Study of the Effects of Mobility on Residual Path Lifetime in Mobile Ad Hoc Networks

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***Abstract*— In mobile ad hoc networks, a communication path often spans multiple hops. Knowledge of the residual path lifetime may be quite useful in path selection algorithms, where the source node can select one of multiple paths to the destination node. In this paper, we study the effect of mobility on the residual path lifetime and demonstrate that the intuitive conjecture that "the older the path, the sooner it will break" is not always true. We observe that, for old enough links, the age of the oldest link of a multi-hop path is not significantly correlated with the paths mean residual path lifetime. Furthermore, this conjecture is also valid for other than the oldest link on a path. Additionally, we study the effects of mobility on the residual lifetime of a multi-hop path under different mobility models. Understanding of how the path lifetime behaves in a topologically dynamic environment may help us in designing an effective path-selection algorithm that selects the most reliable path among all candidate paths.**

I. Introduction

A mobile ad hoc network (MANET) is composed of mobile, autonomous nodes. Unlike cellular networks and Wireless Local Area Networks, a MANET does not have a fixed infrastructure to support its network functions and, therefore, must rely on the network nodes to assist in relaying packets between nodes separated by large geographical distances. The absence of infrastructure, coupled with the constraints on the physical size of the nodes, results in networks with scarcity of resources such as available bandwidth and battery power. Because of the mobility of the nodes, the network topology and the network connectivity are dynamic over time. A communication path between a source and a destination often spans multiple links (referred to as *hops*); such a path is termed a *multi-hop path*. A MANET is most suitable for applications that require rapid deployment of a communications network in an environment without permanent infrastructure. Some of its potential applications include battlefield operations, disaster recovery missions, and trade shows.

Owing to the richness of paths in ad hoc networks, quite often a routing protocol will find multiple routes between two communicating nodes. The source node needs then to select one of this multiplicity of paths. Depending on the application, the selection process would rely on an appropriate metric or metrics. For transmission of time-sensitive traffic, the selection of the path, whose remaining lifetime until it breaks is the longest, is usually the natural choice. However, determination of which of the paths will live the longest is often difficult, because of the dynamic nature of the network topology that is largely due to node mobility. Thus, a model that would allow predicting at the time of a path discovery how long it would take until the path breaks, which is defined as the *residual path lifetime* (RPL), would be a key component of such a path selection algorithm. Predicting a RPL would also allow the routing protocol to take preemptive measures and safeguard the traffic session before the path fails. Analytically modeling the residual lifetime of a multi-hop path has been considered by various researchers to be very difficult. The reason for this difficulty stems from the fact that a RPL cannot be treated as a simple extension of the residual lifetimes of individual links along the path due to correlation among these links. As a result, most of the research in this area is carried out via simulations.

In this paper, we study the effect of a path residual lifetime under different mobility models. Our study reveals that the intuitive conjecture that "the older a path is, the sooner it will break" is often erroneous. In fact, the surprising observation of our work is that the mean residual path lifetime becomes mostly uncorrelated with the age of the oldest link of the path. Furthermore, in this paper, we discuss the effects of several mobility parameters on the RPL.

The paper is organized as follows. Section II presents some related previous works, which studied the link and (multi-hop) path lifetimes. Section III presents simulation results of our study of the residual path lifetime under three different mobility models. Section IV provides some directions for our future research. Finally, Section V concludes the paper.

II. Related Work

The lifetime of a communication link with respect to the underlying mobility model has been the subject of many studies in the technical literature. Turgut, Das, and Chatterjee proposed the expected path lifetime as an important metric and obtained the analytical expressions of expected link lifetime for four mobility models [11]. The authors argued that a deterministic mobility pattern allows the lifetime of a path to be determined exactly, and a "chaotic" mobility pattern adds an uncertainty component. However, no experimental or simulated results were provided to validate their conclusions.

This work has been supported in part by the National Science Foundation grant numbers ANI-0329905 and by the DoD MURI (Multidisciplinary University Research Initiative) Program administered by the Air Force Office of Scientific Research (AFOSR) under contract F49620-02-1-0217.

Several studies aim to analytically model the link lifetime. McDonald and Znati ([6]) proposed a random-walk-based *Mobile Ad Hoc Mobility Model*. Their analytical model allows to calculate the probability of a link being up at a future time instant given that the link is available at the present time. Their model, however, has some limitations, if it is to be used for continuous link durability without breakage. Su, Lee, and Gerla ([9]) suggested the use of Global Positioning System (GPS) to predict the link expiration time for the nodes traveling with the *Billiard Mobility model*. However, the use of GPS in each mobile node restricts the use of the scheme to environments where GPS works well (e.g., not an indoor use) and increases the cost of the implementation. Samar and Wicker ([8]) analytically computed the expected link lifetime when nodes move according to the Billiard Mobility model. They assumed the knowledge of individual nodes speeds in their derivations, which limits the practicality of the solution. Additionally, their solution is computationally intensive.

Some researchers have explored link stability in the context of designing routing protocols. Gerharz et. al. ([3]) studied the relationship between link age and the mean residual link lifetime and proposed several methods to estimate link stability. Toh ([10]) introduced the Associativity-based Routing (ABR) that evaluates the longevity of a link by the past associations of the two nodes joining the link. It considers older links to be more stable than younger ones. ABR assumes a particular mobility model suitable for slow speed movement in an indoor environment, and the results from this model may not necessarily be indicative of the more general scenarios.

Very little has been published in the literature concerning the residual lifetime of a multi-hop path. One paper by Bai, et. al. ([1]) explored the path duration in the MANET under four mobility models. They related the expected path duration to the performance of reactive routing protocols. A major contribution of their work is that they showed that the distribution of the residual path lifetime can be modeled as exponential under some mobility models, provided that the path is at least two hops in length, and that the average relative speed of all nodes in the network is medium to high.

III. Residual Path Lifetime under Different Mobility Models

We study the residual path lifetime of a multi-hop path under three *mobility models*: the *Random Waypoint Model (RWP)*, the *Random Mobility Model (RM)*, and the *Gauss-Markov Mobility Model (G-M)*. A mobility model is a collection of attributes that dictates how a node moves in a physical area. These attributes include, but are not limited to, distributions of speed and direction, distribution of pause time, correlation between velocities, etc. In the following, we describe the attributes of these three mobility models.

A. Mobility Models

RWP is popularly used for conducting mobility simulations in ad hoc networks [2]. In our implementation of this model, each node independently and randomly selects a speed and a target location. The node then travels at the chosen velocity until it reaches the target location. It then pauses for a fixed duration before randomly selecting a new speed and a new target location, and repeats the above procedure. The network roaming area is a torus as opposed to an area bounded by boundaries, thereby mitigating the well known "clustering" effect of the RWP model [7].

In the RM model, each node independently and randomly chooses the speed and direction of the node, which moves accordingly for a constant time duration. At the end of this time duration, the node, without pause, randomly chooses a new speed and direction, repeating the above procedures.

The G-M mobility model differs from the previous models in that it permits correlation between successive velocities of a node in order to eliminate abrupt changes in speed and direction [5]. A node calculates the next values of speed and direction, each of which is Gaussian-distributed and independent of the other. The calculated values are correlated with the previous values of speed and direction; this correlation is quantified by a parameter $\alpha \in [0, 1]$. The node moves at the new velocity for a constant time duration. At the end of this traveling period, and without pause, a new velocity is computed, and the process repeats.

We have selected these mobility models in our study because they also represent various degrees of randomness in their respective mobility profiles. That is, the RM model has the highest degree of randomness, followed by RWP and G-M, thus allowing us to observe the effects of how randomness in mobility models affects the RPL.

B. Analysis of Residual Path Lifetime

A multi-hop path fails when any one of its constituent links breaks. Eq. 1 describes the residual path lifetime $Y(t)$ of an L-hop path as the minimum of all the residual lifetimes of its constituent links at time t (denoted as $X_i(t)$):

$$Y(t) = min\{X_i(t)\},\ \forall i = 1, 2, \ldots, L. \tag{1}$$

Intuitively, the longer a path has been up, the shorter its residual lifetime should be. However, we shall show that this is not always the case for multi-hop paths in MANET, where nodes move with one of the above mobility models.

We first analyze the behavior of the mean residual path lifetime as a function of the oldest link along the path and with respect to each one of the three mobility models. We choose to evaluate the RPL as a function of the oldest link on a path because of the intuition that the oldest link on a path is more likely than the others to break first.

Three simulation scenarios are set up, in each of which the nodes move under one of the three aforementioned mobility models. The simulation parameters are listed in Table I. Note that these parameters define a network with a very dynamic topology. Each path is discovered by the Dijkstra shortest-path algorithm, and at the time of the path discovery, the oldest link age on the path is recorded. $800,000$ residual lifetime statistics are collected for each of the one-, two-, three-, and four-hop paths under each mobility model.

Figs. 1, 2, and 3 demonstrate the average residual path lifetime as a function of the oldest link age on the path.

Parameters	Values
Network Size$[m^2]$	700 x 700
Num. of Nodes	40
TX Range[m]	150
Min. Speed [m/s]	5 (RM and RWP)
Max. Speed [m/s]	20 (RM and RWP)
Average Speed [m/s]	12.5 (G-M)
Std. Dev. of Speed [m/s]	3 (G-M)
Std. Dev. of Direction [deg]	30 (G-M)
Pause Time[sec]	5 (RWP)
Node Velocity Update Interval [sec]	10 (RM and G-M)

TABLE I

SIMULATION PARAMETERS

The figures show that the mean RPL remains constant with increasing oldest link age for paths of two hops or longer, for the three mobility models. This is a surprising result, as our intuition would say that *the older a path is, the shorter its residual lifetime would be*. The explanation of this phenomenon is given as follows.

The intuitive conjecture holds if all the links along a path continuously increase until one of them exceeds the transmission range, at which point the link breaks, and the path fails. This can be visualized in Fig. 4(a), where the arrow on each node of the four-hop path indicates the direction of node movement. However, this is generally not true in a mobility model where each node's velocity is chosen independent of the others'. Fig. 4(b) demonstrates what the node movements are more likely to be in the three mobility models. When nodes A and B move closer, the link $l_{(A,B)}$ tends to have a longer residual lifetime, at the expense of shortened residual lifetime of its adjacent link $l_{(B,C)}$, as B and C move further apart. This effect is called the *adjacent link correlation* (ALC), illustrated between pairs of adjacent links in Fig. 4(b). We have observed that ALC has a significant impact on the RPL; however, the amount of impact also depends on the age of the oldest link. When the oldest link on a path is still young, a path failure is more likely caused by the oldest link than by any other constituent links. That is, there is correlation between the oldest link and the mean RPL. As the age of the oldest link is beyond some threshold, and the path is still up, all the constituent links become equally likely to break first, which suggests a diminished impact by the ALC. The mean residual path lifetime therefore becomes uncorrelated with respect to the oldest link age on the path.

In fact, the phenomenon in mean RPL can be observed not only with respect to the oldest link age, but also to any of the constituent links of the path. The lack of correlation between the mean RPL and link age presents a challenge to devising a path-selection algorithm that aims at finding a path with the longest residual path lifetime from all the candidate paths. It implies that, given a set of paths of equal length, having the knowledge of the ages of the links does not differentiate among them in regards to how much longer, on the average, each path would remain up. Thus, the mean RPL may be a poor choice as a criterion in a path-selection algorithm when all the paths discovered are of equal length. Indeed, such an algorithm can be shown to perform only as well as a random path-selection algorithm, where any one of the candidate paths (of equal length) is randomly chosen.

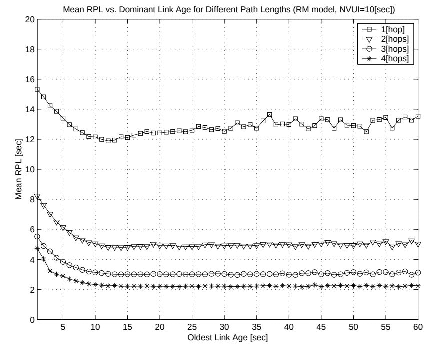


Fig. 1. Mean RPL vs. oldest link age for various path lengths (RM)

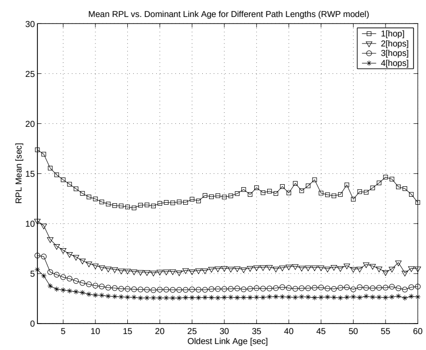


Fig. 2. Mean RPL vs. oldest link age for various path lengths (RWP)

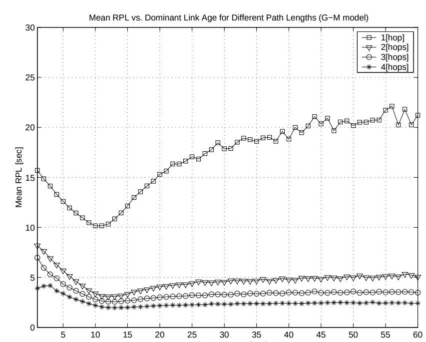
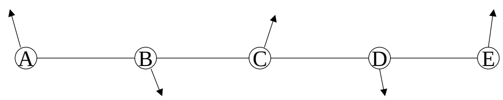
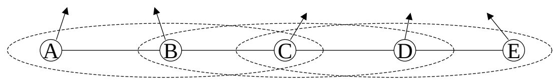


Fig. 3. Mean RPL vs. oldest link age for various path lengths (G-M)

We have also observed that, as the path length increases, the mean RPL progressively decreases, but at a reduced rate. Using Fig. 1 as an example, we see that for two-hop paths, their mean RPL ranges from $5[sec]$ to $8[sec]$ depending on the corresponding range of the age of the oldest link. For three-hop paths, the mean RPL further "flattens" at the younger link ages, and decreases to about $3[sec]$. For four-hop paths, the mean RPL has further decreased to about $2.5[sec]$. That is, the decrease in mean RPL from three-hop to four-hop paths is much less than that from two-hop to three-hop paths. It can be deduced that this trend continues for longer paths as well; the relative decrease in the mean RPL is smaller and smaller



(a)



(b)

Fig. 4. Node movements and adjacent link correlation on a path

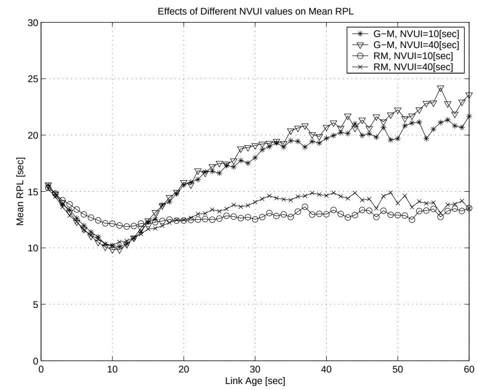


Fig. 5. The effect of the NVUI on the mean RPL vs. link age in one-hop paths (for the RM and the G-M mobility models)

as the path length increases, until it approaches 0 when the path length approaches infinity.

C. The Effect of the Network Parameters on the RPL

We now investigate the effect of some network parameters on the residual path lifetime. Specifically, we study the following parameters: *node density*, *node velocity update interval* (NVUI) for the RM and the G-M models, and *pause time* for the RWP model. Changing the network dimensions while maintaining the number of nodes and transmission range changes the node density of the network, i.e., the average number of neighbors per node. The larger the NVUI value is, the more likely it is that a nodes velocity remains unchanged and the more predictability there is to its trajectory. The pause time plays an important role in affecting the degree of dynamics in the network topology. The longer the pause time is, the less dynamic is the network topology. Due to space constraints, we show just representative results in this paper, by summarizing those in the ensuing paragraphs.

Our simulations have shown that the network density has only an insignificant effect on the mean RPL for a path of any length under the three mobility models. For example, for the RM model, the mean RPL for two-hop paths in a $900 \times 900[m^2]$ network (i.e., a network density of $3.49[nbrs/node]$) has only a small drop (approximately $0.5[sec]$) relative to a $700 \times 700[m^2]$ network (i.e., a network density of $5.77[nbrs/node]$). And for longer paths, the difference between the two cases becomes indistinguishable. This may be explained by the fact that the path is discovered using the Dijkstra shortest-path algorithm, which always attempts to connect the source and the destination nodes through intermediate nodes that are as far apart as possible (i.e., shortest path). Having additional intermediate nodes in between does not affect the search for the shortest path, and therefore bears no influence over the resultant residual lifetime of the path.

When the value of NVUI is changed from $10[sec]$ to $40[sec]$, the significant change is observed only in one-hop paths (i.e., links) under the RM and the G-M mobility models. Very negligible variations are observed in mean RPL in longer paths for both mobility models. Fig. 5 presents these changes for one-hop paths. It can be seen that in both models, increasing the NVUI slightly increases the mean lifetime of the link when the link age is older than $20[sec]$. This is because in these models, a link that has already persisted for a long time is more likely to have a longer residual lifetime if the two nodes maintain their respective velocities unchanged. Furthermore, in the RM model, a young link age results in lower mean RPL for $NVUI = 40[sec]$ than for $NVUI = 10[sec]$. This is because, as we have observed from our simulations, a more frequent and independent change in node velocity (i.e., no correlation between successive velocities) is more likely to result in a longer residual lifetime. The last observation is intuitive, since a frequent change in nodes movement direction may steer the node back into the coverage of the other communicating node, increasing the chances that the link will not be broken.

We also changed the value of the pause time used by the RWP model from $5[sec]$ to $50[sec]$. Fig. 6 shows the mean RPL with respect to the oldest link age for a pause time of $50[sec]$. The results suggest that the pause time leads to a significant impact on the behavior of the mean RPL for shorter paths (i.e., one- and two-hop paths). When the pause time is $5[sec]$, the network is in a very dynamic state, where nodes move almost all the time. At $50[sec]$, each node stays longer close to the other communicating node, and the network becomes less dynamic. In such a case, not only does a longer pause time increase the mean RPL for a given age of the oldest link, but it also results in a more fluctuating mean RPL with respect to the increasing age of the oldest link. However, it is to be pointed out that with a longer path length, the mean RPL still tends to be uncorrelated with the age of the oldest link, mitigating the effects of a large pause time.

The above results suggest that the mean RPL of a multi-hop path is extremely resistent towards the changes in many mobility attributes. In the next section, we discuss the implications of this phenomenon.

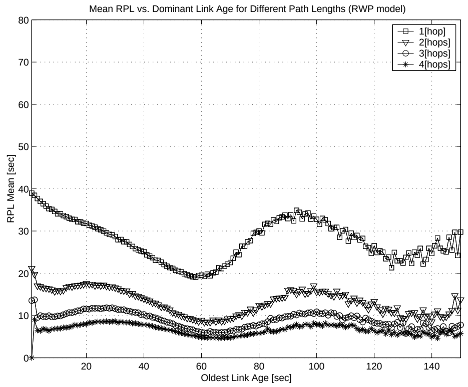


Fig. 6. The effects of pause time on the mean RPL vs. link age (for the RWP mobility model)

IV. Discussions and Future Work

In a mobile ad hoc network, it is often the case that multiple paths exist between the source and destination at one time. A simultaneous break-down of all these paths due to changes in network topology is unlikely. Thus, an important application for studying the residual path lifetime in MANET is devising a path selection algorithm that bases its selection on the longevity of the paths. A good path-selection algorithm should be capable of distinguishing among all the available paths and determining which one is most likely to have the longest residual path lifetime. The longest-lived path, when used to carry data traffic, will significantly enhance the network performance by bringing down the overhead associated with path maintenance, repair, and rediscovery, as well as lowering in-flight data loss due to abruptly broken paths.

One novel area of study is the problem of age-based (multi-hop) path selection. Such an approach forms the basis for the ABR ([10]) and other works, such as the work undertaken by Gerharz et. al. ([4]). Our investigation has led us to believe that, for the set of mobility models that we have studied and for mean RPL as the selection criterion, when attempting to choose a path from several available paths of equal path length, basing the path-selection decision on the link age does not necessarily yield meaningful performance improvement. This presents a challenge to the designers of the path selection algorithm, when the only available information about the paths is the ages of their constituent links. Simply put, our results show that, in a set of candidate paths, one should always choose the path with the fewest number of hops. But among the set of equal-length candidate paths, the best path-selection algorithm is equivalent to a random path-selection algorithm when the selection criterion is the mean RPL. Such an algorithm is clearly not satisfactory if we wish to significantly improve the quality of path selection.

In our future research, we intend to study how to design a path-selection algorithm that can achieve better performance, when additional information about the paths is available. We also intend to investigate how the results of this work are affected by the particular characteristics of the different mobility models.

V. Concluding Remarks

In this paper, we studied the effects of mobility on the residual lifetime of a multi-hop path in mobile ad hoc networks under three mobility models: the Random Mobility model, the Random Waypoint mobility model, and the Gauss-Markov mobility model. We have observed in our simulations that the mean residual path lifetime is uncorrelated with the age of the oldest link, after this age is larger than some threshold, which depends on the particular mobility model. Our observation is counter-intuitive, as we tend to think that an older link would always have larger chance of being broken, relative to a younger link. Moreover, some of the mobility parameters, which have often been extensively used in the published literature to study the various aspects of network behavior, do not seem to have substantial effects on the mean RPL of multi-hop paths. These results suggest that the mean RPL in a dynamic network is an invariant quantity, and it is inappropriate to choose it alone as a criterion in designing future path-selection algorithms.

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