On Link Reliability in Wireless Mobile Ad Hoc Networks

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***Abstract*— In mobile ad hoc networks (MANETs), packets are forwarded by a series of nodes to the desired destination. Previously, we have studied the network connectivity of MANETs. In this paper, we study the reliability of an established route between a source to a destination. The route is considered reliable only when all links in the route remain connected for packet relaying. We analyze the link reliability under the condition that the forwarding nodes are mobile. With this analysis, we derive the time period that the established route remains reliable for packet forwarding. Simulation is conducted to validate our analysis.**

I. Introduction

Wireless mobile ad hoc networks (MANETs) provide solutions for rapid deployment in areas where infrastructure networks do not exist. MANETs are generally formed by a collection of wireless communications devices commonly known as *nodes*. The packet delivery in a MANET relies on relaying of packets from a source to a series of forwarding nodes until they reach the desired destination. Hence the reliability of these networks depends on the robustness of the link communications between forwarding nodes.

In MANETs, a source must establish a route to the destination either proactively or reactively prior to actual data transmissions. In this process, a set of forwarding nodes are selected to form a route between the source and the destination depending on the routing strategy. Due to the mobility of the nodes, this route may remain reliable for a finite time period before a link breakage occurs, and link repair or route reestablishment must take place. Inevitably, a brief pause of data transmissions, or more seriously, a disconnection of a communication session between the source and the destination may appear. Hence, prediction of the robustness of a link in terms of link connectivity duration provides insight to the reliability of the communications and helps improve the routing protocol design.

Our considered one-dimensional (1D) MANET is shown in Fig. 1 where nodes are constrained to one dimensional movement on, for example, a freeway or a walking path. The distance between the source node, S, to the destination node, D, is fixed i.e. the source and the destination do not move. Previously, we studied the network connectivity of such a network [1], [2]. Since the stationary property applies only to the source and the destination, forwarding nodes remain mobile. The link between two adjacent forwarding mobile nodes may break; thus, breaking an established route from the source to the destination. In this paper, we evaluate the individual *link reliability* by modeling the period of time a link between two adjacent forwarding nodes remains connected. Considering all links in an established route between the source and the destination, we further analyze the *connectivity period*, which measures the period of time an end-to-end established route remains valid for packet forwarding. Previous work on the mean connectivity period is given in [3].

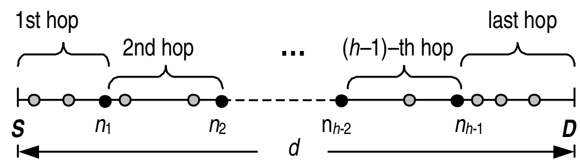

Fig. 1. One dimensional MANET.

This paper is organized as follow. Section II describes the scenario and the assumptions that we follow in the analysis. Section III presents the analysis of link reliability between two adjacent forwarding nodes. In section IV, we describe the connectivity period distribution of the end-to-end route from the source to the destination. Some important conclusions of this work are drawn in Section V.

II. Scenario Description and Discussion

In our considered MANET (see Fig. 1), the source and the destination is separated with a fixed distance d, which is normalized to the transmission range of the nodes. Within them, n additional nodes are placed. The nodes are statistical identical, and we consider a uniform placement of nodes. The network implements a certain reactive routing protocol. As we are studying the period of connectivity, we assume that the network starts in a connected state i.e. there is a defined series of forwarding nodes that establish the route between the source and the destination. The issue of network connectivity has been addressed separately in [1], [2] and also in [4]–[7]. From our simulation experiments, we also observe that with a particular reactive routing protocol, the distribution of the link distance between two adjacent forwarding nodes normalized to the radio range can be approximately described by the following probability distribution function

$$f(x) = \begin{cases} 2x, & l = 1, n_h \\ 4x^3, & l = 2, 3, \ldots, n_h - 1 \end{cases} \tag{1}$$

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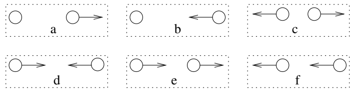

Fig. 2. Possible motions of two adjacent nodes.

where l denotes the hop distance from the source ($l = 1$ means that it is the first hop, $l = 2$ refers to the second hop, $l = 3$ refers to the third, and so on).

We assume that the source and destination nodes are stationary. Note that our analysis is easily modified to cater for non-stationary source and destination nodes. The speed of the forwarding nodes are uniformly distributed with a maximum speed of m. In other words, the speed of the nodes are selected from a uniform distribution in the range of $(0, m)$. Similar with the distance, d, the maximum speed, m, is also normalized to the transmission range of the nodes.

To derive the source to destination connectivity period, we must first look at the connectivity period between two adjacent forwarding nodes. In 1D MANET, there are six possible combinations of the motions of two adjacent nodes (Fig. 2). In Fig. 2a and b, one of the nodes is stationary, which corresponds to the first and last hops of our scenario, where the source and destination nodes are stationary. Fig. 2c and d show the cases where the two adjacent nodes are moving to the opposite direction and Fig. 2e and f show two adjacent nodes moving to the same direction.

Define *motion a* as the motion described in Fig. 2a and similarly for the rest of the possible motions. Consider motion a and motion b; the link connecting the two adjacent nodes in motion a, with high probability, will break before the link in motion b. Similarly, the link in motion c will break before the link in motion d. When two nodes moving to the same direction, there are two possible scenarios: (1) the node in front is moving faster than the node behind; and (2) the node behind is at least as fast as the node in front. In this case, with high probability, scenario 1 will have its link break faster than the link in scenario 2. We argue that it is not necessary to derive all the possible motion scenarios to achieve the end-to-end connectivity period distribution; we will discuss this further in section IV. Having all these, in the next section we derive the connectivity period between two adjacent nodes, which we call *link connectivity period*.

We verify our analytical model using ns2 [8] simulations. We use AODV [9] for the routing protocol and random waypoint model [10] for the nodes mobility.

III. Link Connectivity Distribution

In this section we derive the link connectivity period of three scenarios that, with higher probability, will break the link between two adjacent nodes before the other scenarios (as described previously). They are (1) nodes moving away from each other (Fig. 2c), (2) nodes moving to the same direction with faster node in front (Fig. 2e and f), and (3) node moving away from a stationary node (Fig. 2a).

A. Nodes moving away from each other

In this subsection, we use a convention of a negative speed to indicate that a node is moving to the opposite direction of the other node. Therefore, we have two adjacent nodes with speed r and s; r is selected uniformly from the range of $(0, m)$ and s is selected uniformly from the range of $(-m, 0)$. The distribution of the distance between two adjacent forwarding nodes follows (1).

Define T_{od} as the time duration when the link between two adjacent forwarding nodes break. We found it easier to first derive the *complementary cumulative distribution function* (CCDF) of the link connectivity period, $Pr\{T_{od} > t\}$, than the *cumulative distribution function* (CDF) $Pr\{T_{od} \leq t\}$.

Consider two adjacent forwarding nodes with a distance of x, the link between these two nodes will break if the two nodes travel to opposite direction for a total distance of $1 - x$. The time needed to travel this distance, t, is easily computed by

$$t = \frac{1 - x}{r - s}. \tag{2}$$

Note that $r - s$ is the total travel speed per unit time (s is negative, hence the $r - s$). With simple arithmetic, we have the relation of x, the distance between the two nodes, with the speeds of the nodes and the time needed to break the link

$$x = 1 - t(r - s). \tag{3}$$

Assuming r and s, we can integrate the density function of x in (1)[1] from 0 to $1 - t(r - s)$ to yield the cumulative probability that the link will not break on time less than t: $\int_0^{1-t(r-s)} 4x^3\, dx$. This equation is easily explained from another perspective: given a time t and the speeds r and s, $1 - t(r - s)$ is the exact distance traveled where the link will break at time t; the integration starts at zero as with zero distance, the link will not break. Unconditioning on r and s, we have the CCDF

$$\begin{aligned} Pr\{T_{od} > t\} &= \int_0^m \int_{-m}^0 \int_0^{1-t(r-s)} \frac{4x^3}{m^2}\, dx\, ds\, dr \\ &= \int_0^m \int_{-m}^0 \frac{\left(\left[1 - t(r - s)\right]^+\right)^4}{m^2}\, ds\, dr. \end{aligned} \tag{4}$$

The definition of x^+ is given by

$$x^+ = \begin{cases} x, & \text{if } x > 0 \\ 0, & \text{otherwise.} \end{cases} \tag{5}$$

This condition is necessary as this probability measure contains samples that are not applicable to our case, which is when $t(r - s) > 1$. In derivation, we use a specific formula for each range of t, therefore, removing the unapplicable situations. For

[1] Note that here, we do not consider scenarios of the first and the last hops as they are handled separately in subsection III-C.

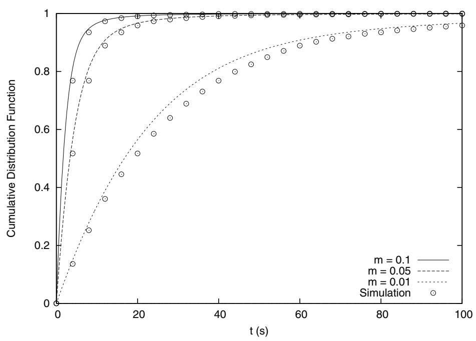

Fig. 3. CDF of connectivity period for two adjacent forwarding nodes moving to the opposite direction.

the range of $t > \frac{1}{m}$, we have

$$Pr\{T_{od} > t\} = \Bigg[\int_{-m}^{m-\frac{1}{t}} \int_{0}^{\frac{1}{t}+s} \frac{\big(1-t(r-s)\big)^4}{m^2}\, dr\, ds + \int_{m-\frac{1}{t}}^{0} \int_{0}^{m} \frac{\big(1-t(r-s)\big)^4}{m^2}\, dr\, ds\Bigg] = \frac{1}{30m^2t^2}, \tag{6}$$

The CCDF for $\frac{1}{2m} < t \leq \frac{1}{m}$ is given by

$$Pr\{T_{od} > t\} = \int_{-\frac{1}{t}}^{0} \int_{0}^{\frac{1}{t}+s} \frac{\big(1-t(r-s)\big)^4}{m^2}\, dr\, ds = \frac{1-2(1-mt)^6}{30m^2t^2}. \tag{7}$$

and for the range of $0 < t \leq \frac{1}{2m}$, we have

$$Pr\{T_{od} > t\} = \int_{-m}^{0} \int_{0}^{m} \frac{\big(1-t(r-s)\big)^4}{m^2}\, dr\, ds = \frac{(1-2mt)^6 - 2(1-mt)^6 + 1}{30m^2t^2}. \tag{8}$$

Combining (7)-(8), $Pr\{T_{od} \leq t\} = 1 - Pr\{T_{od} < t\}$, the connectivity period when two nodes move to opposite direction can be expressed in closed form as

$$Pr\{T_{od} \leq t\} = \begin{cases} 1 - \dfrac{1}{30m^2t^2}, & \text{for } t > \dfrac{1}{m} \\ 1 - \dfrac{1-2(1-mt)^6}{30m^2t^2}, & \text{for } \dfrac{1}{2m} < t \leq \dfrac{1}{m} \\ 1 - \dfrac{(1-2mt)^6 - 2(1-mt)^6 + 1}{30m^2t^2}, & \text{for } 0 < t \leq \dfrac{1}{2m} \\ 0, & \text{otherwise.} \end{cases} \tag{9}$$

In Fig. 3, we show the link connectivity period distribution, comparing the analytical and the simulation results. The simulation results are close to the analytical results; hence, verifying the accuracy of our analysis. We see that for normalized m of 0.1/s, 90% of the links are broken before 6s. If for example we have a transmission range of 200m, this scenario corresponds to two nodes (or two vehicles) moving to the opposite direction with a maximum speed of 20m/s or 72km/hour. With m of 0.05/s, which corresponds to a maximum speed of 10m/s or 36km/hour in the previous example, 90% of the links are broken before 12s. We observe that the link cannot be maintained for long in these scenarios, which is a typical transportation network scenario. With $m = 0.01$, it takes 60s for 90% of the links to break. This scenario corresponds to a maximum speed of 2m/s or 7.2km/hour with a transmission range of 200m.

B. Nodes moving to the same direction

The approach for nodes moving to the same direction is similar with that in the previous subsection. As described in section II, here we will consider only the case where the node in front is moving faster, which has higher probability to break the source to destination route before the reverse case. This is because the end-to-end connectivity is broken as soon as the first link in the path broke. We restrict our study to the cases where the link is the *weakest* i.e. has higher probability to break before the other links.

As shown in Fig. 2e and f, there are two possible directions the nodes can move to. These two cases are symmetric; we can compute the CCDF for each direction, $Pr\{T_{sd} > t\}$, by

$$Pr\{T_{sd} > t\} = \int_{0}^{m} \int_{0}^{r} \int_{0}^{1-t(r-s)} \frac{4x^3}{\frac{1}{2}m^2}\, dx\, ds\, dr = 2\int_{0}^{m} \int_{0}^{r} \frac{\Big(\big[1-t(r-s)\big]^+\Big)^4}{m^2}\, ds\, dr, \tag{10}$$

where $1 - t(r-s)$ is the distance traveled to break the link, which have been described in previous subsection by (3). We purposefully omit the cases where the node in front is not faster than the node behind from the integration; hence, the limit of the inner integration ends at r.

We now derive the CCDF for each specific range of t to remove the x^+ operator, hence deriving a simple closed form formulas. For the range of $t \leq \frac{1}{m}$, we have

$$Pr\{T_{sd} > t\} = 2\int_{0}^{m} \int_{0}^{r} \frac{\big(1-t(r-s)\big)^4}{m^2}\, ds\, dr = \frac{2}{30m^2t^2}\big[6mt + (1-mt)^6 - 1\big], \tag{11}$$

and the CCDF for $t > \frac{1}{m}$ is given by

$$Pr\{T_{sd} > t\} = 2\Bigg[\int_{0}^{\frac{1}{t}} \int_{0}^{r} \frac{\big(1-t(r-s)\big)^4}{m^2}\, ds\, dr + \int_{\frac{1}{t}}^{m} \int_{r-\frac{1}{t}}^{r} \frac{\big(1-t(r-s)\big)^4}{m^2}\, ds\, dr\Bigg] = \frac{2}{5mt} - \frac{1}{15m^2t^2}. \tag{12}$$

Similar with the previous subsection, the CDF, $Pr\{T_{sd} \leq$

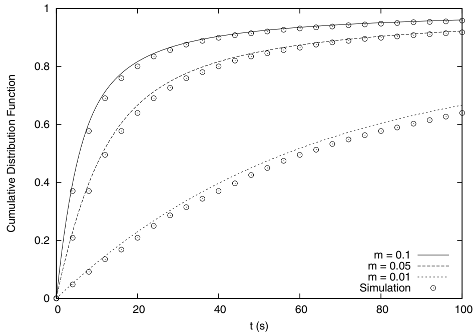

Fig. 4. CDF of connectivity period for two adjacent forwarding nodes moving to the same direction.

$t\}$, is derived from the CCDF in (11) and (12)

$$Pr\{T_{sd} \leq t\} = \begin{cases} 1 - \left(\frac{2}{5mt} - \frac{1}{15m^2t^2}\right), \text{ for } t > \frac{1}{m} \\ 1 - \frac{2}{30m^2t^2}\left[6mt + (1-mt)^6 - 1\right], \\ \qquad\qquad\qquad\qquad \text{for } 0 < t \leq \frac{1}{m} \\ 0, \qquad\qquad\qquad\qquad \text{otherwise.} \end{cases} \tag{13}$$

Fig. 4 shows the connectivity period distribution of two nodes moving to the same direction, comparing the analytical and the simulation results. In this scenario, the analytical results also provide a good match to the simulation results. Using a similar scenario as before, setting the transmission range to 200m, we see that some of the links can be maintained for much longer compared with the case where the nodes are moving away from each other. These links can be maintained because of the speeds of the two adjacent nodes are similar, hence it takes much longer time to break the link. It takes 40s and 80s to break 90% of the links with m equals to 0.1/s (72km/hour) and 0.05/s (36km/hour) respectively. With slower speed, it takes more than 200s to break 90% of the links.

C. Node moving away from a stationary node

In this scenario, we have only one speed variable, r. The time when the link will break when the distance between the nodes is x can be computed by

$$t = \frac{1-x}{r}. \tag{14}$$

Thus, we have the equation relating the distance x to the time t and the speed r:

$$x = 1 - tr. \tag{15}$$

Assuming r, we can integrate the density function of x from 0 to $1 - tr$ to yield the cumulative probability that the link will not break on time less than t. Unconditioning on r, we have the CCDF

$$Pr\{T_s > t\} = \int_0^m \int_0^{1-tr} \frac{2x}{m}\, dx\, dr = \int_0^m \frac{\left(\left[1-tr\right]^+\right)^2}{m}\, dr. \tag{16}$$

For the range of $0 < t \leq \frac{1}{m}$, we have

$$Pr\{T_s > t\} = \int_0^m \frac{\left(\left[1-tr\right]^+\right)^2}{m}\, dr = \frac{\left(m^2t^2 - 3mt + 3\right)}{3}. \tag{17}$$

For the range of $t > \frac{1}{m}$, we have

$$Pr\{T_s > t\} = \int_0^{\frac{1}{t}} \frac{\left(\left[1-tr\right]^+\right)^2}{m}\, dr = \frac{1}{3mt}. \tag{18}$$

Having the CCDF, we can easily derive the CDF by

$$Pr\{T_s \leq t\} = \begin{cases} 1 - \frac{1}{3mt}, \qquad \text{for } t > \frac{1}{m} \\ 1 - \frac{1}{3}\left(m^2t^2 - 3mt + 3\right), \\ \qquad\qquad\qquad \text{for } 0 < t \leq \frac{1}{m} \\ 0, \qquad\qquad\qquad \text{otherwise.} \end{cases} \tag{19}$$

IV. Distribution of the Source to Destination Connectivity Period

In this section, we consider the connectivity period of the end-to-end route from a source to a destination. To derive the distribution of the end-to-end connectivity period, we need to account all the possible combinations of the nodes' motion.

Let k_n denotes the direction of the n-th node in the sequence of forwarding nodes that form a route from the source to the destination. Let $\mathbf{V}_h$ denotes a vector with h components, $\{k_1, k_2, \ldots k_h\}$. This vector defines the motion of all the forwarding nodes in a 1D MANET (the vector does not contain the source and the destination, as they are stationary). Hence, if we have a source connected to a destination in five hops, the number of forwarding nodes h is equal to 4.

As discussed in section II, we have six possible combinations of the two nodes' motions. Now we define $\alpha_{\mathbf{V}_h}$ as the number of motion e and motion f in a scenario defined by $\mathbf{V}_h$. Similarly, define $\beta_{\mathbf{V}_h}$ as the number of motion c and $\gamma_{\mathbf{V}_h}$ as the number of motion a in the scenario $\mathbf{V}_h$. We assume that in motion b and motion d, the links will never break as these links will, with high probability, break after the links in the other motion scenarios break. The end-to-end connectivity period is mainly characterized by the motion scenarios which links break the fastest as when any of the link breaks, the whole route breaks; hence, the contribution of motion b, motion d, and the case in motion e and motion f where the node behind is faster to the connectivity period distribution is insignificant.

We can easily omit motion b and motion d from the final calculation, but we need a special treatment to remove the special case in motion e and motion f. When two nodes moving to the same direction with uniform speed distribution, the probability that one node is faster than the other is 0.5. The CCDF of the case where the two nodes are moving to the same direction, $Pr\{T_{ef} > t\}$ is then given by

$$Pr\{T_{ef} > t\} = 0.5 \cdot Pr\{T_{sd} > t\} + 0.5 \cdot 1, \tag{20}$$

$$Pr\{T_{s2d} \le t\} = 1 - \frac{\sum_{\forall \mathbf{V}_h} \left(Pr\{T_{ef} > t\}^{\alpha_{\mathbf{V}_h}} \cdot Pr\{T_{od} > t\}^{\beta_{\mathbf{V}_h}} \cdot Pr\{T_s > t\}^{\gamma_{\mathbf{V}_h}} \right)}{2^h}. \quad (21)$$

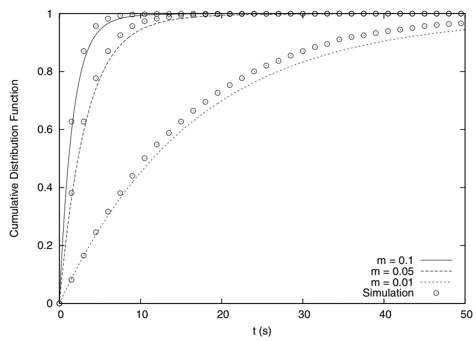

Fig. 5. CDF of end-to-end connectivity period for five hops route.

where $Pr\{T_{sd} > t\}$ is given in (11)-(12).

Having all the possible combinations of $\mathbf{V}_h$, The CDF of the end-to-end connectivity period is, then, can be computed by (21), where 2^h is the number of possible combinations of $\mathbf{V}_h$. The CCDF $Pr\{T_{ef} > t\}$ is given in (20), $Pr\{T_{od} > t\}$ is computed by (7)-(8), and $Pr\{T_s > t\}$ is given by (17)-(18).

The variables $\alpha_{\mathbf{V}_h}$, $\beta_{\mathbf{V}_h}$, and $\gamma_{\mathbf{V}_h}$ are calculated using recursive operations. Consider a vector, $\mathbf{V}_h$, with components $\{k_1, k_2, \ldots, k_{h-1}, k_h\}$; the last two components of the vector determines the motion scenario for the last hop. Let 0 and 1 mean that the node is moving to the right and to the left respectively[2]. With this definition, $k_{h-1} = 1$ and $k_h = 0$ describe motion c in Fig. 2c, and $k_{h-1} = k_h$ describe either motion e or motion f. As the source and destination nodes are omitted from $\mathbf{V}_h$, k_1 and k_h characterize the first and the last hop respectively.

The formulas to compute $\alpha_{\mathbf{V}_h}$ are $\alpha_{\mathbf{V}_1} = 0$ and

$$\alpha_{\mathbf{V}_h} = \begin{cases} \alpha_{\mathbf{V}_{h-1}} + 1, & \text{if } k_{h-1} = k_h \\ \alpha_{\mathbf{V}_{h-1}}, & \text{otherwise.} \end{cases} \quad (22)$$

To compute $\beta_{\mathbf{V}_h}$, we have $\beta_{\mathbf{V}_1} = 0$ and

$$\beta_{\mathbf{V}_h} = \begin{cases} \beta_{\mathbf{V}_{h-1}} + 1, & \text{if } k_{h-1} = 1 \text{ and } k_h = 0 \\ \beta_{\mathbf{V}_{h-1}}, & \text{otherwise.} \end{cases} \quad (23)$$

Finally, we compute $\gamma_{\mathbf{V}_h}$ by $\gamma_{\mathbf{V}_1} = 1$ and

$$\gamma_{\mathbf{V}_h} = \begin{cases} 0, & \text{if } k_1 = 1 \text{ and } k_h = 0 \\ 2, & \text{if } k_1 = 0 \text{ and } k_h = 1 \\ 1, & \text{otherwise.} \end{cases} \quad (24)$$

Given the distance between the source and the destination, d, using (1) which indicates the link distance between two forwarding nodes, we can compute the mean number of hops for the established route between the source and the destination. We show the distribution of end-to-end connectivity period for five hops route in Fig. 5. The figure shows close match between the simulation results and the analytical results, which proves that our approximation does not cause perceptible error. For this scenario, we assume a transmission range of 200m and source is transmitting to a destination that is five hops away. With m of 0.1/s (72km/hour), 90% of the links will break after 3.5s; for $m = 0.05$/s (36km/hour), it takes 7s for 90% of the links to break. With slower speed of 7.2km/hour), it takes 35s to break 90% of the links.

[2]We use left and right for easy notations to describe the two possible directions in a 1D MANET (note that the considered network might not form a straight line).

V. Conclusion

In this paper, we characterize the connectivity period of the route from a source to a destination in 1D MANETs, which implements a reactive routing protocol. We derived the CDF of the connectivity period of each link that connects two adjacent forwarding nodes, as well as the end-to-end connectivity period. We observe that with high mobility nodes, most of the end-to-end routes can only be maintained for few seconds. This result suggests that for high mobility scenarios, each source should maintain more than one active route to reduce the route discovery overhead. Another possibility for vehicular scenarios is to employ better antenna system, which can increase the transmission range of the nodes for higher route reliability.

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