On Route Lifetime in Multi-hop Mobile Ad-hoc Networks

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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 multi-hop 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. Through such investigation, we hope to provide further insight into issues such as route selection, route maintenance, and network scalability related to MANETs.

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*

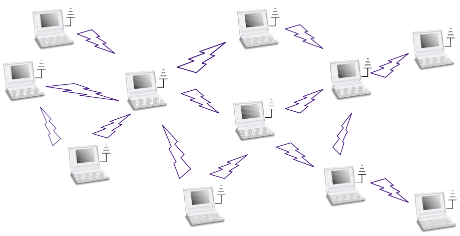


Figure 1: An example of mobile ad hoc network (MANET).

(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 *multi-hop* 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 powers 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 vs. route length tradeoff.

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].

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 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 the 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 [12] also assumes a random independent walk model. Instead of a cellular model as used in our work, it adopts a random waypoint model. Approximations of *link availability* and *path availability* are derived, where link availability is defined to be the probability of 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 $[t, t+\Delta t]$. We do consider such possibility in our work. Under the random walk model, [13] develops an efficient node proximity model to measure the stability of a 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.

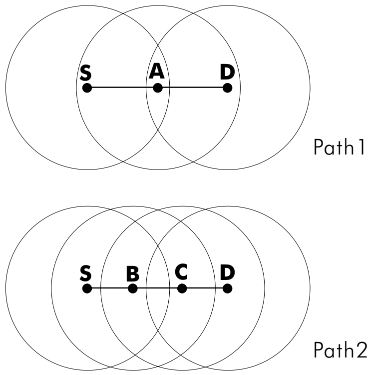


Figure 2: Reliability of routing paths in a MANET.

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 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).

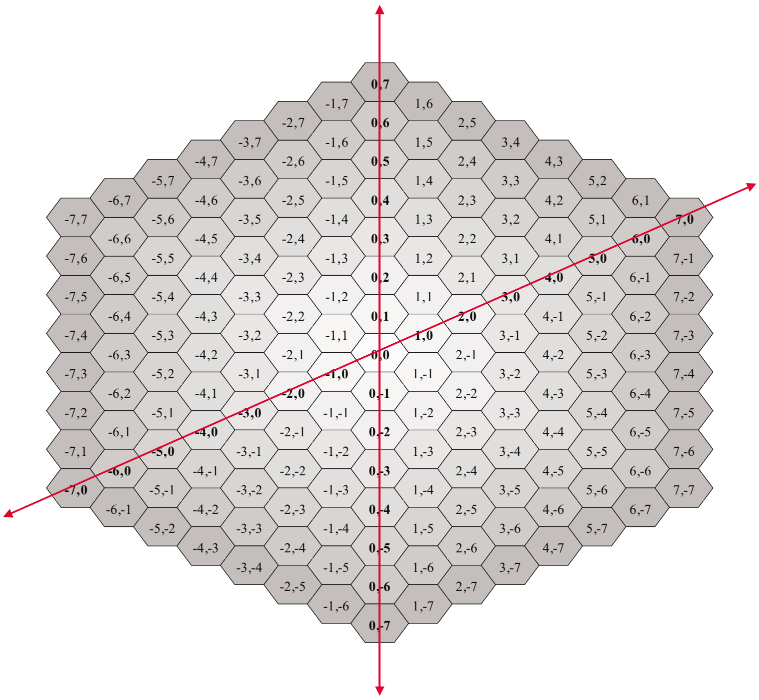


Figure 3: The cellular system to model the locations of mobile hosts.

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 n-th layer (including the n-th 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 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 6 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

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

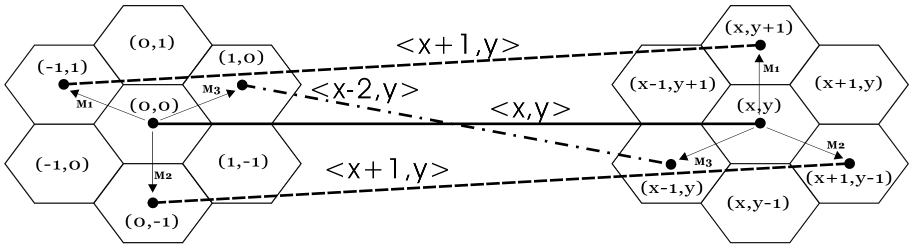


Figure 4: Example of link state changes.

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. 5(a) denote cell types after the merging, where cells of the same number are of the same types. Fig. 5(b) 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].

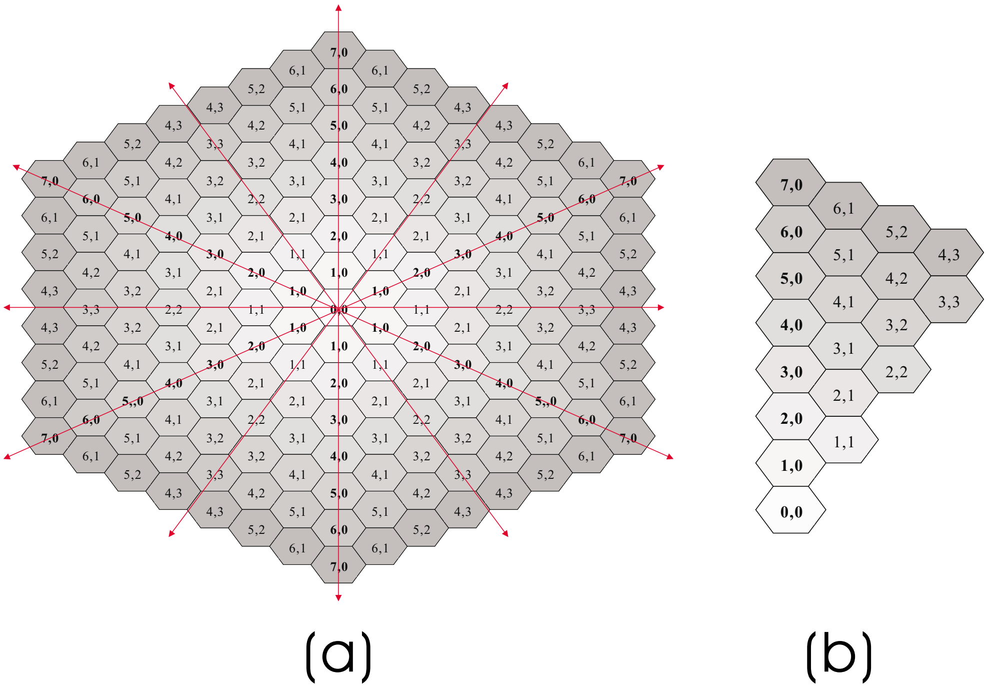


Figure 5: Merging equivalent states of wireless links: (a) partitioning the cells into 12 sectors and (b) equivalent states after merging.

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 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

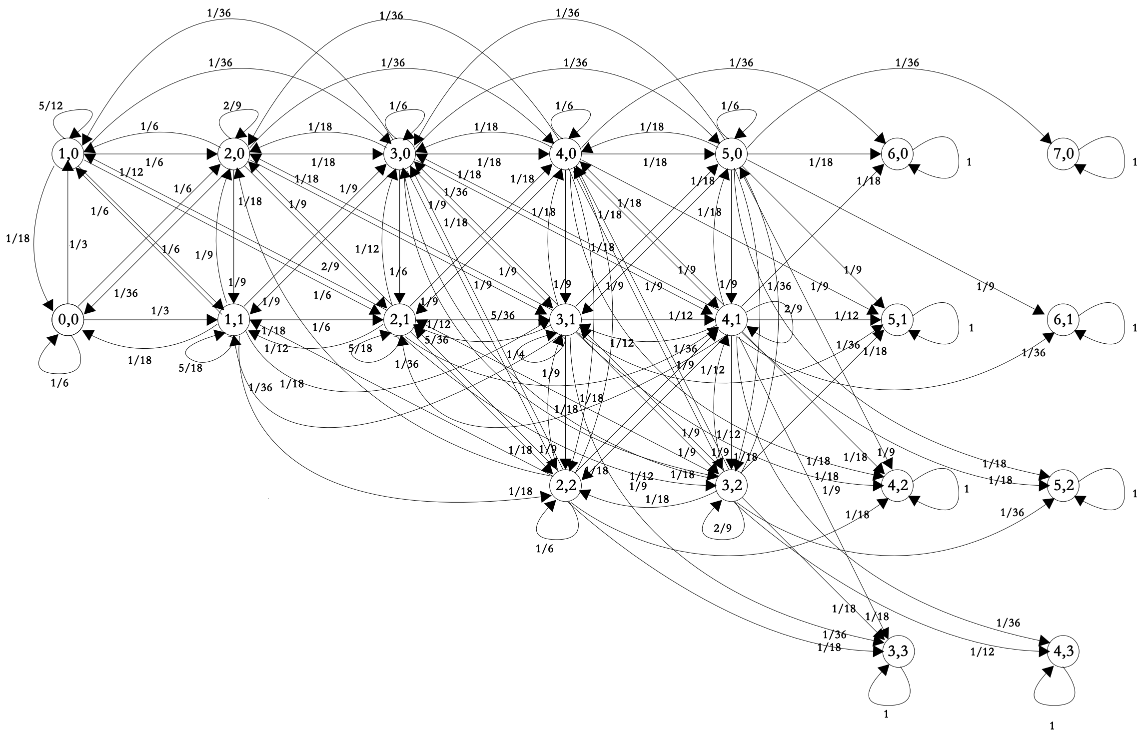


Figure 6: State transition diagram of a wireless link when $n = 5$.

matrix M such that each element $M_{i,j}$ represents the probability to transit from the i-th state to the j-th 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 k-th 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,

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

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

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 simply 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

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

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

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

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

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

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.

4.1 Determining the Level of Accuracy

Recall the route lifetime in Eq. (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 Eq. (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 Fig. 8(a) and Fig. 9(a) 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 $t_{max} = 1000$. So we will set $t_{max} = 500$ and 1000 when $n = 15$ and 25, respectively, for the rest of the simulations.

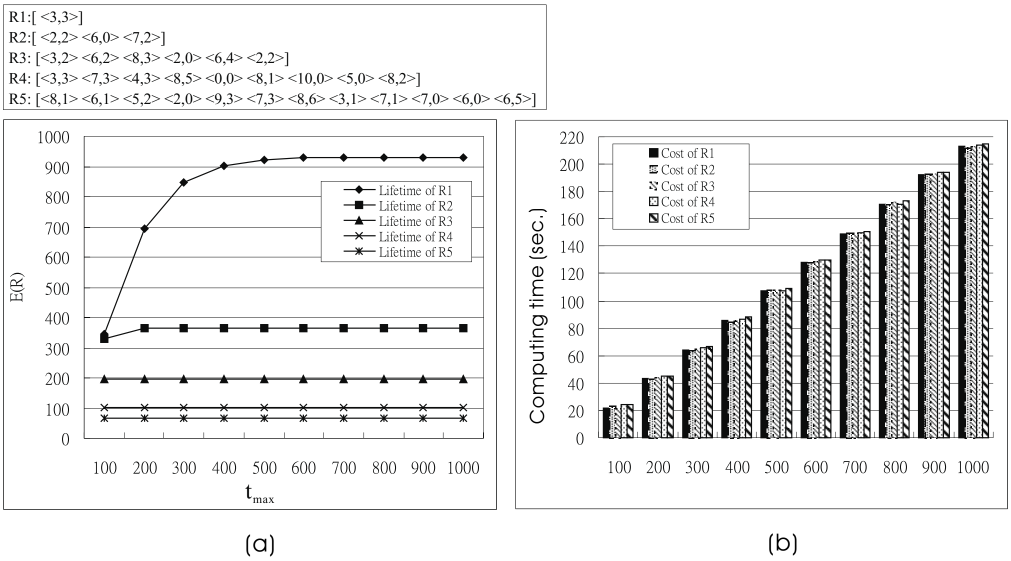


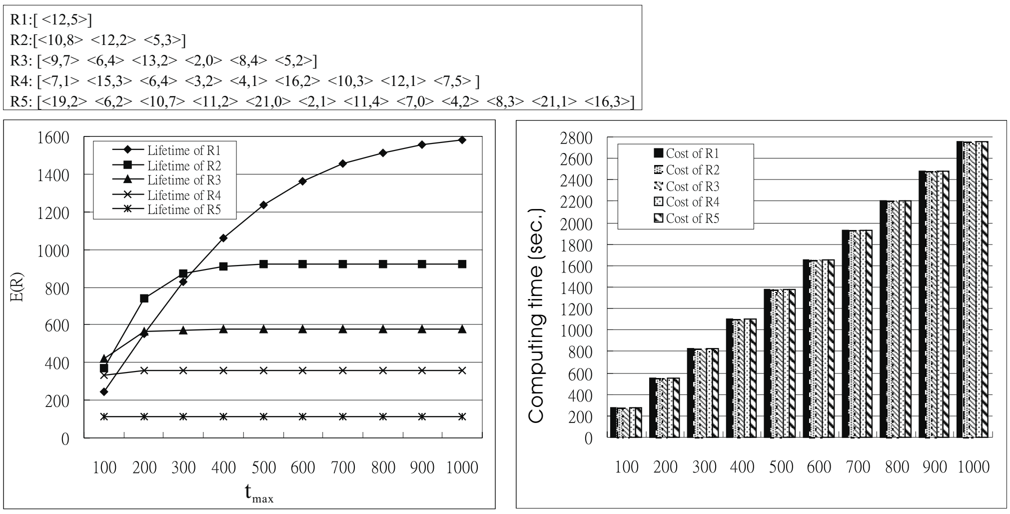
Figure 8: The expected route lifetime vs. t_{max} when $n = 15$.

Fig. 8(b) and Fig. 9(b) 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 $n = 15$, $C(n+2) = 4913$). 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

[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)

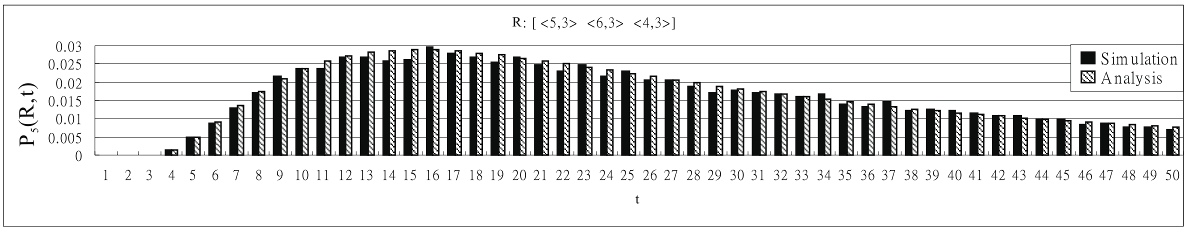
Figure 9: The expected route lifetime vs. t_{max} when $n = 25$.

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.

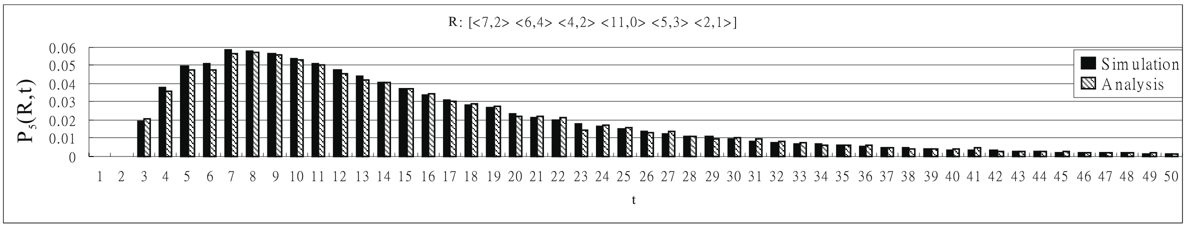
Fig. 10 and Fig. 11 compare the probability distribution of route breakage time (i.e., $P_5(R, t)$) obtained from such random simulation against our numerical analysis for several different routing paths when $n = 15$ and 25, respectively. The route being simulated is listed on the top of each illustration. 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.

4.3 Application 1: Cost-Effectiveness Routing Paths

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 large MANET. Intuitively, long routing paths with large hop counts may suffer higher route breakage probability. So more route-searching efforts may



(a)



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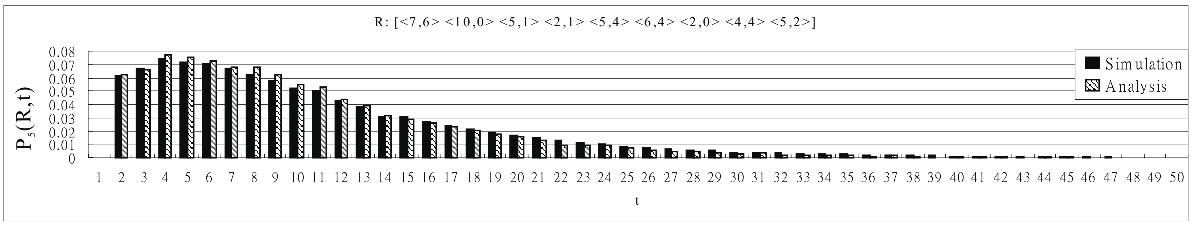

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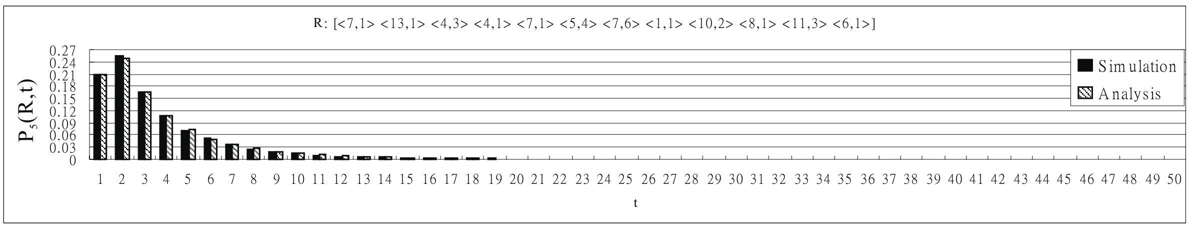
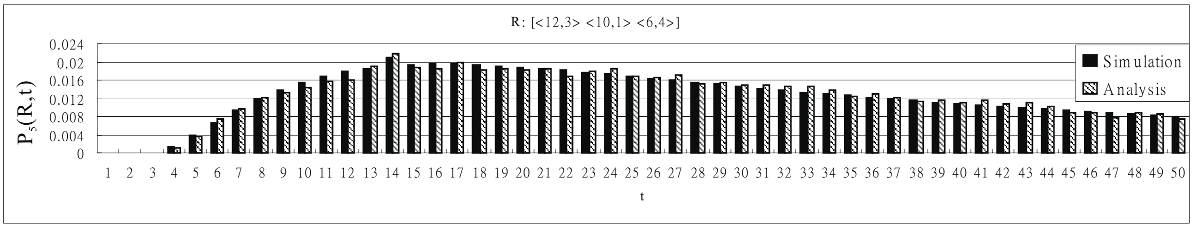
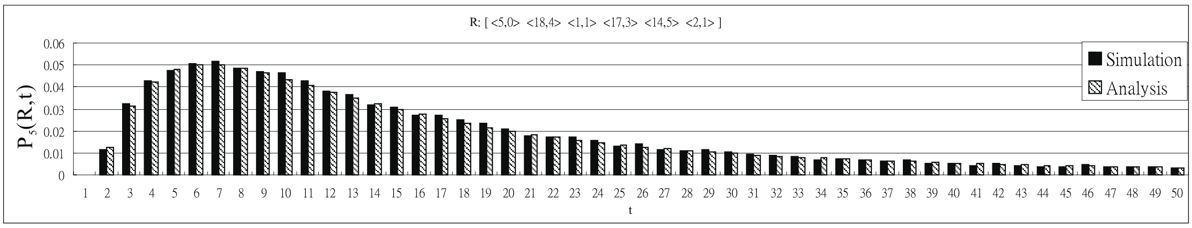


(d)

Figure 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 link.



(a)



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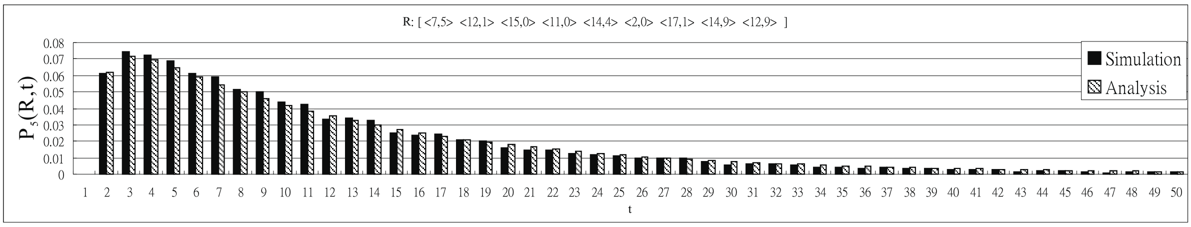

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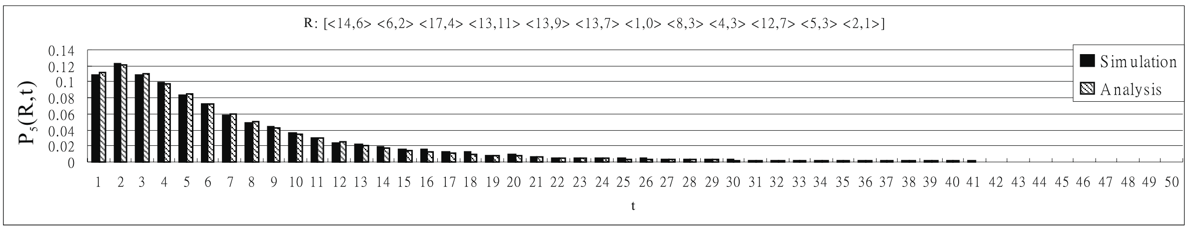

(d)

Figure 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 link.

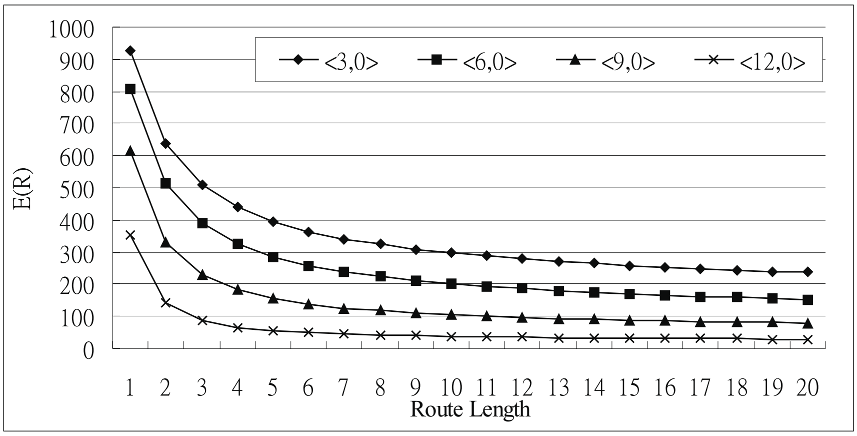

Figure 12: The expected route lifetime vs. route length when $n = 15$. Each route consists of links of the same state.

be incurred to reestablish the connection. 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 Fig. 12 and Fig. 13. We see that route lifetimes all degrade significantly from 1 to 5 hops. So practical sizes of MANETs would range within around 5 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

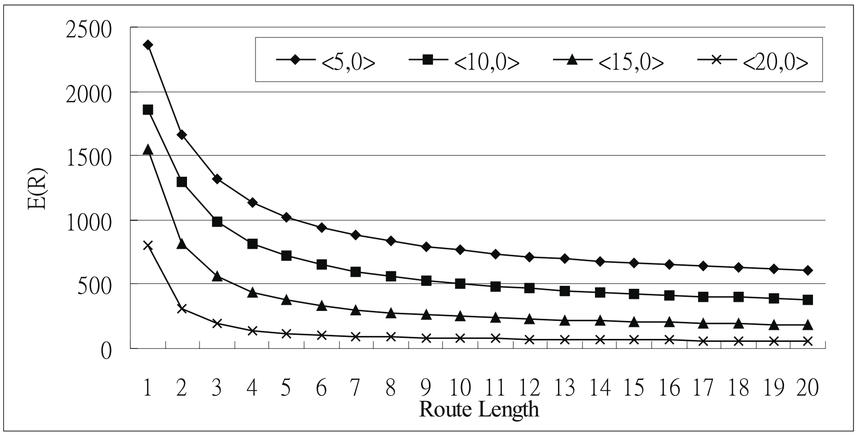

Figure 13: The expected route lifetime vs. route length when $n = 25$. Each route consists of links of the same state.

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 i-th host will be placed at cell $(\lfloor \frac{50 \times i}{h} \rfloor, 0)$, $i = 1..h-1$. We then evaluate the 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 to 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 is similar: when h ranges in 12 to 18, the expected route lifetime increases sharply, after which the route lifetime even degrades.

5 Conclusions

In this paper, we have formally derived the probability distribution of a 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 each wireless link consisting a routing path as the route lifetime. The result can be used in eval-

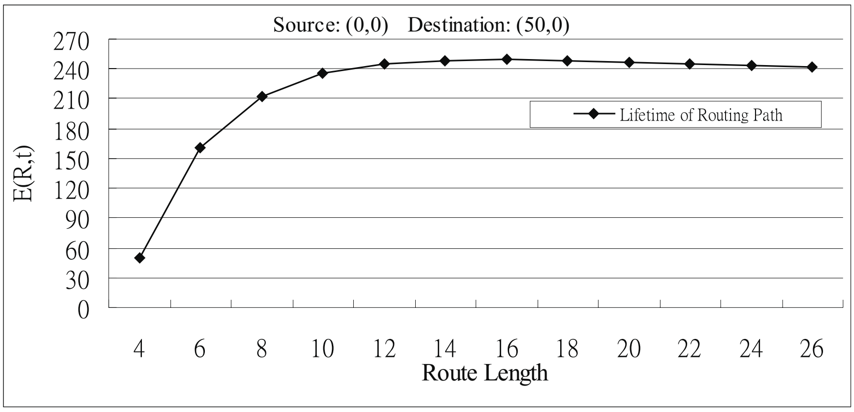

Figure 14: The expected route lifetime vs. route length with fixed source and destination hosts when $n = 15$. The relay hosts are spaced regularly and form a straight line.

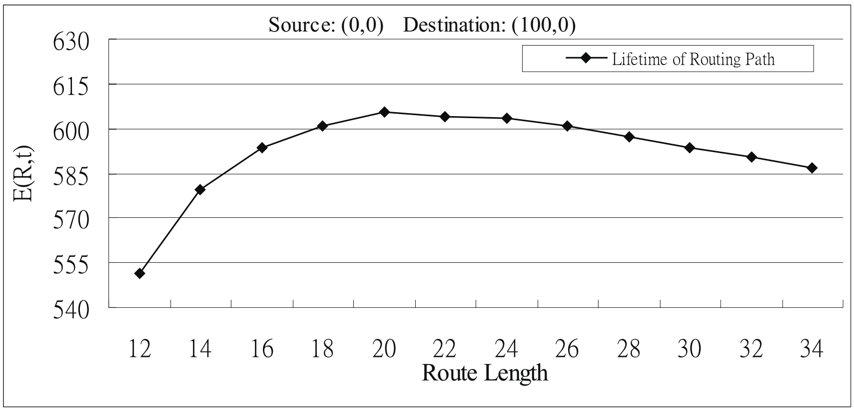

Figure 15: The expected route lifetime vs. route length with fixed source and destination hosts when $n = 25$. The relay hosts are spaced regularly and form a straight line.

uating routing paths in route selection. Future work includes considering more complicated roaming models into the route lifetime prediction problem.

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