo code in Figure 2) in our simulations. Let G (V, E) be a unit disk graph representing a snapshot of the network topology at the instant during which we want to find a set of multi-paths between source s and destination d. Note that V and E represent the set of vertices and edges respectively.

Input: Graph G (V, E), source s and destination d
Output: Set of link-disjoint paths P_L
Auxiliary Variables: Graph G' (V, E')
Initialization: G' (V, E') ← G (V, E), P_L ← φ.

Begin

While ($\exists$ at least one s-d path in G')
 p ← Minimum hop s-d path in G'.
 P_L ← P_L U {p}
 $\forall_{edge, e \in p}$ G' (V, E') ← G' (V, E'-{e})
end While
return P_L

End

Figure 1: Algorithm to Determine the Set of Link-Disjoint Paths (Source: [1])

Let P_L and P_N denote the set of link-disjoint and node-disjoint s-d paths to be determined. To start with, we use the O(n^2) Dijkstra algorithm [7] to determine the minimum hop s-d path in a graph of n nodes. If there exist at least one s-d path in G, we include the minimum hop s-d path p in both the sets P_L and P_N. To add more paths to P_L, we remove all the links that were part of p from the graph G and obtain a modified graph G'(V, E'). We then determine the minimum hop *s-d* path in the modified graph $G'(V, E')$, add it to the set P_L and remove the links that were part of this path to get a new updated $G'(V, E')$. We repeat this procedure until there exists no more *s-d* paths in the network. The set P_L is now said to have the link-disjoint *s-d* paths in the original network graph G at the given time instant.

Input: Graph $G(V, E)$, source s and destination d
Output: Set of node-disjoint paths P_N
Auxiliary Variables: Graph $G''(V'', E'')$
Initialization: $G''(V'', E'') \leftarrow G(V, E)$, $P_N \leftarrow \varphi$.

Begin

1 **While** ($\exists$ at least one *s-d* path in G'')
2 $p \leftarrow$ Minimum hop *s-d* path in G''.
3 $P_N \leftarrow P_N \cup \{p\}$
4 $\forall_{\substack{vertex, v \in p \\ v \neq s,d \\ edge, e \in Adj-list(v)}} \quad G''(V'', E'') \leftarrow G''(V''-\{v\}, E''-\{e\})$
5 **end While**
6 **return** P_N

End

Figure 2: Algorithm to Determine the Set of Node-Disjoint Paths (Source: [1])

Similarly, to add more paths to P_N, we remove all the intermediate nodes (nodes other than the source s and destination d) that were part of the minimum hop *s-d* path p in the original graph G and obtain the modified graph $G''(V'', E'')$. We then determine the minimum hop *s-d* path in the modified graph $G''(V'', E'')$, add it to the set P_N and remove the intermediate nodes that were part of this *s-d* path to get a new updated $G''(V'', E'')$. We repeat this procedure until there exists no more *s-d* paths in the network. The set P_N is now said to have the set of node-disjoint *s-d* paths in the original network graph G.

4. SIMULATION ENVIRONMENT AND METRICS

The network dimension used is a 1000m x 1000m square network. The transmission range of each node is assumed to be 250m. The number of nodes used in the network is 50, 75 and 100 nodes representing networks of low, medium and high density with an average distribution of 10, 15 and 20 neighbors per node respectively. For every mobility model except the Gauss-Markov model, we use constant velocity values of 25 and 45 miles per hour (mph). For the Gauss-Markov model, the mean speed of the mobile nodes is assigned to be 25 and 45 mph.

For every mobility model, we conduct simulations of the node-disjoint and link-disjoint multi-path routing algorithms and the single-path routing algorithm for scenarios comprising of each combination of network density and node velocity. In multi-path routing, the minimum hop path within the link-disjoint / node-disjoint path set is used until it no longer exists. The path is then removed from the set and each minimum hop path within the set is used successively until it no longer exists. Over time, the size of the multi-path set will decrease to 0. When the set is empty, another run of the multi-path algorithm is performed. The single-path algorithm employed is the Dijkstra algorithm such that the discovered minimum-hop path is used as long as it exists and once the path breaks, the algorithm is again run to determine a minimum hop path. This procedure is repeated for the entire simulation time period. All the simulations were conducted in a discrete-event simulator developed by the authors in Java. All the five mobility models and the three routing algorithms are implemented in this simulator. The simulation time is 1000 seconds.

For the Random Waypoint, Random Direction and Gauss-Markov mobility models, the nodes are initially uniform-randomly distributed in the network. For the City Section and Manhattan mobility models, we assume the network is divided into grids: square blocks of length (side) 100m. The network is thus basically composed of a number of horizontal and vertical streets. Each street has two lanes: one for each direction (north and south direction for vertical streets, east and west direction for horizontal streets). A node is allowed to move only along the grid lines representing the horizontal and vertical streets. Initially, we assume the nodes are placed uniform-randomly along the grid lines.

The performance metrics studied through the simulations are the following:

(i) *Lifetime per Multi-path Set*: This is the time between successive runs of the multi-path routing algorithms, averaged over all the *s-d* sessions for the entire simulation time.

(ii) *Multi-path Set Size*: This is the number of disjoint paths discovered for every run of the node-disjoint or link-disjoint multi-path routing algorithms, averaged over all the *s-d* sessions for the entire simulation time.

(iii) *Average Hop Count per Multi-path Set*: This is the time-averaged hop count of all the *s-d* paths used throughout the simulation time, averaged across all the *s-d* sessions. For example, in a 20 second simulation, if *s-d* paths with hop counts 2, 3 and 1 are used for 5, 12 and 3 seconds respectively, then the time-averaged hop count of this *s-d* path is: (2*5 + 3*12 + 1*3) / 20 = 2.45.

The performance results for each metric displayed in Figures 3 through 5 are an average of the values obtained from simulations conducted with 10 sets of mobility profiles for each of the scenarios considered and 50 randomly picked *s-d* pairs for each scenario. For each mobility model, the network connectivity in each of the scenarios considered was observed to be in the 98%-100% range.

5. SIMULATION RESULTS

In this section, we present the simulation results obtained for each of the above three performance metrics with respect to the five mobility models considered for link-disjoint and node-disjoint multi-path routing and single-path routing.

5.1 Lifetime per Multi-path Set

Our results show that both the set of node-disjoint paths and the set of link-disjoints determined under the Gauss-Markov model sustain the largest lifetime compared to the other mobility models. The Random Waypoint mobility model yields the longest lifetime with respect to single-path routing. The clustering of nodes under both the Gauss-Markov and the Random Waypoint mobility models could be attributed for the better performance. Following is the ranking of the mobility models in the decreasing order of the lifetimes per multi-path set, for both link-disjoint and node-disjoint routing: (i) Gauss-Markov, (ii) Random Waypoint, (iii) City Section, (iv) Manhattan and (v) Random Direction models. For a given network density, as we increased the node velocity from 25 mph to 45 mph (by 80%), the lifetime per multi-path set and the single-path under each of the mobility models decreased by about 40%-50%.

For a given level of node mobility and network density, as expected, under each of the mobility models, the lifetime per link-disjoint path set is always higher than the lifetime per node-disjoint path set. Also, the lifetimes per link-disjoint path set and per node-disjoint path set are far more than that observed for the single-path scenarios. The difference in the lifetime per link-disjoint path sets and the node-disjoint path sets is the minimum in the case of the Random Waypoint model (4%-16%) and is the maximum in the case of the Gauss-Markov and Manhattan models (20%-35%). The difference in the lifetime per link-disjoint path set and per single path is the minimum in the case of the Random Direction model (58%-170%) and maximum in the case of the Gauss-Markov model (145%-300%).

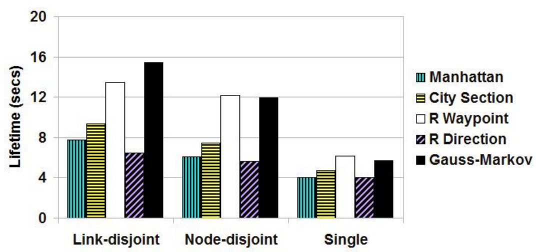

Figure 3.1: 50 Nodes at 25 mph

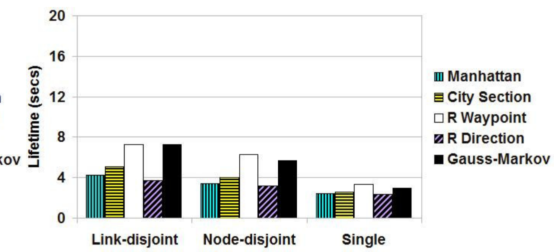

Figure 3.2: 50 Nodes at 45 mph

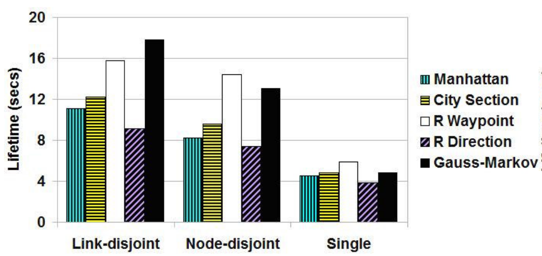

Figure 3.3: 75 Nodes at 25 mph

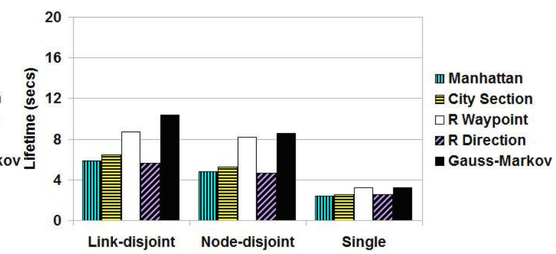

Figure 3.4: 75 Nodes at 45 mph

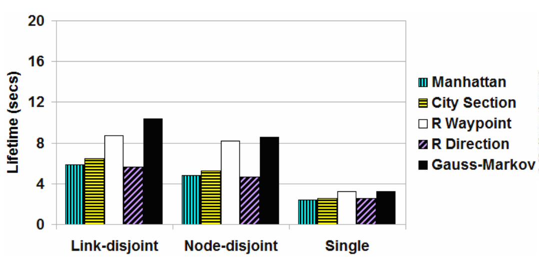

Figure 3.5: 100 Nodes at 25 mph

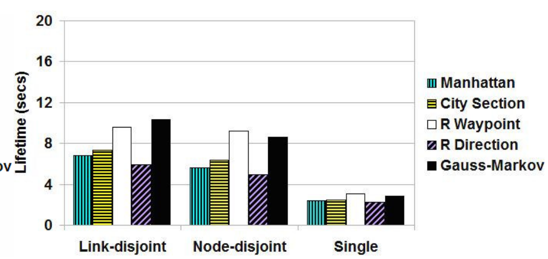

Figure 3.6: 100 Nodes at 45 mph

Figure 3: Lifetime per Multi-path Set vs. Single Path

For both link-disjoint and node-disjoint routing, for a given level of node mobility and network density, the City Section model, Manhattan model, Random Direction model and the Random Waypoint model yielded a lifetime per multi-path set that is about 60%-73%, 50%-63%, 42%-56% and 90%-100% of that incurred by the Gauss-Markov mobility model. The lifetime of the node-disjoint path sets under the Random Waypoint model is very close to that obtained under the Gauss-Markov model.

An interesting observation is that for a given level of node mobility, as we increase the network density from 50 nodes to 100 nodes, the Random Direction mobility model (that incurs the lowest absolute value for the lifetime per multi-path set) incurs the highest percentage increase in the lifetime per multi-path set, by 55%-65%. On the other hand, the Gauss-Markov model (that incurs the largest absolute value for the lifetime per multi-path set) incurs a percentage increase of only 30%-45%. Overall, we observe that as we double the network density, the lifetime per multi-path set under any of the mobility models for link-disjoint routing and node-disjoint routing, as well as single path routing, does not increase proportionately.

In the single-path scenario, if we increase the network density for a given level of node mobility, the lifetime per minimum hop path decreases for all the mobility models. This is contrary to what has been observed for multi-path routing. The lifetime per minimum-hop path decreases as large as by 20%. The Random Waypoint model incurs the largest decrease in the lifetime, where as the Random Direction model incurs the smallest decrease in the lifetime.

5.2 Multi-path Set Size

Figures 4.1 through 4.6 show the average number of paths per multi-path set for each mobility model. In the case of single path routing, only one path is discovered each time the minimum hop routing algorithm is run. In the case of multi-path routing, several node-disjoint and link-disjoint paths are discovered, each time these algorithms are run.

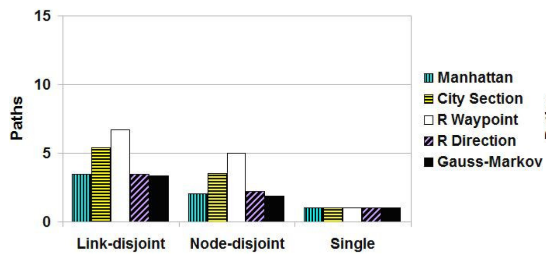

Figure 4.1: 50 Nodes at 25 mph

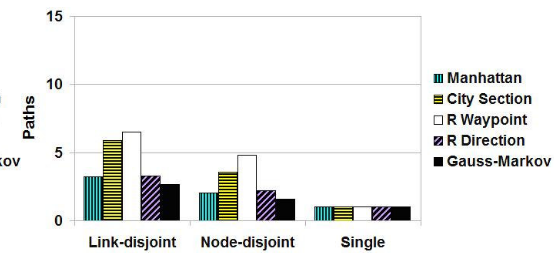

Figure 4.2: 50 Nodes at 45 mph

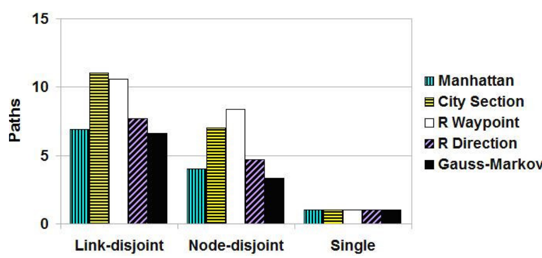

Figure 4.3: 75 Nodes at 25 mph

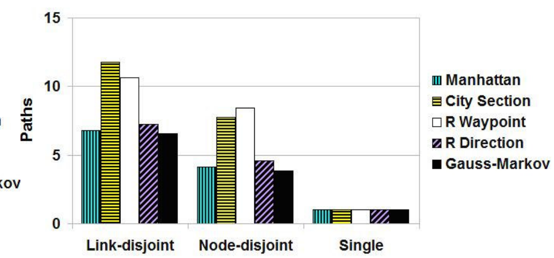

Figure 4.4: 75 Nodes at 45 mph

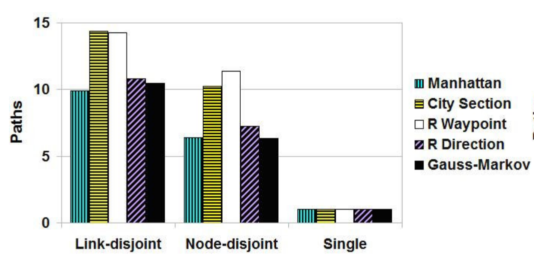

Figure 4.5: 100 Nodes at 25 mph

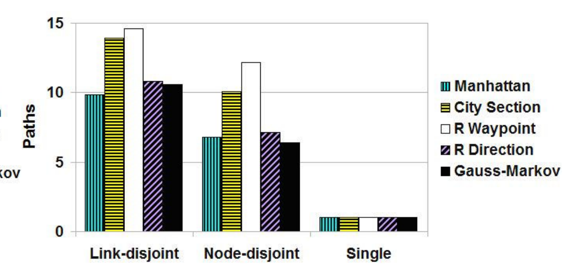

Figure 4.6: 100 Nodes at 45 mph

Figure 4: Multi-path Set Size

Our results suggest the following ranking of the mobility models in the decreasing order of the multi-path set size: (i) Random Waypoint, (ii) City Section, (iii) Random Direction, (iv) Manhattan and (v) Gauss-Markov models. It is interesting to observe that the Gauss-Markov model has the smallest number of paths per multi-path set, but still incurs the largest lifetime per multi-path set. Also, the Random Direction model has a relatively higher number of paths per multi-path set, but the lifetime per multi-path set (as observed in Section 5.1) is almost always the lowest. The above observations indicate that it may not be always true that larger the number of paths in a multi-path set, the larger would be the lifetime per multi-path set.

As expected, the number of constituent paths in a link-disjoint multi-path set is more than that of a node-disjoint path set. For a given level of node mobility and network density, the number of link-disjoint paths per multi-path set is 38%-65%, 65%-96%, 46%-71%, 49%-64% and 20%-35% more than the number of node-disjoint paths per multi-path set under the City Section, Gauss-Markov, Manhattan, Random Direction and Random Waypoint models respectively. The Random Waypoint model yielded on average 4%, 57%, 65%, and 74% more link-disjoint paths and 22%, 88%, 108% and 133% more node-disjoint paths than the City Section, Random Direction, Manhattan and Gauss-Markov models respectively.

An interesting observation (similar to the observation made for lifetime per multi-path set) is that for a given level of node mobility, as we increase the network density from 50 nodes to 100 nodes, the Gauss-Markov model (that incurs the lowest absolute value for the multi-path set size) incurs the highest percentage increase in the multi-path set size, by 215%-300%. On the other hand, the Random Waypoint model (that incurs the largest absolute value for the multi-path set size) incurs the lowest percentage increase of about 120%-150% only. Overall, as the network density is doubled, the multi-path set size for all the mobility models increases significantly. But the increase in the multi-path set size does not translate to a proportional increase in the lifetime per multi-path set.

5.3 Average Hop Count per Multi-path Set

Hop Count is a critical metric for energy consumption and end-to-end delay per data packet delivered. We observe the Random Waypoint model and the Gauss-Markov model to have a fewer average hop count per multi-path set. This further illustrates the clustering effect of the two models. The highest average hop count is observed with the Random Direction model. The Manhattan model had 8% fewer hops than the Random Direction model in low density networks and an equal hop count in high density networks. The City Section, Gauss-Markov and Random Waypoint models had 14%, 23% and 40% fewer hops than the Random Direction model in low density networks and 7%, 12%, and 30% fewer hops in high density networks respectively.

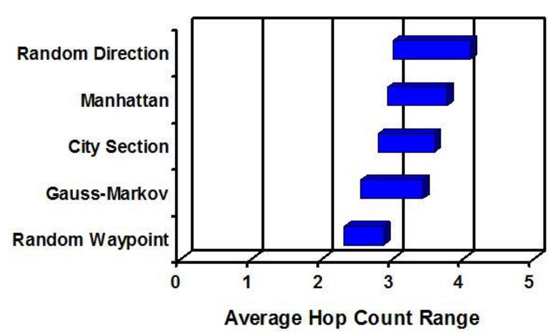

Figure 5: Average Hop Count per Multi-path Set

6. Conclusions And Future Work

The lifetime per multi-path set is 50%-300% better than the lifetime incurred with single path routing. We observe the Gauss-Markov mobility model to yield the largest lifetime per multi-path set, even though the model yields the lowest number of paths per multi-path set. The number of link-disjoint paths per multi-path set could be as large as twice the number of node-disjoint paths per multi-path set. On the other hand, the lifetime per link-disjoint multi-path set is at most 35% more than the lifetime per node-disjoint multi-path set. The above observations with the mobility models and the multi-path routing algorithms indicate that it need not be always true that larger the number of paths per multi-path set, the larger will be the lifetime per multi-path set. As future work, we would study the impact of group mobility models on multi-path routing as well as study the impact of the mobility models on multicast routing. Also, more realistic concepts such as traffic patterns would be added to the City Section and Manhattan mobility models.

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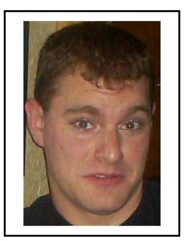

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