Route Dynamics for Shortest Path First Routing in Mobile Ad Hoc Networks

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***Abstract*—This paper investigates the route dynamics of Shortest-Path First (SPF) routing in mobile ad hoc networks (MANETs). In particular, we find, from a statistical analysis of route duration and route change interval, that route dynamics may require complex modelling. Our analysis considers various mobility models, node velocities and node densities of the MANET network. Our findings show that, in a MANET with moderate or high rate of mobility, the route duration could be approximated by an exponential distribution with approximate parameters, while the route duration of specific lengths could not. Our findings suggest that minimum hop-count routing in MANETs may be inappropriate and that further investigation is required in order to develop models that let us understand MANET route dynamics.**

I. Introduction

As the global landscape of telecommunications aims to provide ubiquitous connectivity, there is interest in integrating other technologies, for example the 3GPP project for Long Term Evolution (LTE). One technology that could be used in the access network is that used for mobile-ad hoc networks (MANETs). MANET routing can be used in many edge network scenarios, e.g. sensor networks, wireless LANs, and therefore presents itself as an important technology for 'last mile' integration. Hence, it is important to understand the characteristics of such networks in order that such integration can take place.

The characteristics of MANETs, such as link duration and route duration, will vary over time and be much more dynamic than for fixed networks. The transience of local and global network connectivity may significantly affect the performance of MANET routing protocols. So, assumptions that may be made about link duration and route duration in fixed networks may not hold for MANETs, and there may be causal effects observed in other metrics, such as loss and throughput.

For example, node movement results in the disruption of established routes, which directly leads to packet loss, which could cause lower throughput and service degradation. Topology changes in a MANET may cause the routing protocol to perform route recalculation and reselection, e.g. based on the Shortest Path First (SPF) algorithm as in Optimised Link State Routing Protocol (OLSR) [1]. Moreover, fast topology changes in such link-state protocols may lead to inconsistency of routing states between mobile nodes, generating routing loops, and leading to packet drops due to expiry of the Time-To-Live (TTL).

Therefore, in order to provide a more robust service in MANETs, it is essential to understand the transient behaviour of MANET routing protocols and their impact on routing performance under various scenarios and factors, especially for pro-active routing protocols such as OLSR [1].

In this paper we investigate the route dynamics of Shortest-Path First (SPF) routing protocols in MANETs by examining the performance of OLSR. An empirical approach is developed to obtain the network statistics of link and route durations, including probability density functions (PDFs) and cumulative density functions (CDFs). We aim to gain insight into MANET protocol performance under various mobility patterns, node velocity and node density.

There have been several studies on reactive route dynamic analysis [2], [3]. Johansson et al proposed the relative motion between mobile nodes to distinguish the different mobility models used for their scenario-based study [4]. Gerharz et al [5] presented distributions of link lifetime, under various simulation parameters. Prince et al [6] developed a mathematical model on the statistics of link dynamics, and concluded that the link change inter-arrival time density can be modelled by an exponential function. Sadagopan et al [2], [7] used statistical methods to examine the impact of mobility on path duration in *reactive* MANET routing protocols under various mobility models. They discovered that, at moderate and high velocities the exponential distribution is a good approximation of the path duration for a range of mobility models.

However, there has been no examination of route duration and link duration in *proactive* MANET routing protocols. Considering their difference in routing selection and maintenance, the route dynamics of *proactive* routing protocols may differ from those of *reactive* routing protocols. Proactive routing protocols consider optimal route selection, using algorithms such as Dijkstra's Algorithm, hence their behaviour is likely to be complex.

The rest of the paper is organised as follows. Section II presents the background of this study. The experimental methodology including performance metrics and simulation settings is presented in Section III. Observations and discussions of the results are shown in Section IV. The conclusions and future work are stated in Section V.

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II. Background

In this section, we present some background information on the operation of *proactive* routing protocols, highlighting the differences when compared with *reactive* routing protocols.

A. Operation of Proactive Routing

In proactive routing protocols, each node maintains a routing table that contains the next-hop information to all reachable destinations. The following operations are carried out in order to build and keep the routing tables up to date at all times.

- **Neighbour Sensing.** In this operation, each node detects its neighbour changes, including new neighbour arrivals as well as loss of a neighbour. The basic mechanisms used in this operation include:
  - Cross layer notification: if a packet fails to be acknowledged by a neighbour, the medium access control (MAC) layer notifies the routing agent about such failure and thus a *neighbour loss* is detected.
  - HELLO messages: each node broadcasts periodically a heartbeat message - a HELLO message. The node senses a new neighbour on first receiving its HELLO message. A lost neighbour is detected if no HELLOs have been received within a given time period.
- **Topology Advertisements.** In link-state routing protocols the nodes advertise periodic topology information to the whole network. Routes are re-computed after the nodes receive topology advertisement messages in order to find the shortest path to the destination, even if the current route is still functional.

B. Proactive Routing vs. Reactive Routing

Route maintenance mechanisms of proactive routing protocols [1], [8] are different from those of reactive routing protocols [9], [10] in several aspects. In a proactive routing protocol like OLSR, the route between any two nodes may vary over time even if each link in the route still exists. It may get stalled because it is no longer the shortest route. The route between two nodes may be re-computed, triggered by topology changes. In a reactive routing protocol like AODV, the route between any two nodes will not be changed until notification of a neighbour loss.

These differences might lead to variation in route change behaviour between these two types of routing protocols. Intuitively, the mean route duration of proactive routing protocols should be smaller than that of reactive routing protocols. More frequent route changes are expected to be observed in proactive MANETs. Therefore, it is necessary to investigate the route dynamics of proactive ad hoc networks under various mobility models.

III. Methodology

In this section, we explain the methodology used in this investigation, including performance metrics and the related measurement methods. We use a simulation-based approach.

TABLE I
SYMBOLS

n	Number of nodes in a mobile ad hoc network
l_{ij}	Length of the shortest path between node i and j
r_{ij}	Shortest path between node i and j
R	Transmission range of a node

A. Performance Metrics

To evaluate the performance of a routing protocol, quantitative metrics need to be defined. In general, metrics such as link duration and link change interval [7] are independent of the routing protocols. For example, link duration is associated with node property (i.e. radio range), node mobility (i.e. node velocity, mobility patterns) and network properties (i.e. node density). Route duration, on the other hand, is determined by the routing protocols, including route discovery and route selection algorithms. In the following paragraphs, we define two protocol-dependent metrics: *route duration (RD)* and *route change (arrival) interval (RCI)* [2]. The symbols used are as shown in Table I.

- **Route Duration (RD).** For a shortest route r_{ij} between node i and node j with k intermediate nodes and length l_{ij}, at time t_1, the route duration is the maximum period $[t_1, t_2]$ during which (a) each of the $k-1$ links between the nodes is connected and symmetric; (b) the route represents the shortest path between the two nodes. Moreover, at time $t_1 - \varepsilon$ and time $t_2 + \varepsilon$, $\varepsilon > 0$, either at least one of the $k-1$ link does not exist, or there exists a new route r'_{ij}, such that $l'_{ij} < l_{ij}$.
- **Route Change Interval (RCI).** Any change in the set of routes may be due to the breakage of an established active route or due to re-selecting a new route. For nodes i, j, at time t_1, the duration of the route r_{ij} is the maximum period $[t_1, t_2]$ during which there are no route breakage or route re-selection events; and for any $\varepsilon > 0$, there exist route change events at $t_1 - \varepsilon$ and $t_2 + \varepsilon$.

B. Approximation of Route Distribution

With a large set of samples collected, we use the relative frequency approach of probability theory to estimate the probability density functions (PDFs) of the RD and RCI across different mobility models. Once the PDFs are determined, we calculate the mean RD value and mean RCI value.

In order to approximate the distribution, we use standard curve fitting techniques to analyse the PDFs of the RD and RCI values across the different mobility models; the results of the curve fitting are listed in tables to facilitate further analysis.

We evaluate goodness-of-fit by how well a statistical model fits a set of observations. Measures of goodness-of-fit typically summarise the discrepancy between observed values and the values expected under the model in question. Besides the visual examination of the fitted curve displayed, we use *Sum of Squares due to Error (SSE)*, *R-square*, *adjusted R-square (aR-square)* and *Root Mean Squared Error (RMSE)* to assess the goodness-of-fit.

TABLE II
MAC/PHY LAYER CONFIGURATIONS

MAC Protocol	IEEE 802.11
Radio Propagation Type	TwoRayGround
Interface Queue Type	DropTailPriQueu
Antenna Model	OmniAntenna
Channel Capacity	2Mbits
Interface Queue Length	50

The *SSE* statistic is the least squares error of the fit, with a value closer to zero indicating a better fit.

The *R-square* statistic is the square of the correlation between the response values and the predicted response value, with a value closer to 1 indicating that a greater proportion of variance is accounted for by the model.

The *adjusted R-square* statistic is generally the best indicator of the fit quality when additional coefficients are added to the models.

The *RMSE* statistic measures the standard error of the fit, with a value closer to zero indicating a good fitting.

C. Simulation Set-up

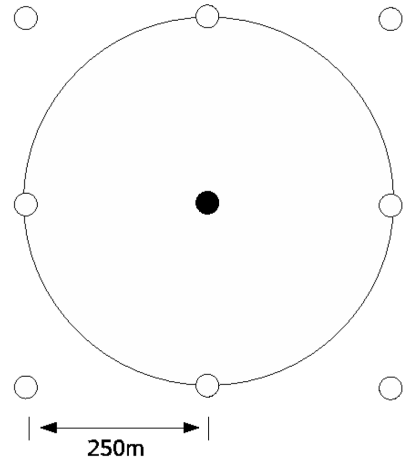
The investigation is conducted with the OLSR implementation that runs in version 2.9 of NS2 [11] and uses the ad-hoc networking extensions provided by CMU [12]. The configuration parameters are shown in Table II.

In particular, the radio radius is set varied across the set of values $50m$, $100m$, $150m$, $200m$, $250m$, $300m$, $400m$ in separate simulation runs.

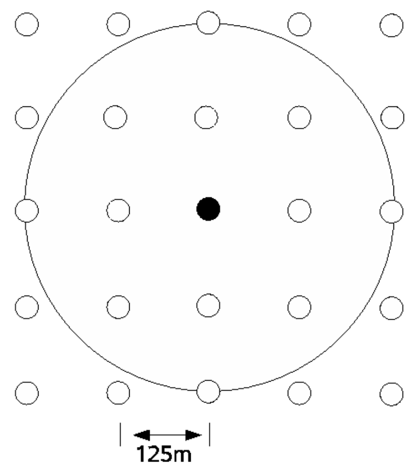
Nodes are placed in a fixed area of $1000m \times 1000m$. We use a network consisting of n nodes: $n = 20$ to simulate a low-density network, $n = 50$ to simulate a high-density network. To illustrate, if the nodes are evenly distributed, in a low-density network, each node has 4 nodes in its transmission range (Fig 1(a)), while in a high-density network, each node has 12 nodes in its transmission range (Fig 1(b)). We use the Random Trip Mobility Model [13], Reference Point Group Model (RPGM), Freeway Model and Manhattan Model. The maximum velocity is set to $5m/s$, $10m/s$, $20m/s$ and $30m/s$ separately for each mobility model, while the minimum velocity is set to non-zero, e.g. $1m/s$ in our cases. The RPGM model has 4 groups, with velocity deviation ratio set to be 10% of the maximum velocity. We use a range of velocity $v \leq 5m/s$ to simulate low-mobility networks (e.g. walking velocity or slow moving ground based vehicles), $v > 5m/s$ to simulate moderate and high mobility networks (e.g. ground-based vehicles or slow-moving airborne vehicles objects).

The mobility patterns of the Freeway Model, the RPGM and the Manhattan Model are generated by [14]. The mobility patterns of Random Trip Model are generated by [15].

For each sample point presented, 10 random mobility scenarios are generated. The simulation results are thereafter statistically presented with the mean of the metrics.



(a) Low-Density Network



(b) High-Density Network

Fig. 1. Low-Density Network vs. High-Density Network ($R = 250$)

IV. OBSERVATIONS AND DISCUSSIONS

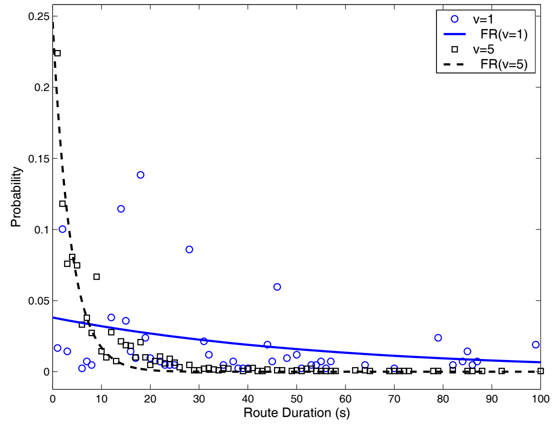
In this section, we present the observations on the route dynamics under various mobility models. Due to space restrictions, we focus on the observations of *route duration* distribution, with a radio range of $250m$ under the Random Trip model. The phenomena described below have been observed under all the other mobility models used in this work, including Freeway, Manhattan and RPGM models.

We have shown the values of *SSE*, *R-square*, *aR-square*, and *RMSE* to 3sf, so that we can show non-zero values for all our statistics. The calculated coefficients are at 95% confidence.

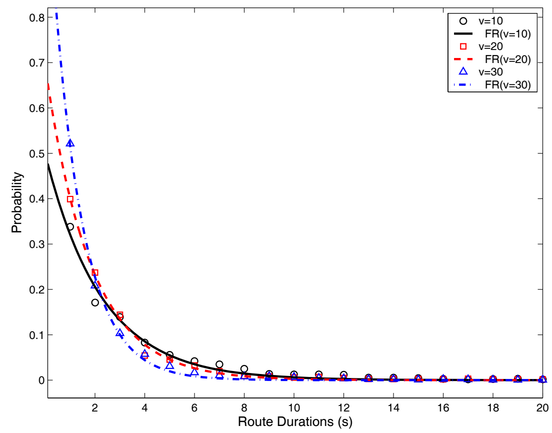
A. Route Duration

From the distribution of route duration (Fig 2, Fig 3, Fig 4, and Fig 5)[1] and the curve fitting results (Table III, Table IV, Table V and Table VI) we can see that, under the Random Trip model:

[1] In these figures, $FR(v = v_0)$ labels the curve of the fitting model for route duration distribution when the maximum node velocity is v_0.

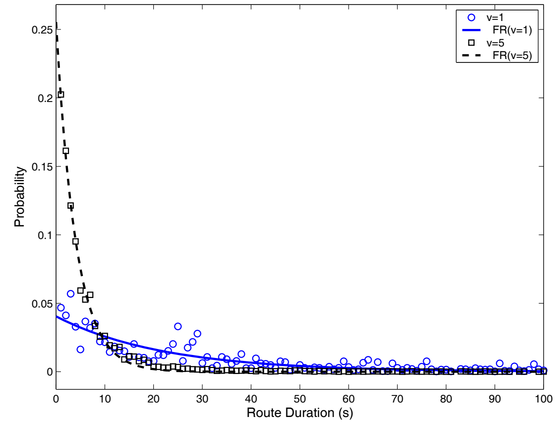


(a) Low Mobility

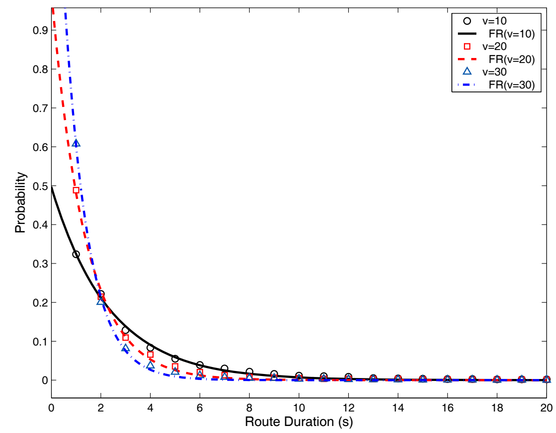


(b) High Mobility

Fig. 2. PDF of Route Duration for Random Trip Model ($n = 20$)



(a) Low Mobility



(b) High Mobility

Fig. 3. PDF of Route Duration for Random Trip Model ($n = 50$)

- When the velocity is relatively small (i.e. $v \leq 5m/s$), the RD distribution is non-exponential. For example, the $R-square$ is 0.051 when the maximum node velocity is set to be $1m/s$, indicating a very small proportion of variance is accounted for by the exponential model.
- With higher network mobility (i.e. $v > 5m/s$), the RD could be approximated by an exponential distribution with 95% confidence and satisfactory goodness of fit ($SSE < 0.003$, $R-square > 0.990$, $RMSE < 0.008$).

In particular, as shown in Fig 4(a) and Fig 5(a), the route duration of a low-mobility network are relatively evenly distributed. The mean route duration in such networks is larger than that of high-mobility networks. With the increase of node velocity, the route duration decreases since mobility brings more frequent route changes, which leads to an exponential distribution.

By comparing Table III with Table V, and comparing Table IV with Table VI we can see that, with the same node velocity, the route duration of high-density networks shows a better fit to an exponential property than that of low-density networks. For example, when the node velocity is $5m/s$, the $R-square$ of a low-density network (i.e. $n = 20$) is 0.906, while that of a high-density network (i.e. $n = 50$) is 0.992. This is because the link change rate increases with node density [2].

TABLE III
GOODNESS OF FIT (FIG 2(A))

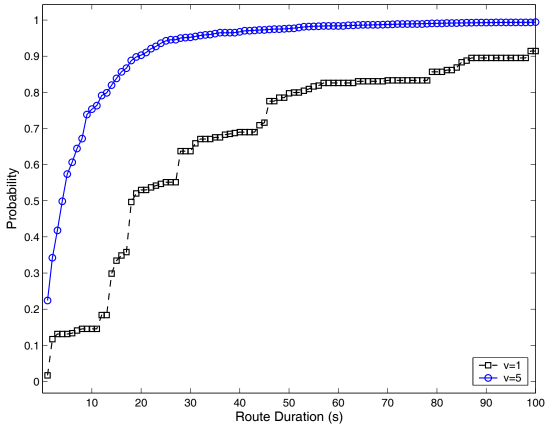
	SSE	R-square	aR-square	RMSE
$v = 1$	0.044	0.051	0.030	0.031
$v = 5$	0.007	0.906	0.905	0.011

Note that the observations so far are based on the route duration sets with variable route lengths (L), the number of links/hops in the selected route. The route duration of specific route lengths is shown in Fig 6, Table VII and Table VIII. From the route duration of certain route lengths (Fig 6) we can see that under the Random Trip Model:

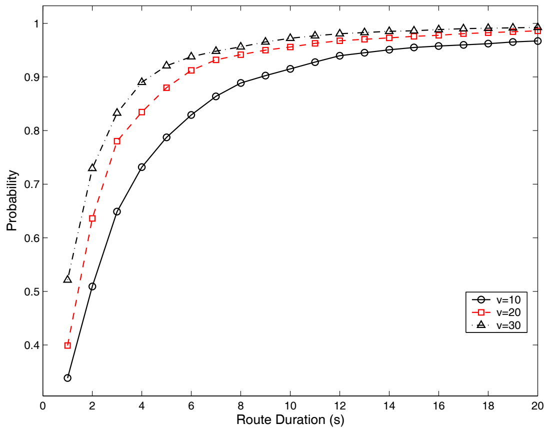
- At high mobility, longer routes show better fit to an

TABLE IV
GOODNESS OF FIT (FIG 2(B))

	SSE	R-square	aR-square	RMSE
$v = 10$	0.002	0.986	0.986	0.006
$v = 20$	0.001	0.996	0.996	0.004
$v = 30$	0.001	0.997	0.996	0.005

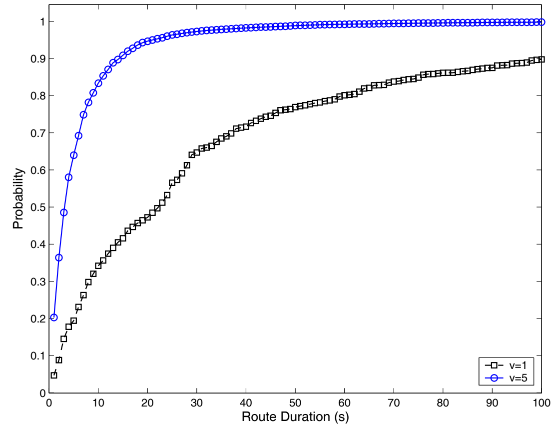


(a) Low Mobility

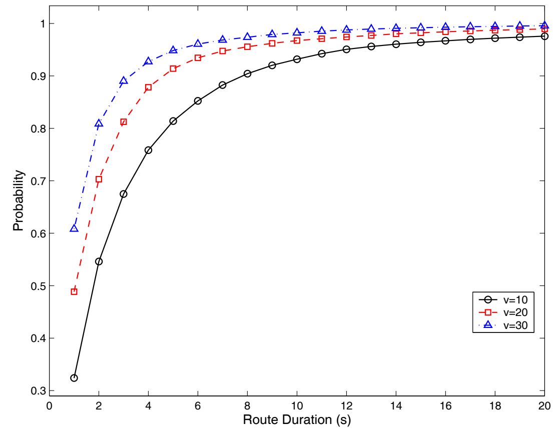


(b) High Mobility

Fig. 4. CDF of Route Duration for Random Trip Model ($n = 20$)



(a) Low Mobility



(b) High Mobility

Fig. 5. CDF of Route Duration for Random Trip Model ($n = 50$)

TABLE V
GOODNESS OF FIT (FIG 3(A))

	SSE	R-square	aR-square	RMSE
$v = 1$	0.013	0.353	0.346	0.012
$v = 5$	0.001	0.992	0.992	0.003

exponential distribution than shorter routes. As shown in Table VIII, the RD of short routes (i.e. $L < 4$) is not exponentially distributed, while the RD distribution of longer routes (i.e. $L \geq 4$) can be approximated with an exponential distribution. This is because longer routes involve more links and therefore have the route as a whole has a higher probability in suffering a broken link or a shorter (alternative) route being found at the next route recalculation.

TABLE VI
GOODNESS OF FIT (FIG 3(B))

	SSE	R-square	aR-square	RMSE
$v = 10$	0.001	0.997	0.997	0.002
$v = 20$	0.001	0.997	0.997	0.003
$v = 30$	0.001	0.998	0.998	0.003

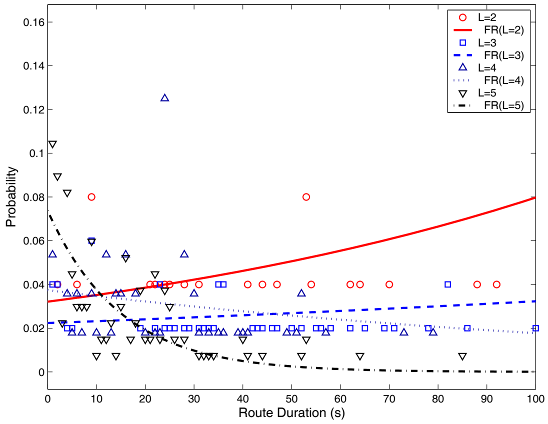
TABLE VII
GOODNESS OF FIT (FIG 6(A))

	SSE	R-square	aR-square	RMSE
$L = 2$	0.013	0.182	0.137	0.027
$L = 3$	0.009	0.022	-0.005	0.016
$L = 4$	0.014	0.049	0.019	0.021
$L = 5$	0.011	0.505	0.491	0.017

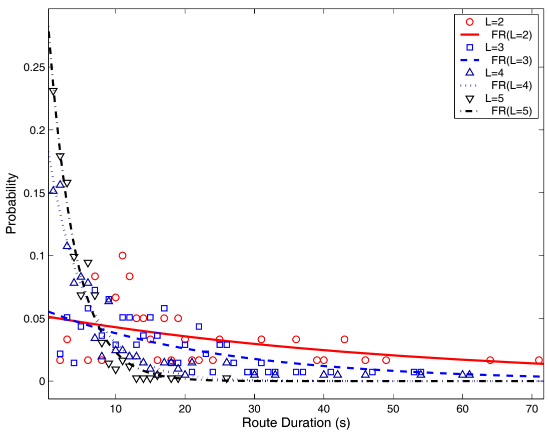
- At low mobility, route duration with specific route lengths is non-exponential. For example, as shown in Table VII, the $R - square$ value is smaller than 0.6 when the node velocity is $5m/s$, which indicates poor fit to the exponential model.

TABLE VIII
GOODNESS OF FIT (FIG 6(B))

	SSE	R-square	aR-square	RMSE
$L = 2$	0.013	0.173	0.142	0.022
$L = 3$	0.008	0.466	0.450	0.015
$L = 4$	0.003	0.937	0.935	0.011
$L = 5$	0.003	0.972	0.970	0.012

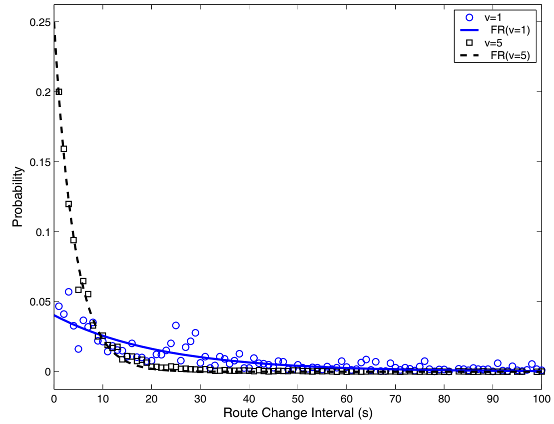


(a) $v = 5m/s$

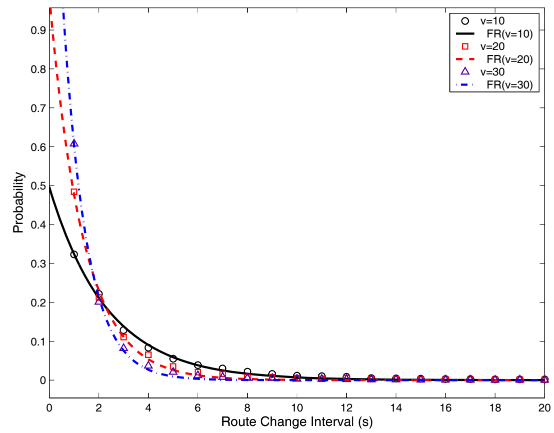


(b) $v = 20m/s$

Fig. 6. PDF of RD with Specific Route Lengths ($n = 20$)



(a) Low Mobility



(b) High Mobility

Fig. 7. PDF of RCI for Random Trip Model ($n = 50$)

TABLE IX
GOODNESS OF FIT (FIG 7(A))

	SSE	R-square	aR-square	RMSE
$v = 1$	0.013	0.353	0.346	0.012
$v = 5$	0.001	0.993	0.993	0.003

B. Route Change Interval

Similar phenomena have been observed in the distribution of route change interval (RCI). For example, as shown in Fig 7(b) and Table X, in a network with moderate or high mobility (i.e. $v \geq 5m/s$), the RCI can be approximated by an exponential distribution with 95% confidence and satisfactory goodness of fit ($SSE < 0.001$, $R - square > 0.990$, $RMSE < 0.004$). Meanwhile, the RCI in a low-mobility network can not (Fig 7(a) and Table IX).

C. Comparison between SPF Routing and Reactive Routing

The route duration of SPF routing has similar distribution to that of reactive routing. However, the (mean) route duration of SPF routing is much smaller than that of reactive routing. The route duration of SPF routing shows better fit to an exponential model than that of reactive routing.

For example, as shown in [2], the average path duration of reactive routing for $v < 20m/s$ and $R = 250m$ is larger than $10s$. However, the average route duration for SPF routing is less than $5s$. This matches our expectations (Section II-B).

The other difference between these protocols is the route duration of SPF routing with specific route lengths show no fit to an exponential model, while that of reactive routing does [2].

V. CONCLUSIONS AND FUTURE WORKS

This paper investigates the impact of mobility on proactive MANET routing protocols using the Shortest Path First (SPF) algorithm. A statistical approach is used to obtain the statistics of route duration and route change interval, including probability density functions (PDFs) and cumulative density functions

TABLE X
GOODNESS OF FIT (FIG 7(B))

	SSE	R-square	aR-square	RMSE
$v = 10$	0.001	0.997	0.997	0.002
$v = 20$	0.001	0.997	0.997	0.004
$v = 30$	0.001	0.998	0.998	0.003

(CDFs). This study shows that at moderate or high mobility, the distribution of route duration (and route change intervals) of proactive MANET routing protocols may be approximated by an exponential distribution.

The numerical results presented in this work show evidence of the weakness of minimum hop-count routing [16], especially in high-mobility networks. Minimum-hop-count routing, although having smaller end-to-end delay, may lead to poor throughput and lower capacity than the best paths that exist in the network. This suggests that more attention should be paid to stability-based route selection algorithms in the presence of node mobility. A hybrid route selection algorithm is currently being designed and will appear in our future work.

The route selection algorithm is expected to have significant impact on route duration. Therefore, the results presented in this work are only applicable to proactive routing protocols using an SPF algorithm. Further studies on the route statistics based on other route selection algorithms, such as power-aware algorithms and link quality aware algorithms and also the analysis on impact of node velocity on the route statistics will appear in our future work.

This study makes multiple assumptions on transmission range and traffic patterns. Therefore, the models are derived from simplified scenarios. In future studies, it would be interesting to investigate richer analytical models to analyse the quantitative relationship between other performance metrics (such as protocol overhead) and extra factors (such as node density).

The original data used in this study are all available on request from the authors.

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