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Link Availability Prediction in Ad Hoc Networks

Lei Gong, Yuebin Bai, Ming Chen, Depei Qian
School of Computer
Beihang University
Beijing, 100191, China

Abstract

Since mobility may cause radio links to break frequently, one pivotal issue for routing in Mobile Ad Hoc Networks is how to select a reliable path that can last longer. Several metrics have been proposed in previous literatures, including link persistence, link duration, link availability, link residual time, and their path equivalents. In this paper, we present a novel algorithm for predicting continuous link availability between two mobile ad hoc nodes. By a rough estimation of the distance between two nodes, our approach is able to accurately predict link availability over a short period of time. Simulation results are given to verify our approach. This study could serve as groundwork for further ad hoc network researches including analyzing and optimizing other network protocols.

1. Introduction

Due to the rapid development in the mobile devices technology, wireless networks are becoming more and more popular. Wireless networks can be classified into two major types - infrastructure-based networks (for e.g., cellular networks) and Mobile Ad Hoc Networks (MANETs). The former ones use fixed base stations, which are responsible for coordinating the communications between the mobile hosts (nodes). The latter consist of several wireless hosts that are capable of communicating with each other without the use of a network infrastructure or any centralized administration. Since these networks are self-organizing and self-configuration, they can be used for emergency situations like disaster-relief, military applications, and emergency medical situations.

In MANETs, two nodes communicate with each other in a peer-to-peer fashion. The routes between nodes may include multiple hops, and hence are called multi-hop networks. Each node can communicate with the node in its range, and those which are beyond its range; the node needs other intermediate nodes to relay its messages. In other words, each node can act as a router to forward messages of its peers. However, terminal mobility may cause radio links to be broken frequently, how to select reliable paths that can last as long as possible becomes one critical issue for routing. Therefore, using stable links is crucial for establishing reliable communication paths between mobile nodes.

Various metrics have been proposed as measures of topological change in networks. Here, we focus on the notion *link availability*. Throughout this paper, the term of link availability is defined as the probability that a link will be continuously available from t_0 to t_0+t, given that it is active at t_0.

In this paper, an analytical expression of link availability for mobile ad hoc networks is derived using probabilistic and statistical computing. Our work is based on Random Walk Mobility Model, which is a continuous time stochastic process that characterizes the random movement of nodes in a two-dimensional space. Remember that the prediction algorithm presented in this paper can be extended to other mobility models. By a rough estimation of the distance between two nodes, our approach is able to accurately predict link availability over a short period of time. Simulation results are given to verify our theory. This study could serve as groundwork for further ad hoc network researches including analyzing and optimizing other network protocols.

The rest of this paper is organized as follows. First, in Section 2, related works are introduced. Then, in Section 3 we derive analytical expressions for link availability with Random Walk Mobility Model. Simulation results are presented in Section 4 to verify our proposed approach. Finally, Section 5 draws conclusion.

2. Related Works

In the literature, simulation has been the primary tool utilized to characterize and evaluate link dynamics in ad hoc and sensor networks. Some efforts have been directed at designing routing schemes that rely on identification of stable links in the network. Nodes make on-line measurements in order to categorize stable links, which are then preferen-

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tially used for routing, as [1] and [2] depicted. A common weakness of these works is that they cannot reflect possible changes in link status happening in the future. That is, a link deemed stable based on past or current measurements may become worse with time due to the dynamic nature of mobile environments.

Many previous studies concentrate on statistical analysis of link availability in ad hoc networks. Basing on experimental results obtained through simulation, N. Sadagopan et al. [10] shows that link duration has a multi-model distribution when the node's speed is slow, and the path duration can be approximated by an exponential distribution at moderate and high velocities. However, since the solutions provided by these studies are valid only for some specific circumstance, they could not be fully extended to universal ad hoc networks and practical MANETs applications.

Link availability is considered as a fundamental parameter when evaluating mobility in MANETs. However, analytical studies for analyzing description of this variable have been limited. In [11], an analytical framework is created and analytic expressions characterizing the statistics for link lifetime, new link inter-arrival time, link breakage inter-arrival time and link change inter-arrival time were derived based on Constant Velocity Model, which simply assumes that two mobile nodes move in a straight direction before the link breaks up. Obviously, this assumption is too idealistic.

In [4], a prediction-based link availability estimation algorithm was developed and investigated with Random Walk Mobility Model. The algorithm tries to predict the probability that an active link between two nodes will be continuously available for a certain period T_p, which is obtained based on the current node's movement. However, shown by the simulation results, this algorithm cannot accurately calculate the link availability; it can only reflect the general tendency of the link availability, that is, L(T_p) can approximate T_r/T_p , where T_r is the mean time that a link will be continuously available corresponding to a prediction T_p. For a given t that is not equal to T_p, this approach cannot compute the continuous link availability from t_0 to $t_0 + t$.

In this paper, we develop a mathematical model to derive analytical expression of link availability with Random Walk Mobility Model. Compared to previous studies, our prediction algorithm can accurately estimate continuous link availability over any short period of time, at both low and high velocity. So our prediction algorithm is advantageous for a wide range of wireless applications.

3. Link Availability Estimation

In this section, we derive analytical expressions for link availability with Random Walk Mobility Model. Based on this model, each node's movement consists of a sequence of random length intervals called mobility epochs, during which a node moves in a constant direction at a constant speed. The speed and direction of each node varies randomly from epoch to epoch. The epoch length is exponentially distributed random variables with mean $1/\lambda$. The speed and direction of mobile during each epoch is uniformly distributed over (v_{min}, v_{max}) and $(0, 2\pi)$ respectively. Speed, direction and epoch length are uncorrelated. Node mobility is uncorrelated and links fail independently. The aim of this work is to give an accurate estimation of $L(d_0, t)$, which is the probability that the link will be continuously available from t_0 to t_0+t given the initial distance $d_0(d_0 \le R)$. An accurate estimation of d_0 can be obtained through signal strength [7] or GPS.

To analyze link availability, we assume a node has a bidirectional communication link with any other node within a distance of R meters from it. The link breaks if the node moves to a distance greater than R. These assumptions are widely used in the literature such as [4], [5] and [9]. To simplify the discussion, we further assume that each node has the same mean epoch length. However, the following derivation can be extended for the case of different mean epoch lengths.

3.1. Relative Movement after One Epoch

As showed in Figure 1, when the epoch starts, the initial position of A and B are A_i and B_i. After the epoch, A and B arrive at A_j and B_j independently, where $A_iB_i = d_0$ and $A_jB_j = d$. Meanwhile, let $\vec{V}_A$ and $\vec{V}_B$ be the random variables representing velocity vectors of the given pair of nodes. Accordingly, V_A and V_B denote the magnitude of $\vec{V}_A$ and $\vec{V}_B$.

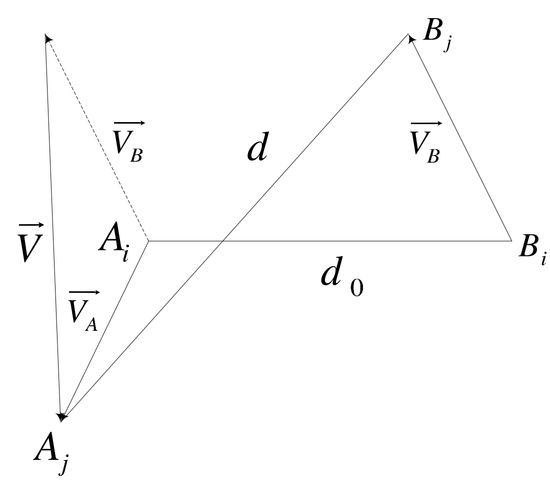


Figure 1. Relative movement between two nodes after one epoch

Now, we calculate the Probability Density Function (PDF) of the relative movement between A and B, whose movements are i.i.d. As depicted in Figure 2, the relative movement vector $\vec{V}$ is

$$\vec{V} = \vec{V}_A - \vec{V}_B. \tag{1}$$

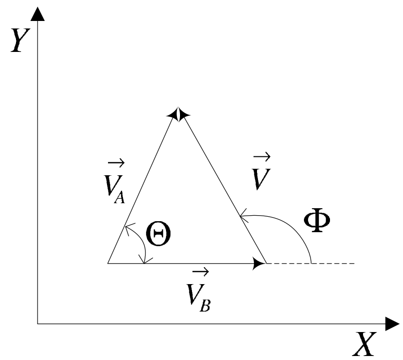


Figure 2. Relative velocity

The acute angle Θ between $\vec{V}_A$ and $\vec{V}_B$ is uniformly distributed in $[0, \pi]$, and positive X axis makes an angle Φ with $\vec{V}$, here, Φ is uniformly distributed in $[0, 2\pi]$. Using the cosine rule, the relative movement V(magnitude of $\vec{V}$) can be expressed by

$$V = \sqrt{V_A^2 - 2V_A V_B \cos\Theta + V_B^2}. \tag{2}$$

Since Θ, V_A and V_B are independent, so we have the joint PDF

$$f_{V_A,V_B,\Theta}(v_A, v_B, \theta) = \frac{1}{\pi(v_{\max} - v_{\min})^2}. \tag{3}$$

Thus, the joint PDF can be obtained via Jacobian transform, that is

$$f_{V_A,V_B,V}(v_A, v_B, v) = \frac{\partial\theta}{\partial v} f_{V_A,V_B,\Theta}(v_A, v_B, \theta), \tag{4}$$

where $\frac{\partial\theta}{\partial v}$ can be computed as

$$\frac{2v}{\sqrt{2v_A^2 v^2 + 2v_B^2 v^2 + 2v_A^2 v_B^2 - v^4 - v_A^4 - v_B^4}}. \tag{5}$$

Through the integration of the V_A and V_B, the marginal PDF of the magnitude of the relative movement can be derived,

$$f_V(v) = \int_{v_{\min}}^{v_{\max}} \int_{v_{\min}}^{v_{\max}} f_{V_A,V_B,V}(v_A, v_B, v) dv_A dv_B. \tag{6}$$

As Figure 3 depicted, most of the relative speed distributes within the range $(0.2 - 1.4)(v_{max} - v_{min})$, which implies very few nodes remain relative static. Remember that

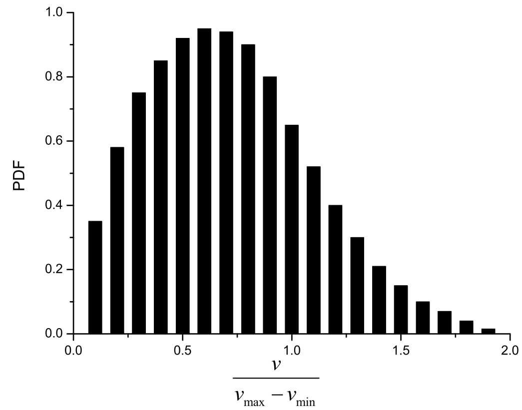


Figure 3. PDF of the relative movement.

although our analysis here is only specific to a certain mobility model, the methodology could still be applied to other models.

3.2. Conditional Probability of Separation Distance

Based on the aforementioned work, we now derive the analytical expression of $C(d_0, d, t)$, which is the probability that the distance between two nodes is shorter than d after an epoch of t seconds, given the initial distance is d_0. It can be expressed in a simple mathematical form

$$C(d_0, d, t) = P\left\{A_j B_j < d \,|A_i B_i = d_0\right\}. \tag{7}$$

According to Figure1 and Figure2, without lose of generality, we get the relationship between d_0, d, v and t by the law of cosine.

$$d = \sqrt{d_0^2 + 2vtcos\varphi + v^2t^2}. \tag{8}$$

If the initial distance d_0 between two nodes is smaller than d,

$$C_1(d_0, d, t) = \frac{1}{2\pi} \int_0^{2\pi} \int_0^{g_1(\varphi)} f_V(v) dv d\varphi \tag{9}$$

and

$$g_1(\varphi) = \frac{-d_0\cos\varphi + \sqrt{d^2 - d_0^2 \sin^2\varphi}}{t}. \tag{10}$$

In the other case,

$$C_2(d_0, d, t) = \frac{1}{2\pi} \int_{\pi - \arcsin\frac{d}{d_0}}^{\pi + \arcsin\frac{d}{d_0}} \int_{g_2(\varphi)}^{g_1(\varphi)} f_V(v) dv d\varphi \tag{11}$$

and

$$g_2(\varphi) = \frac{-d_0 \cos\varphi - \sqrt{d^2 - d_0^2 \sin^2\varphi}}{t} \qquad (12)$$

Therefore, from Eq. 9, Eq.10, Eq.11 and Eq.12, we get

$$C(d_0, d, t) = U(d - d_0)C_1(d_0, d, t) + U(d_0 - d)C_2(d_0, d, t) \qquad (13)$$

where U(.) is the standard unit step function.

3.3. Analytical Expressions

For a given pair of nodes A and B, we can divide the transmission range of $(0, R)$ into a serious of small intervals of width ε . When we consider the relative movement of B with respect to A, their relative distance d between two nodes can be regarded as a random variable, whose state space is $(S_1, ..., S_n)$, where S_i corresponds to $(i-1)\varepsilon \le d \le i\varepsilon$. Therefore, when the initial distance between two mobile nodes falls into a small range of $(i\varepsilon, (i+1)\varepsilon)$, we can use the following equation to approximate the CDF of relative distance for one mobility epoch, if ε is small enough.

$$C(d_0,\ d,\ t) \approx C\left((i + \frac{1}{2})\ \varepsilon,\ d,\ t\right) \qquad (14)$$

Let $a_{ij}(t)$ be the probability of transition from S_i to S_j in a given epoch of t seconds. From Eq.14, we have the analytical expression of $a_{ij}(t)$

$$a_{ij}(t) = C\left((i - \frac{1}{2})\varepsilon,\ j\varepsilon,\ t\right) - C\left((i - \frac{1}{2})\varepsilon,\ (j-1)\varepsilon,\ t\right) \qquad (15)$$

For a given pair of nodes and their initial distance d_0, we have the initial vector

$$\mathbf{I}_s(d_0) = \{x_1,\ \cdots,\ x_n\} \qquad (16)$$

$$x_i = \begin{cases} 1, \text{if}(i-1)\varepsilon \le d_0 \le i\varepsilon \\ 0, \text{otherwise} \end{cases} \qquad (17)$$

This vector means the probability of the initial relative distance d_0 being in each of the state space $(S_1, ..., S_n)$. Suppose the joint movement lasts for t seconds and experiences k changes in relative velocity (or consist of $k+1$ mobility epochs), we define the following matrix

$$M(t_i) = \begin{pmatrix} a_{11}(t_i) & \dots & a_{1n}(t_i) \\ \vdots & \ddots & \vdots \\ a_{n1}(t_i) & \cdots & a_{nn}(t_i) \end{pmatrix} \qquad (18)$$

where

$$t = \sum_{i=1}^{k+1} t_i \qquad (19)$$

Thus, the final vector $\mathbf{I}_t(d_0)$ can be derived as

$$\mathbf{I}_t(d_0) = \mathbf{I}_s(d_0) \prod_{i=1}^{k+1} M(t_i) \qquad (20)$$

$$\mathbf{I}_t(d_0) = \{y_1 y_2 ... y_{n-1} y_n\} \qquad (21)$$

which denotes the probability of the final relative distance d being in each of the state space $(S_1, ..., S_n)$. Apparently, $L(d_0, t)$ can be further expressed as

$$L(d_0,\ t) = \sum_{i=1}^{n} y(i) \qquad (22)$$

4. Simulation Results

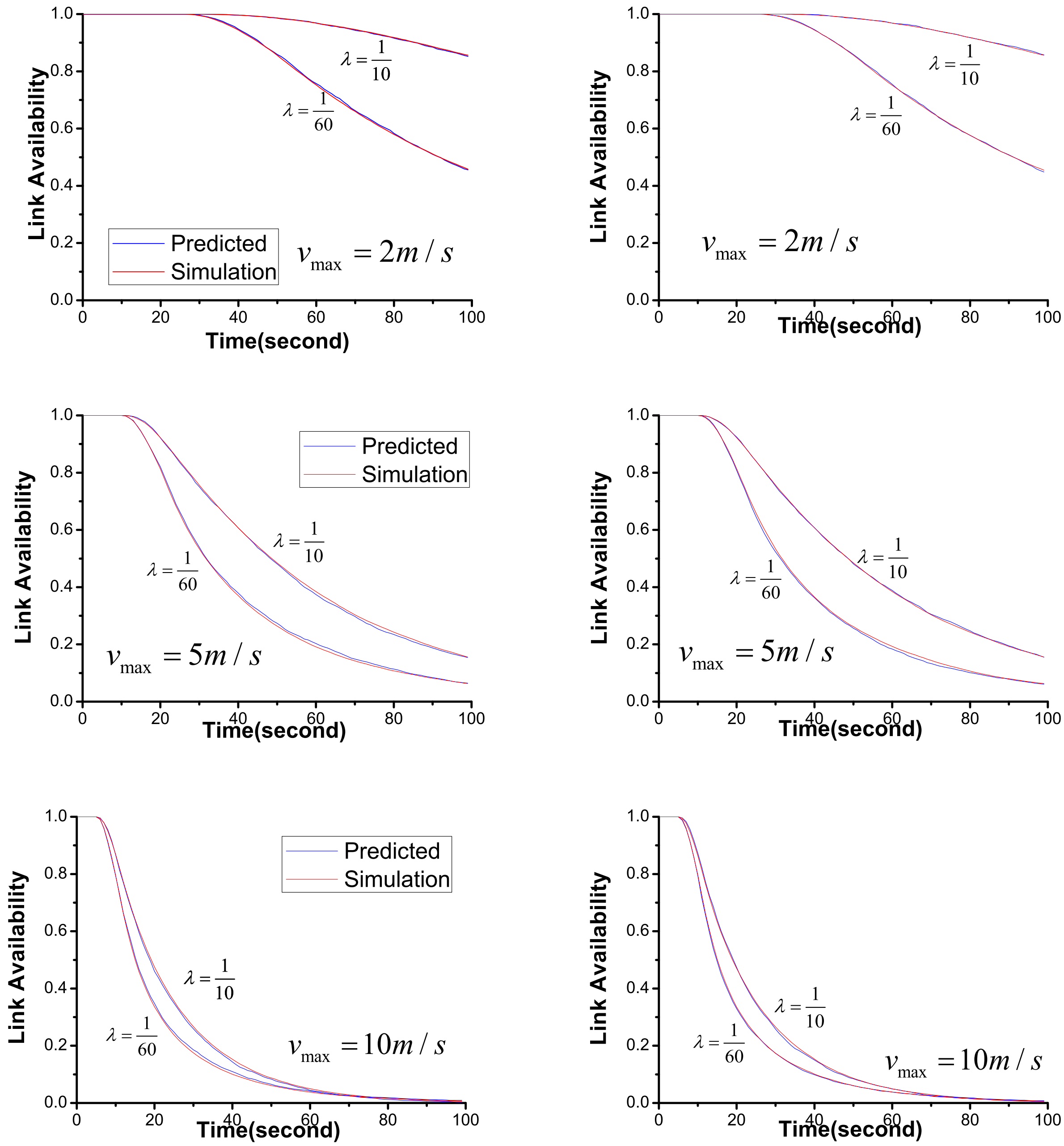
In order to verify the correctness of method, we compared the results of our framework described above with the actual simulation results. The simulation environment is a two dimensional space (2000, 2000), which represents an area of size 2000 meters by 2000 meters. Each simulated curve in Figure 4 is a result of 100,000 independent experiments. In each experiment, we place two nodes a certain distance away, and make them move according to the Random Walk Mobility Model as introduced in section 3. It is worth noting that the effective transmission range is set to 100m for both nodes. Then we statistically calculated the probability that the link was continuously available for t seconds based on all the experimental results. The parameters are summarized in Table 1.

Table 1. Simulation parameters

Parameter	Value
Radio transmission range	100
Speed distribution	Uniform[0,2],[0,5]or [0,10]
Direction distribution	Uniform [0,2π]
Position distribution	Designated
mean epoch length	10 or 60

In Figure 4, each plot is composed of 4 curves. Red lines represent the simulation results and blue lines illustrate the results of our framework. In Figure 4(a), we set the initial distance of the two nodes to 0. In Figure 4(b), the initial distance of the two nodes is set to 50 meters. In each plot, different lines represent different mean epoch lengths. We experimented with two epoch length settings. For each mobile peer, the mean epoch length is either 10 or 60 seconds as indicated in the graph.

It is clear from these plots that the red curves are fairly close with the blue ones which means our framework can be applied to predict link availability in actual mobile environments. We can also observe that in a high speed environment, link availability drops quickly as t increases. For



(a) $d_0 = 0$ (b) $d_0 = 50$

Figure 4. Simulation and Predicted Results

example, when the maximum velocity is 5m/s, as time goes by, link availability drops more quickly than the situation when the max velocity is 2m/s. Therefore, the ability of predicting link availability for a short period of time is very important for MANETs, especially in a highly dynamic environment. As shown from Figure 4, the probability for the link to be continuously available decreases when the mean epoch length increases. This can be explained by the fact that when the initial distance d_0 and the max velocity v_{max} doesn't change, if both nodes change their velocity very often, the link will break soon. By comparing Figure 4(a) and Figure 4(b), we come to the conclusion that the initial distance d_0 has a little influence on the results within certain range.

5. Conclusions

Mobile Ad Hoc Networks (MANETs) are strongly impacted by the mobility of the ad hoc nodes. One of the main challenges in MANETs is the requirement that the link must be continuously available for a period of time to enable uninterrupted data transmission and a smooth media performance.

In this paper, we develop a mathematical model for link availability estimation in MANETs with a random walk mobility model. Our approach tries to predict the probability that the link will be continuously available from t_0 to $t_0 + t$ given the initial distance between two nodes is $d_0(d_0 \leq R)$. Simulation results demonstrate that the link availability estimation algorithm presented in this paper can accurately predict link availability for a given short period of time. Our work can serve as groundwork for analyzing and optimizing other network protocols, and can assist the design of efficient algorithms for medium access and transport control.

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