On Route Lifetime in Multihop Mobile Ad Hoc Networks

Yu-Chee Tseng, *Senior Member*, *IEEE*, Yueh-Feng Li, and Yu-Chia Chang

Abstract—One wireless network architecture that has received a lot of attention recently is the *mobile ad hoc network (MANET)*. It is attractive because the network can be quickly deployed without the infrastructure of base stations. One main feature of MANET is that mobile hosts may communicate with each other through a sequence of wireless links (i.e., in a multihop manner). While many routing protocols have been proposed for MANET by considering criteria such as length, quality, bandwidth, and signal strength [1], [8], [4], [5], [7], [15], the issue of route lifetime has not been addressed formally. This paper presents a formal model to predict the lifetime of a routing path based on the *random walk* model. Route lifetime is derived based on a probabilistic model. Through such investigation, we hope to provide further insight into issues such as route selection, route maintenance, and network scalability related to MANETs.

Index Terms—Ad hoc networks, mobile computing, mobile networks, routing, wireless communication.

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1 INTRODUCTION

The advancement in wireless communications and lightweight, small-size, portable computing devices have made pervasive and mobile computing possible. One wireless network architecture that has attracted a lot of attention recently is the *mobile ad hoc network (MANET)*. A MANET is one consisting of a set of mobile hosts which may communicate with one another and roam around at their will. Mobile hosts may communicate with each other indirectly through a sequence of wireless links without passing base stations (i.e., in a *multihop* manner). This requires each mobile host serve as a router. A scenario of MANET is illustrated in Fig 1.

Applications of MANETs occur in situations like battlefields, festival grounds, outdoor activities, and emergency rescue actions, where networks need to be deployed immediately, but base stations or fixed network infrastructures are not available. For example, in an earthquake disaster, all base stations may be down since there is not electricity. In this case, a MANET driven by battery power can be quickly deployed to set up a network environment. Such technology has been recently applied to wireless sensor networks and personal-area networks too.

Extensive efforts have been devoted to the routing issue on MANET. Routing protocols can be classified as *proactive* and *reactive*. A proactive protocol constantly updates the routing table of each host so as to maintain a (close to) global view on the network topology. One representative proactive protocol is the DSDV (destination-sequenced distance-vector) protocol [15]. On the contrary, a reactive protocol searches for a path in an on-demand manner. This may be less costly than a proactive protocol when host mobility is high. Representative reactive protocols include DSR (dynamic source routing) [8], ZRP (zone routing protocol) [5], CBR [7], and AODV (Ad Hoc On Demand Distance Vector). A review of unicast routing protocols for MANET is in [16].

When choosing a routing path among several candidates, there are usually many factors to be considered, such as route length, route quality, signal strength, path bandwidth, and route lifetime. In this paper, we focus on developing a formal model to evaluate the lifetime of a routing path in a MANET. The result may be used in many applications. For example, it can be used in the route discovery process to choose a most reliable path. It can be used to determine when a route is likely to expire so that a backup route can be searched in advance. As a longer route is likely to suffer higher breakage probability, our result may also be used to determine the cost-effectiveness of establishing a long route. Finally, the result may be used to determine the proper size of a MANET considering the route reliability versus route length trade off.

The route reliability issue has been addressed in several works. In the ABR routing protocol [18], the association stability of links is accounted when choosing routing paths. The Signal Strength Adaptive (SSA) protocol [4] further considers the signal strengths in choosing routes. In [1], a parameter called "affinity" is defined to characterize the signal strength and stability of a link. While choosing routes, the "affinity" of a routing path is set to the minimum link affinity in the path. The affinity concept is further integrated with the transportation layer (i.e., TCP) by accounting for the throughput of a routing path in [14]. A direction-prediction method is proposed in [17], where the *lifetime* of a link is defined based on the current locations, roaming velocities, and roaming directions of the two neighboring hosts. Then, the lifetime of a routing path is defined to be the minimum lifetime of each link in the path. The similar concept is applied to multicasting in [9].

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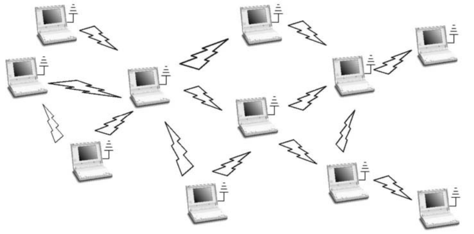


Fig. 1. An example of mobile ad hoc network (MANET).

In this paper, we present a formal model to predict the lifetime of a route in a MANET. We assume that each mobile host roams around following the random walk model. Given a sequence of mobile hosts which form a routing path, the joint probability distribution of route lifetime is derived based on the random walk model. This differs from most existing works which directly calculate the lifetime of a wireless link based on the current locations and roaming directions of two neighboring hosts by assuming that their roaming directions do not change. Also, while most works simply take the minimal lifetime of each link in a path as the lifetime of the path, we formally derive the probability distribution. Based on our analysis, extensive numerical and simulation results are presented.

We comment that the purpose of this paper is not to present a new routing protocol for ad hoc networks. Instead, our goal is to provide a formal model for evaluating the lifetime of a given routing path. This can assist routing protocols in choosing from a multitude of paths. Those routing protocols that are derived based on *geographic forwarding* (e.g., [10], [11]) are not applicable to this case since no route needs to be established prior to sending packets. We are aware that random walk is still too simple to characterize human's real mobility pattern, but is indeed one that is mathematically feasible to conduct analysis. We expect, through this work, to motivate more work in studying the impact of (more complicated) mobility patterns on route lifetime. The work in [12] assumes a *random way-point* model. Each host's movement consists of a sequence of random length intervals called *mobility epoch*, during which the host moves in a constant direction at a constant speed for an exponentially distributed time interval. The speed and direction of each host vary randomly from epoch to epoch. Approximations of *link availability* and *path availability* are derived, where link availability is defined to be the probability that a link is connected at time $t + \Delta t$ given that it is connected at time t, where Δt is a time interval. However, the measure of link availability does not exclude the possibility that the link becomes disconnected at any instant during the time $[t, t + \Delta t]$. In comparison, in this work, we adopt a cellular model and we do consider such "cutoff" possibility in our work. Under the same random way-point model, [13] further develops an efficient *proximity model* to measure the future stability of a given link.

The rest of this paper is organized as follows: The system model is presented in Section 2. The probability distribution of a route's lifetime is derived in Section 3. Section 4 demonstrates some numerical and experimental results. Finally, Section 5 concludes this paper.

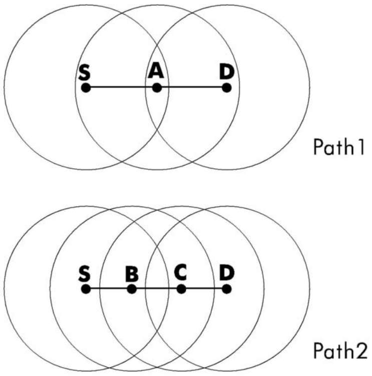


Fig. 2. Reliability of routing paths in a MANET.

2 SYSTEM MODEL

To motivate our work, let's observe the example in Fig. 2. Suppose that we need to establish a route from source S to destination D. In the network, two possible routes are available: $S \rightarrow A \rightarrow D$ and $S \rightarrow B \rightarrow C \rightarrow D$, where the circles indicate radio coverage. The former route is shorter in hop count, but is less reliable because host A can easily roam out of S's and D's radio coverage. The latter is longer, but might be more reliable since each intermediate host has a larger roaming area before the route will become broken.

The above example has indicated a dilemma in route selection. Most routing protocols tend to pick shorter routes for efficiency in using wireless bandwidth. However, such routes may suffer from a higher chance of route breakage. So, route reliability and route length are typically contradicting factors. This has motivated us to develop a formal model to predict the lifetime of routing paths in MANETs.

To develop a formal model, one has to adopt a roaming model for mobile hosts. In this paper, we use the *discrete-time, random walk* model, which has been widely used in personal communication services (PCS) networks [2], [3], [6]. Specifically, the area covered by the MANET is partitioned into a number of *hexagonal cells* each of radius r, as shown in Fig. 3 (note, however, that, unlike PCS networks, there is no notion of base stations here). Each cell is assigned a coordinate (x, y). There are two axes, one pointing to the northeast and the other to the north. Sitting in the center is cell $(0, 0)$. The *i*th cell along the first axis is sequentially numbered $(i, 0)$, while the *j*th cell along the second axis is numbered $(0, j)$. The coordinates of other cells can be obtained by mapping onto these two axes, as normally done in Euclidean coordinates.

Following the formulation in most works, we further partition cells into layers. Cell $(0, 0)$ is said to be on layer 0. The six cells surrounding cell $(0, 0)$ are said to be on layer 1. Recursively, the outer cells surrounding cells at layer i are said to be on layer $i + 1$. The number of cells inside the nth layer (including the nth layer) is $3n^2 + 3n + 1$. In this paper, the transmission range of a mobile host will be modeled by the number of layers that it can reach, assuming without loss of generality that it is currently resident in cell $(0, 0)$.

Although hosts can roam around in the real domain, we will work in a discrete domain by using cells as the basic units to model the locations of mobile hosts. Thus, the smaller the cells are, the finer the locations are. Mobile hosts

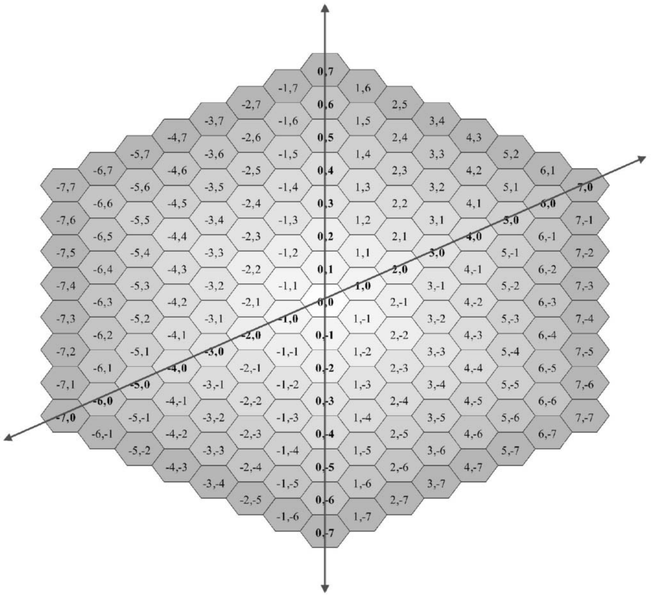


Fig. 3. The cellular system to model the locations of mobile hosts.

roam around in a cell-to-cell basis. We adopt a discrete-time model by dividing time into fixed-length units. Given any cell which represents the current location of a mobile host, the host will roam into the six neighboring cells in the next time unit with equal probabilities (1/6). This is what we mean by discrete-time, random-walk model.

3 ROUTE LIFETIME PREDICTION

This section develops a model to predict the lifetime of a routing path. Given two neighboring mobile hosts located in cells (x, y) and (x', y'), respectively, we denote the wireless link from the former to the latter by a vector $\langle x' - x, y' - y \rangle$. Thus, a routing path can be regarded as a sequence of vectors, each representing one wireless link. For example, a routing path connecting hosts in cells $(0, 1)$, $(3, 1)$, and $(7, -3)$ can be written as $[\langle 3, 0 \rangle, \langle 4, -4 \rangle]$ (here, we use brackets to denote a sequence).

The vector representing a wireless link is called its *state*. Next, we use the random walk model to formulate how a wireless link changes states. Consider any wireless link $\langle x, y \rangle$ connecting two hosts. After one time unit, each of the two hosts may roam into one of its six neighbors. Thus, there are 36 combinations for the next state, each with the same probability of 1/36. Let the resulting vector be $\langle x', y' \rangle$. As some of 36 combinations will result in the same vector, there are only 19 possible $\langle x', y' \rangle$. These vectors, together with the associated probabilities, are shown in Table 1. For example, Fig. 4 shows three possible ways a link $\langle x, y \rangle$ changes states. If the two hosts move along the arrows marked by M_1, the new state is $\langle x + 1, y \rangle$. If they move along M_2, the resulting state is the same. But, if they move along M_3, the new state is $\langle x - 2, y \rangle$.

As mentioned earlier, a routing path will be modeled by a sequence of vectors. After each time unit, each of its links will change state according to the probability distribution in Table 1. Accordingly, the state of the routing path will change, too. If any link exceeds the maximum transmission distance, the path is regarded as broken. Our goal is to model the probability distribution of the route lifetime.

The first step is to do a state reduction to alleviate the computational costs. The number of states for a wireless link in an n-layers cellular network can be as large as $3n^2 + 3n + 1$. This number will increase rapidly as n enlarges. To reduce the computational cost, we adopt the model in [19] to merge equivalent states. Specifically, we can partition an n-layer cellular network evenly into 12 equal-size sectors (refer to Fig. 5). Cells at neighboring sectors with a *reflective* relation (with respect to the 12 axes) are equivalent and can be merged into the same state. Thus, the 12 sectors can be merged into one sector. The numbers in Fig. 5a denote cell types after the merging, where cells of the same number are of the same types. Fig. 5b shows the sector containing all cell types after merging a 7-layer network. The number of states is reduced from 169 to 20. Formal derivation can be found in [19]. The basic observation is that all cells at the same distance from the central cell along the 30-, 90-, 150-, 210-, 270-, and 330-degree axes will have the same probability distribution. This divides the cellular network into six equivalent sectors. Further moving from boundaries of each sector toward its central part, we see, based on symmetry property, that the sector can be folded by half, thus further reducing the number of states by half. Depending of the value of n, the new number of states becomes:

$$C(n) = \begin{cases} 1 & n = 0 \\ \frac{(n+1)(n+3)}{4} & n > 0 \text{ and n is odd} \\ \frac{n(n+4)}{4} + 1 & n > 0 \text{ and n is even.} \end{cases}$$

Based on the state reduction, next we model the state transition of a wireless link. Let n be the number of layers equal to a host's radio coverage. Observe that a state vector of length n may become $n + 2$ in the next time unit (refer to Table 1). So, we need to consider an $(n + 2)$-layer network, which has $C(n + 2)$ types of cells according to the above reduction. For each state, we can develop its state transition probability according to Table 1. For example, Fig. 6 shows

TABLE 1
The Probability Distribution for a Wireless Link to Switch from State $\langle x, y \rangle$ to State $\langle x', y' \rangle$ after One Time Unit

<x',y'>	<x,y>	<x-1,y>	<x-1,y-1>	<x,y-2>	<x+1,y-2>	<x+1,y-1>	<x+1,y>	<x,y-1>	<x+2,y-2>	<x+2,y-1>
Probability	6/36	2/36	2/36	1/36	2/36	2/36	2/36	2/36	1/36	2/36

<x',y'>	<x+1,y+1>	<x,y+1>	<x+2,y>	<x,y+2>	<x-1,y+2>	<x-1,y+1>	<x-2,y+2>	<x-2,y+1>	<x-2,y>
Probability	2/36	2/36	1/36	1/36	2/36	2/36	1/36	2/36	1/36

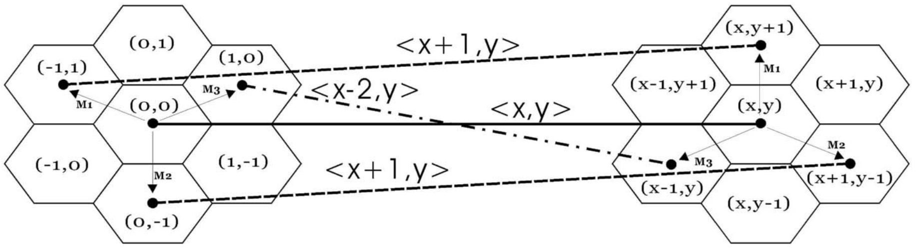
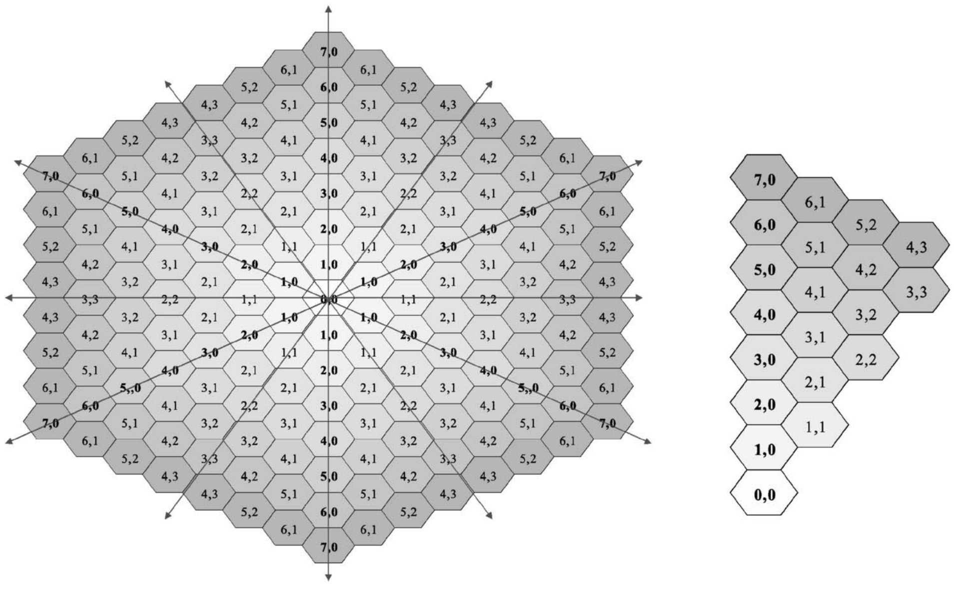


Fig. 4. Example of link state changes.



(a) (b)

Fig. 5. Merging equivalent states of wireless links: (a) partitioning the cells into 12 sectors and (b) equivalent states after merging.

the state transition of a wireless link when $n = 5$. Note that states $\langle 6,0\rangle$, $\langle 5,1\rangle$, $\langle 4,2\rangle$, $\langle 3,3\rangle$, $\langle 7,0\rangle$, $\langle 6,1\rangle$, $\langle 5,2\rangle$, and $\langle 4,3\rangle$ are "absorbing" states since, once entering these states, the link is broken (hence, there is no exit).

The state transition diagram of a wireless link can be translated to a state transition matrix M such that each element $M_{i,j}$ represents the probability to transit from the ith state to the jth state. So, M is a $C(n+2) \times C(n+2)$ matrix. For example, the matrix M corresponding to Fig. 6 is briefly shown in Fig. 7.

Matrix M represents the state transition probabilities after one time unit. It is a simple result that the kth power of M, denoted as M^k, represents the state transition probabilities after k time units. That is, $M^k_{i,j}$ is the probability that a link at state i transits to state j after k time units.

Next, we will develop several probabilistic functions. Suppose that a wireless link is in state i at time unit 0. Let's denote by $P_1(i,t)$ the probability that the link has become broken at time unit t. By matrix M, we can easily derive that

$$P_1(i,t) = \sum_{j \in \text{ layer } n+1, n+2} M^t_{i,j}.$$

Furthermore, we need to know the probability that a wireless link is in state i at time unit 0, remains alive at time unit $t-1$, and becomes broken at time unit t. Let's denote by $P_2(i,t)$ this probability. We can derive that

$$P_2(i,t) = \begin{cases} P_1(i,t) & \text{if } t = 1 \\ P_1(i,t) - P_1(i,t-1) & \text{if } t > 1. \end{cases}$$

The above derivation is for one link. Next, we consider a routing path R, which consists of a sequence of k wireless links $[i_1, i_2, \ldots, i_k]$ at time 0. To simplify the derivation, we assume that the state transitions of adjacent wireless links are independent. The probability that R remains alive at time unit t can be written as

$$\begin{aligned} P_3(R,t) &= (1 - P_1(i_1,t)) \times (1 - P_1(i_2,t)) \times \cdots \times \\ &\quad (1 - P_1(i_k,t)) \\ &= \prod_{j=1}^{k} (1 - P_1(i_j,t)). \end{aligned}$$

It follows that the probability that R has become broken at time t is

$$P_4(R,t) = 1 - P_3(R,t).$$

Let $P_5(R,t)$ be the probability that R remains alive at time unit $t-1$, but becomes broken at time unit t. We have

$$P_5(R,t) = \begin{cases} P_4(R,t) & \text{if } t = 1 \\ P_4(R,t) - P_4(R,t-1) & \text{if } t > 1 \\ \quad = P_3(R,t-1) - P_3(R,t). & \end{cases}$$

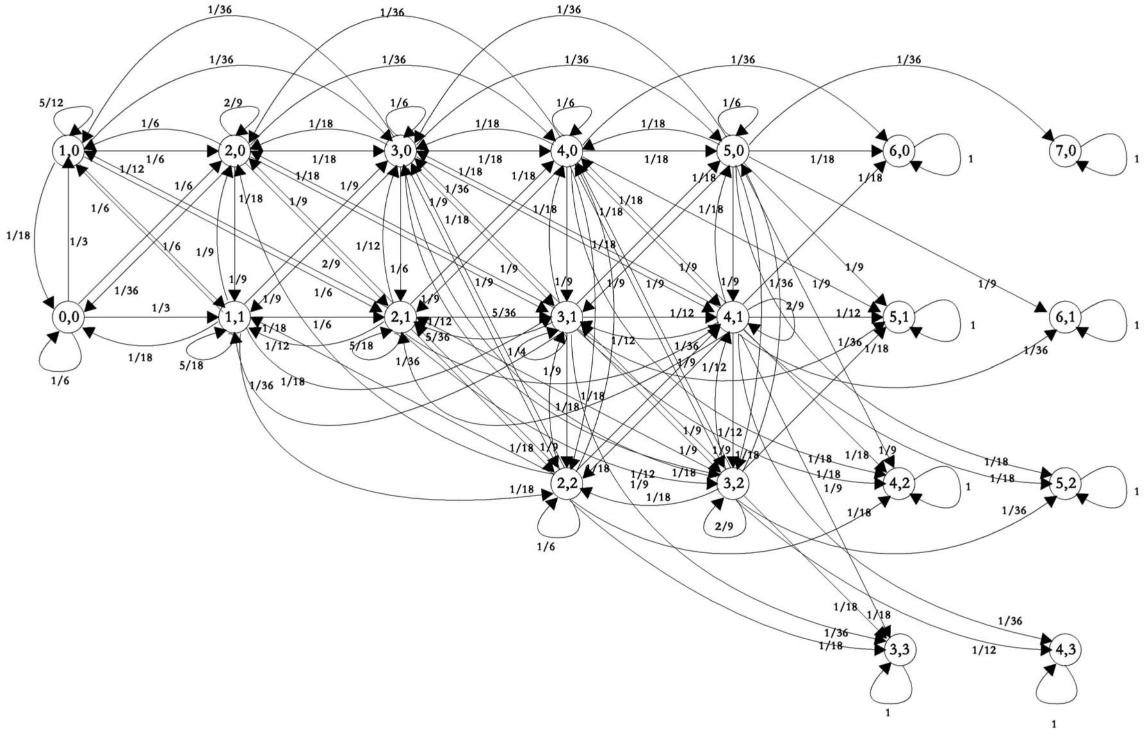


Fig. 6. State transition diagram of a wireless link when $n = 5$.

Finally, we conclude that the expected lifetime of route R, denoted as $E(R)$, is

$$E(R) = \sum_{t=1}^{\infty} P_5(R,t) \times t \times \text{ (length of a time unit)}. \quad (1)$$

4 NUMERICAL AND SIMULATION RESULTS

This section presents some numerical and simulation results. Most current wireless LAN cards' transmission distances range between one to a few hundred meters. So, we set the distance between the centers of two adjacent cells to be 10 meters (i.e., the radius of each cell is $r = 10/\sqrt{3}$). The number of layers (i.e., n) a radio can cover is 15 or 25. Each time unit is 10 seconds. So, this is close to pedestrians' roaming speed. At the end of the section, we also present some simulation results by applying our lifetime prediction scheme to DSR to observe how our prediction can help improve routing efficiency (such as network throughput, packet drop ratio, and routing control overhead).

$$\begin{array}{cc|ccccccc|}
 & & \langle 0,0\rangle & \langle 1,0\rangle & \langle 2,0\rangle & \langle 1,1\rangle & \cdots & \langle 5,2\rangle & \langle 4,3\rangle \\
 & \langle 0,0\rangle & \frac{6}{36} & \frac{12}{36} & \frac{6}{36} & \frac{12}{36} & \cdots & \frac{0}{36} & \frac{0}{36} \\
 & \langle 1,0\rangle & \frac{2}{36} & \frac{15}{36} & \frac{6}{36} & \frac{6}{36} & \cdots & \frac{0}{36} & \frac{0}{36} \\
 & \langle 2,0\rangle & \frac{1}{36} & \frac{6}{36} & \frac{8}{36} & \frac{4}{36} & \cdots & \frac{0}{36} & \frac{0}{36} \\
M = & \langle 1,1\rangle & \frac{2}{36} & \frac{6}{36} & \frac{4}{36} & \frac{10}{36} & \cdots & \frac{0}{36} & \frac{0}{36} \\
 & \vdots & \vdots & \vdots & \vdots & \vdots & \ddots & \vdots & \vdots \\
 & \langle 5,2\rangle & \frac{0}{36} & \frac{0}{36} & \frac{0}{36} & \frac{0}{36} & \cdots & \frac{36}{36} & \frac{0}{36} \\
 & \langle 4,3\rangle & \frac{0}{36} & \frac{0}{36} & \frac{0}{36} & \frac{0}{36} & \cdots & \frac{0}{36} & \frac{36}{36}
\end{array}$$

Fig. 7. The state transition matrix M when $n = 5$.

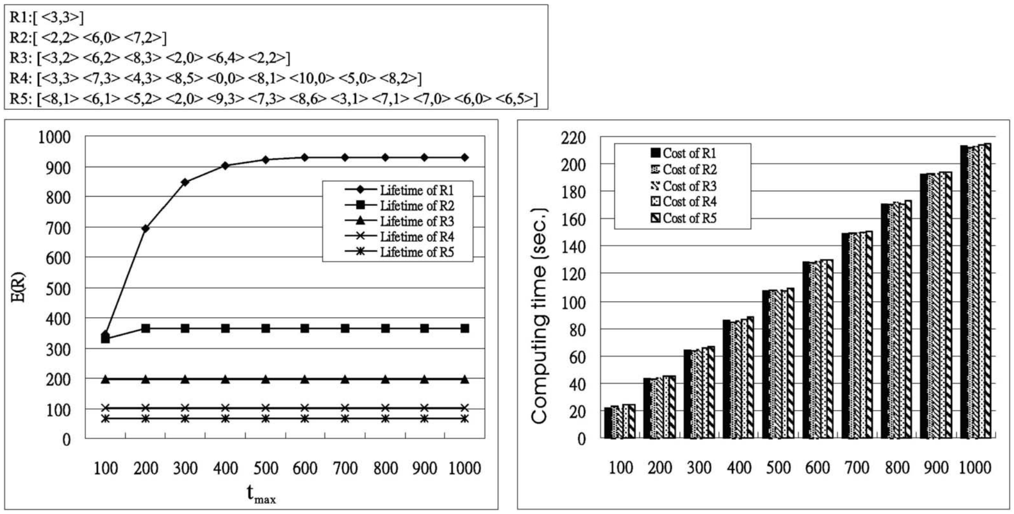
4.1 Determining the Level of Accuracy

Recall the route lifetime in (1). The summation has to be taken from $t = 1$ to the infinity. This is computationally infeasible due to the infinite upper bound. An upper bound has to be set for t to calculate $E(R)$. In this simulation, we randomly generate five routing paths with lengths 1, 3, 6, 9, and 12 and calculate their expected lifetimes by setting t's upper bound from 100 to 1,000 (called t_{max} below). That is, we approximate (1) by the following formula:

$$\sum_{t=1}^{t_{max}} P_5(R,t) \times t \times \text{ (length of a time unit)}.$$

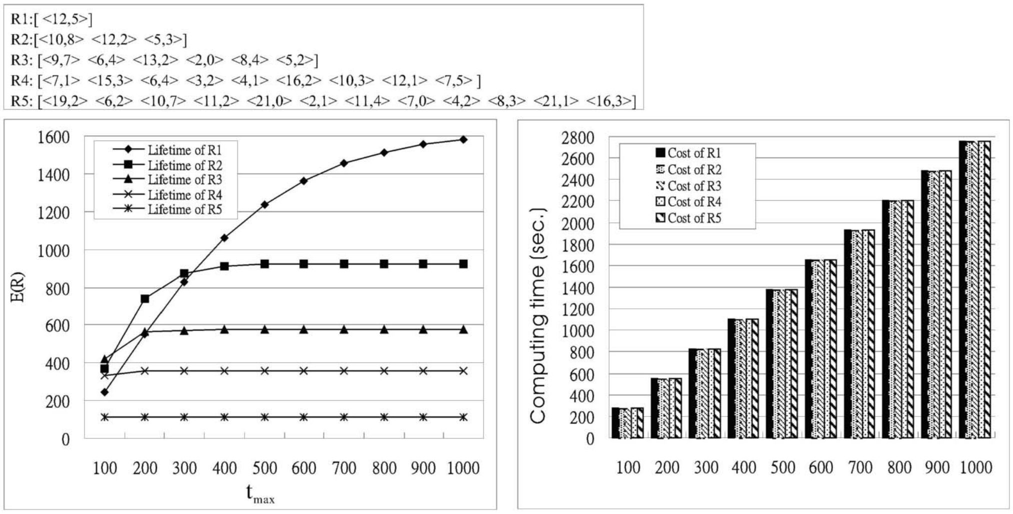
Through such experiments, we hope to determine a reasonable value for t_{max}.

The result is in Figs. 8a and 9a for $n = 15$ and 25, respectively. As can be seen, the expected route lifetime converges when t_{max} enlarges. Longer routes' lifetimes will stabilize at smaller t_{max} than shorter routes'. When $n = 15$, most route lifetimes stabilize at $t_{max} = 500$, while when $n = 25$, most route lifetimes stabilize at $t_{max} = 1{,}000$. So, we will set $t_{max} = 500$ and 1,000 when $n = 15$ and 25, respectively, for the rest of the simulations.



(a) (b)

Fig. 8. The expected route lifetime versus t_{max} when $n = 15$.



(a) (b)

Fig. 9. The expected route lifetime versus t_{max} when $n = 25$.

Figs. 8b and 9b show the computational costs in the above simulations. The costs all increase linearly with respect to t_{max}. Depending on the value of t_{max}, around a few minutes are required for the computation.[1] Our analysis shows that the main cost is on calculating the powers of matrix M. The size of M is $C(n+2) \times C(n+2)$ (for example, when $n = 15$, $C(n+2) = 4,913$). By a typical row-by-column matrix multiplication, each multiplication has time complexity $O(C(n+2)^3)$. Since each M^t has to be calculated, $t = 1 \ldots t_{max}$, the overall time complexity is $O(t_{max} \times C(n+2)^3)$.

4.2 Verifying Numerical Results by Simulations

To verify the correctness of our analytic results, we have also conducted some randomized simulations. Random routing paths of lengths 3, 6, 9, and 12 were generated on a cellular plane. Each host on the routes roamed around randomly following the same discrete-time, random-walk model. After each time unit, we then checked whether the corresponding route still remained alive or not. This was repeated until the route was broken, and then we recorded the lifetime of the route. For each route, 20,000 such simulation runs were executed and we took the average of these route lifetimes.

Figs. 10 and 11 compare the probability distribution of route breakage time (i.e., $P_5(R,t)$) obtained from such random simulation against our numerical analysis for several different routing paths when $n = 15$ and 25, respectively. The route being simulated is listed on the top of each illustration. As we can see, the analytic results fit pretty well with the simulation results. From these figures, we can also see how route lifetime degrades as routes become longer.

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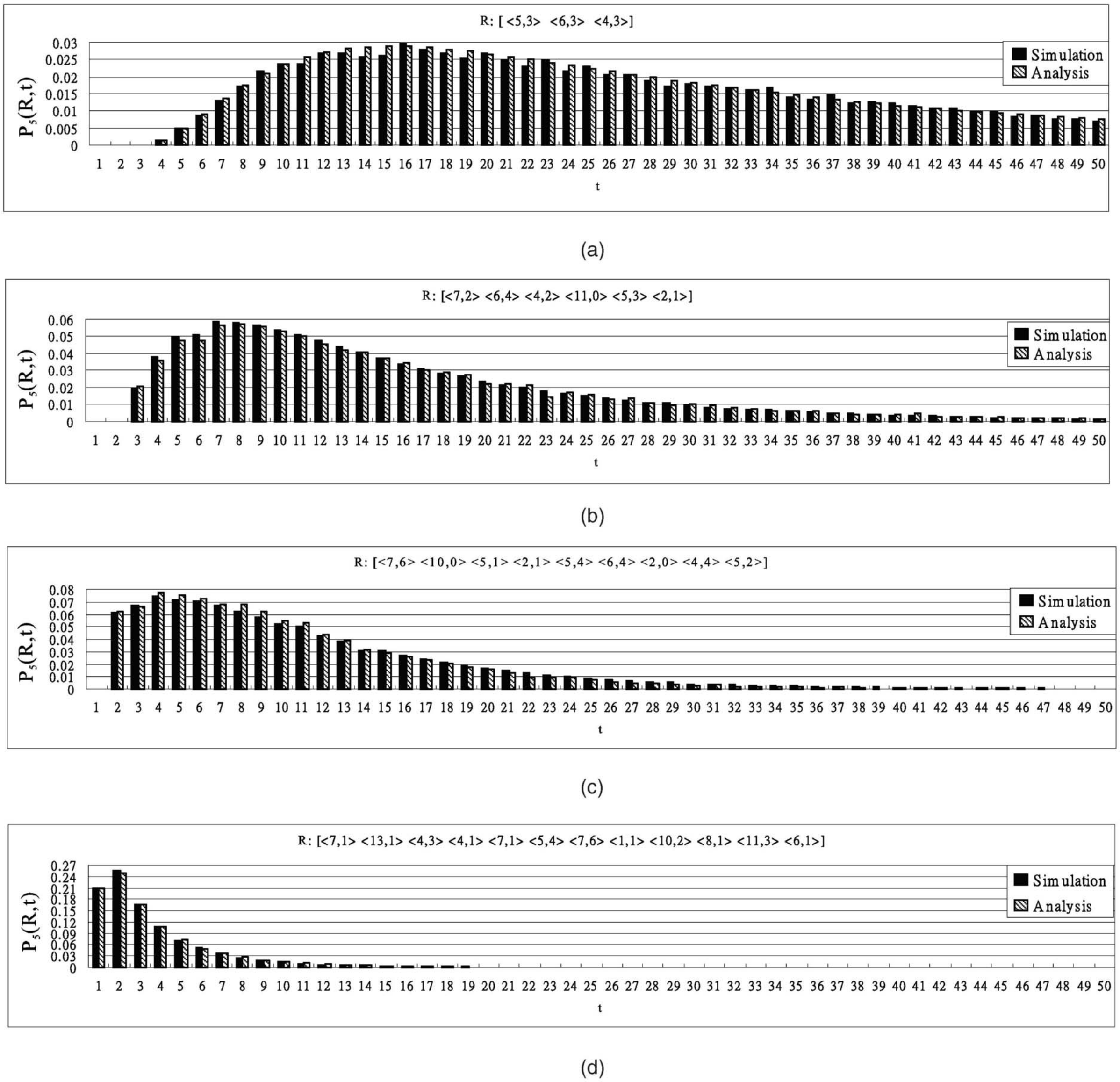
[1] The simulations were run in an IBM-compatible PC with AMD XP1600+with 256 MB DRAM memory. The Operating System was Windows 2000 pro.



(a)

(b)

(c)

(d)

Fig. 10. Comparison of route breakage probability distribution, $P_5(R,t)$, obtained from random simulation and analysis when $n = 15$ with route length equal to: (a) 3 links, (b) 6 links, (c) 9 links, and (d) 12 links.

4.3 Application 1: Determining the Proper Size of a MANET

In the literature, a lot of efforts have been devoted to improve the scalability of routing protocols for MANETs. While this is definitely important, it remains a question whether it is cost-effective to have a very large MANET. Intuitively, long routing paths with large hop counts may suffer higher route breakage probability. So, more route-searching efforts may be incurred if one intends to maintain longer routing paths. Our result provides a formal model, under the random walk assumption, to determine the relationship between route lifetime and route length.

In this experiment, we generate multiple routes by varying their lengths and states. Specifically, we consider routes of length i with state $[\langle j,0\rangle,\langle j,0\rangle,\ldots,\langle j,0\rangle]$, where $i = 1..20$ and $j = 3$, 6, 9, and 12 (for $n = 15$) or $j = 5$, 10, 15, and 20 (for $n = 25$). Then, we evaluate the expected route lifetime. The results are shown in Figs. 12 and 13. We see that route lifetimes all degrade significantly from one to five hops. So, practical sizes of MANETs would range within around five hops.

4.4 Application 2: Choosing Proper Routing Paths

Given multiple paths between a pair of source and destination hosts, different criteria may be used to choose a proper route. Hop counts are probably the most widely used criteria to choose routes. The proposed result can be used to evaluate routes based on their lifetime.

In this experiment, given a fixed pair of source and destination, we uniformly place a number of hosts between them which are spaced by the same distance. The route forms a straight line. Fig. 14 shows one experiment with the source at cell (0, 0) and destination at cell (50, 0) with $n = 15$. When the route length is h, the ith host will be placed at cell $(\lfloor\frac{50\times i}{h}\rfloor, 0)$, $i = 1..h-1$. We then evaluate the

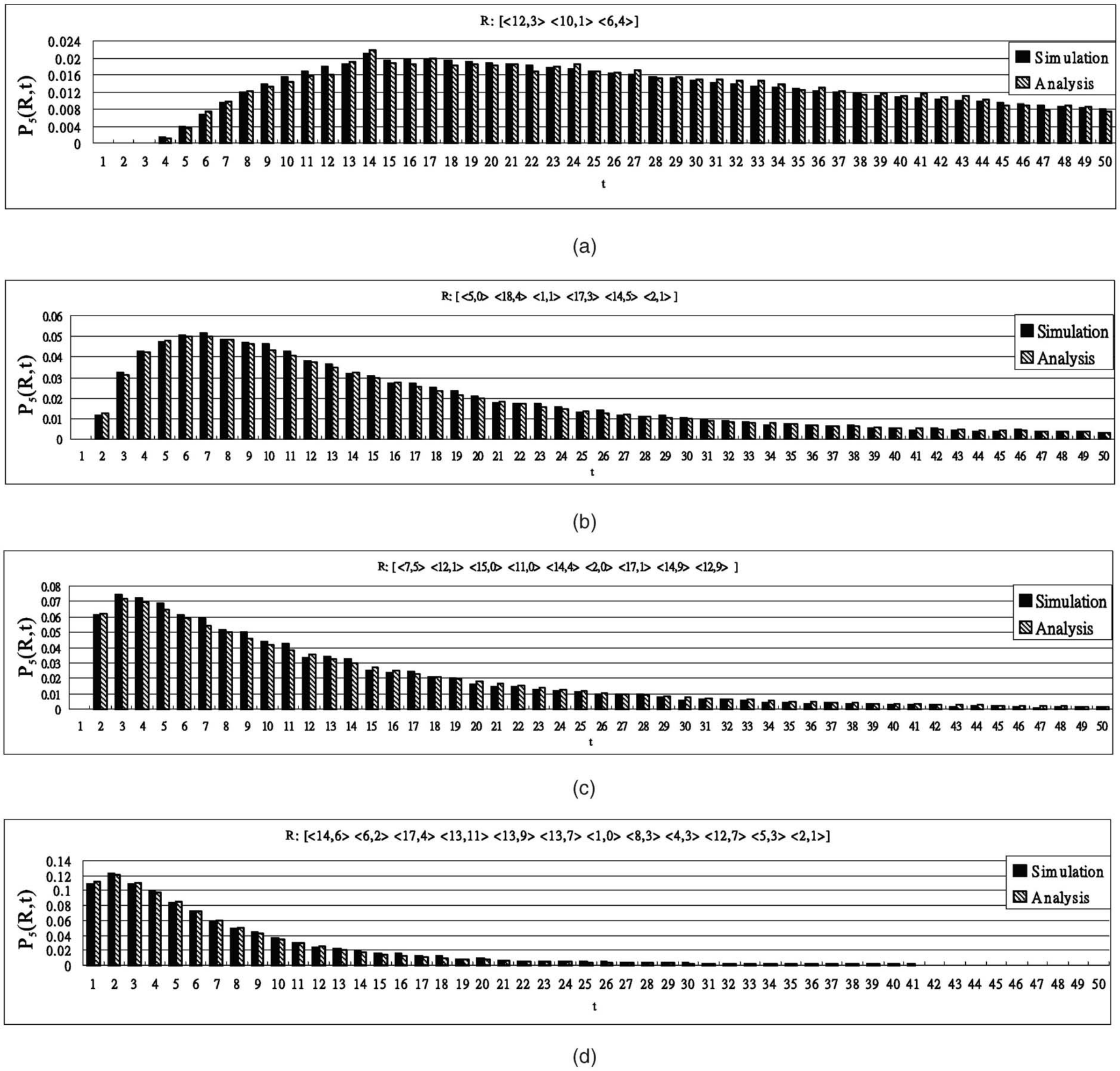


Fig. 11. Comparison of route breakage probability distribution, $P_5(R,t)$, obtained from random simulation and analysis when $n = 25$ with route length equal to: (a) 3 links, (b) 6 links, (c) 9 links, and (d) 12 links.

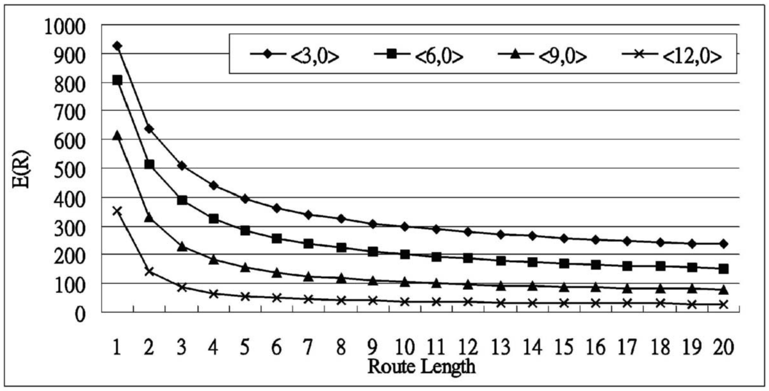


Fig. 12. The expected route lifetime versus route length when $n = 15$. Each route consists of links of the same state.

expected route lifetime for different values of h. As can be seen, the expected lifetime increases rapidly when h ranges between 4 to 10. At this stage, more hops are very helpful for route lifetime because hosts are closer to each other. After $h \geq 12$, there is almost no gain in terms of route lifetime because routes have too many links.

Fig. 15 shows a similar experiment with the source at cell (0, 0) and destination at cell (100, 0) with $n = 25$. The trend

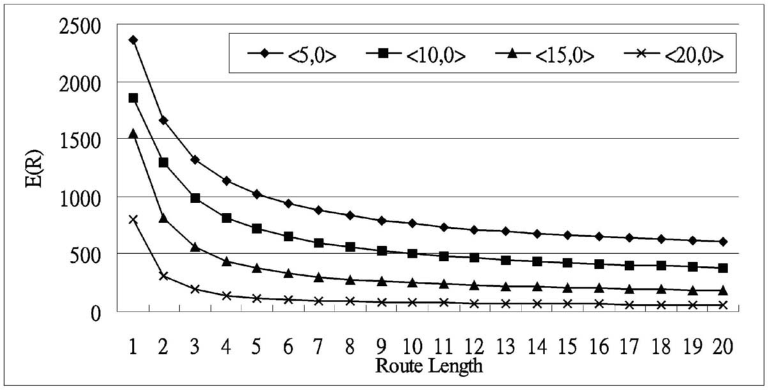


Fig. 13. The expected route lifetime versus route length when $n = 25$. Each route consists of links of the same state.

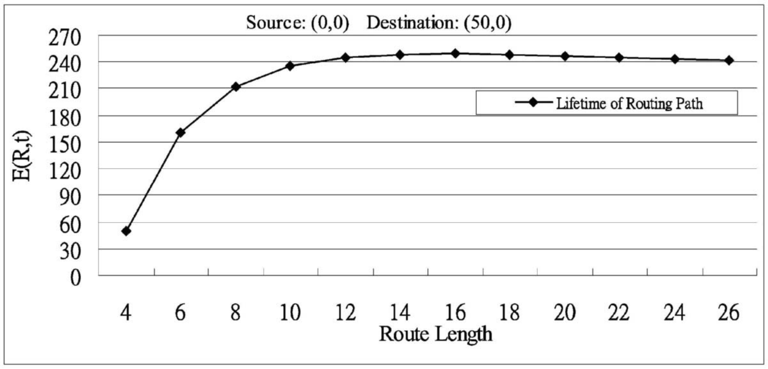


Fig. 14. The expected route lifetime versus route length with fixed source and destination hosts when $n = 15$. The relay hosts are spaced regularly and form a straight line.

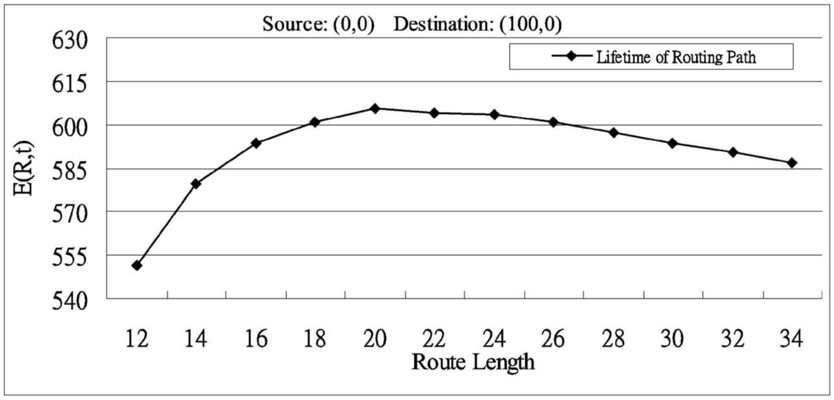


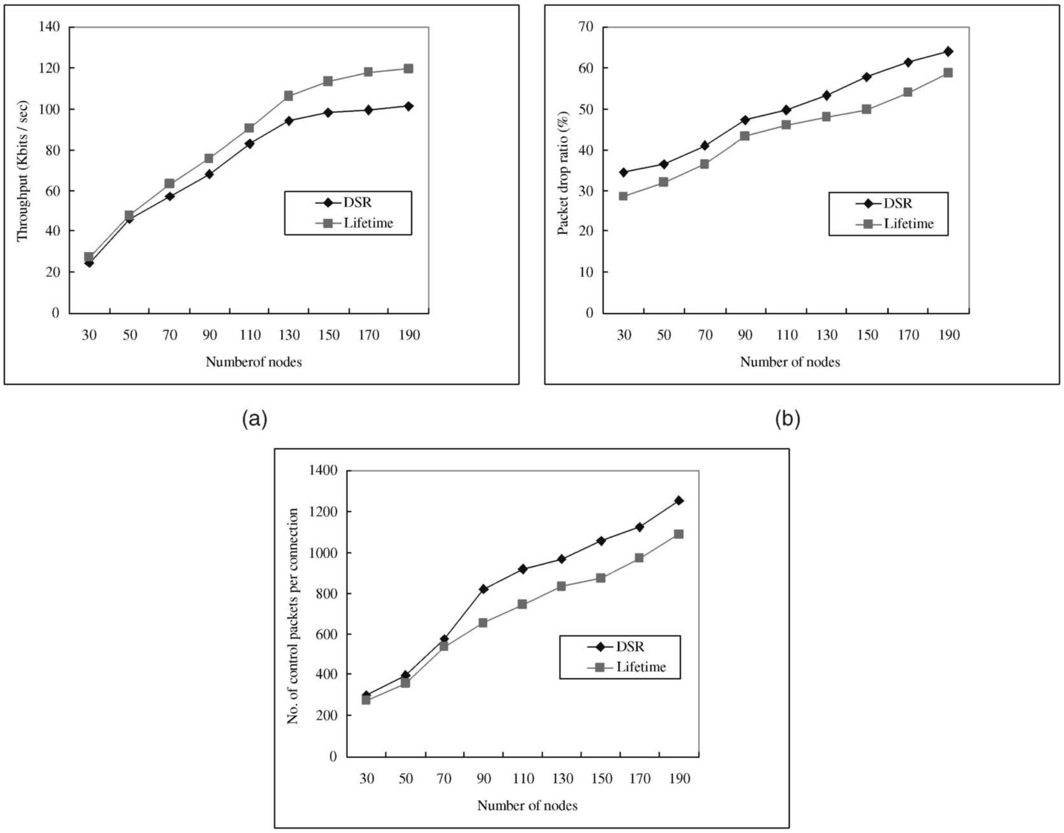
Fig. 15. The expected route lifetime versus route length with fixed source and destination hosts when $n = 25$. The relay hosts are spaced regularly and form a straight line.

is similar: When h ranges from 12 to 18, the expected route lifetime increases sharply, after which the route lifetime even degrades.

4.5 Application 3: Improving the Routing Efficiency of DSR

We also integrate our lifetime prediction algorithm into the DSR routing protocol [8] to observe how our result can help improve routing efficiency. The simulation platform is Glomosim 2.03 [20]. The original DSR adopts shortest-path routing. Our scheme will choose the path with the longest expected lifetime. We compare throughput, packet drop ratio, and routing overhead.

The simulation environment is as follows: The network area is 1,000m x 1,000m. Each radio has a transmission rate of 2 M bits/sec and a transmission distance of 250m. The cell diameter is 10m. So, the central points of two neighboring cells are distanced by $5\sqrt{3}$m, and each radio hop is around $\frac{250}{5\sqrt{3}}$ cells. Each simulation lasts 1,000 sec. The numbers of hosts simulated are: 30, 50, ..., 190. Each host is the source of one connection with a randomly selected destination. So, the number of connections being generated is equal to the number of hosts in the network. Each connection starts at a random time and sustains for an interval of 100 sec. For each connection, packets are generated with a constant rate of 2 packets/sec. Each packet is of size 1,024 bytes. Intuitively, we do not change the offered traffic load of each connection, but we tune the number of connections to vary the load.



(a) (b)

(c)

Fig. 16. Performance comparison: (a) network throughput, (b) packet drop ratio, and (c) routing overhead (DSR adopts shortest-path routing, while "Lifetime" chooses routes with the longest expected lifetimes).

Hosts move following the random-way-point model by interleaving between roaming for 1 second and pausing for 10 seconds. The roaming speed is 10 m/sec, so this is close to a random walk, which changes cells at the rate of one cell per 11 seconds. In route search, a destination will wait for 5ms after the first ROUTE_REQ arrives before responding to the corresponding source. In predicting route lifetime, we use $t_{max} = 300$ in the simulation.

Fig. 16a compares throughputs of the two protocols under different network densities. With lifetime prediction, the saturated network throughput increases about 20 percent compared that of the shortest-path routing. This indicates that choosing the shortest path is not always the best choice. Instead, reliability is more important. To understand the reason, we calculate the *packet drop ratio*, which is defined to be the probability of a packet being deleted in the middle way even if it is sent correctly from a source. The main reason for packet dropping is the existence of broken connections before sources are informed (this is done by ROUTE_ERROR packets in DSR). The simulation result is shown in Fig. 16b. Choosing the shortest paths is sometimes dangerous because they are likely to become broken pretty soon. Not until a source is informed of a broken path, a lot of useless packets will be sent from that source, wasting a lot of bandwidth. Packets would experience longer delays too due to route recovery. Finally, Fig. 16c compares the routing overheads. As expected, DSR spends more control packets to recover and maintain connections. With our lifetime prediction algorithm, there are less route recoveries and, thus, less control packets. The result verifies the effectiveness of our result in real applications.

5 CONCLUSIONS

In this paper, we have formally derived the probability distribution of the lifetime of a given routing path in a MANET based on the discrete-time, random-walk model. Most existing works predict the lifetime of a wireless link based on simpler models and take the minimum lifetime of the wireless links comprised of a routing path as the route lifetime. The result proposed in this work can be used in measuring the scalability of a MANET and in evaluating routing paths during route selection procedure. Human's roaming pattern cannot be characterized by a single mobility model (for example, pedestrians, vehicles, or people of different job nature all exhibit different roaming patterns). Route lifetime prediction is still a challenging question for roaming patterns other than the random walk model. Understanding this factor will greatly facilitate routing protocols in choosing proper routes.

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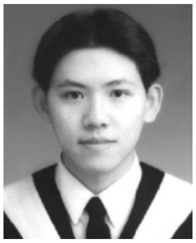

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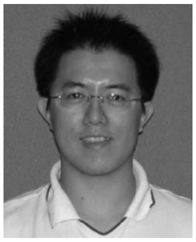

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