On Residual Path Lifetime in Mobile Networks

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***Abstract*—In this letter, we investigate the residual link lifetime (RLL) in a mobile ad hoc network, such as a vehicular network. Although, owing to the underlying mobility of the network nodes, the RLLs of adjacent links are highly correlated, yet previous works typically neglected such correlation. In contrast, our study is based on an accurate modeling of the relative distances and speeds between neighboring mobile nodes. Firstly, a scenario is presented that demonstrates the dependence of RLLs of two adjacent links. We then derive the joint probability distribution of the RLLs of two adjacent links in terms of their parameters. Our model shows that neglecting the correlation between adjacent links results in serious overestimation of the path's lifetime. Simulation is used to verify our model.**

***Index Terms*—MANET, residual link lifetime, link lifetime prediction, path lifetime prediction.**

I. Introduction

In MOBILE Ad Hoc Networks (MANETs), such as Vehicular Networks ([17]) and Connected Vehicles ([18]), multi-hop paths are created from sequences of constituent links. The goal of routing algorithms in MANET is to discover routes (i.e., paths), which are preferably stable enough to carry an anticipated exchange of information. However, due to mobility of the nodes, the status of the links is constantly changing; some links break, while new links are established. Thus, for long enough communication, such as a session of streaming traffic, there is a high likelihood that some of the links of a path fail, and the path becomes unusable. In such situations, new path needs to be proactively discovered. As path discovery is not instantaneous, predicting the residual path lifetime (RPL) ([1]) allows the algorithm to plan ahead of time and to discover the next usable path in time before the current path breaks, so that communication continuity could be supported. Inaccurate RPL prediction tends to degrade the effectiveness of this process. Underestimation of RPL results in engaging the path discovery algorithm too soon and, thus, not utilizing the full paths' lifetime potential. Furthermore, it also results in the unnecessary overhead of engaging the algorithm too frequently. Overestimation of RPL results in engaging the path discovery algorithm too late and, thus, causing route interruptions (i.e., periods of no end-to-end connectivity). Thus accurate RPL prediction is important for an effective MANET operation. Indeed, numerous research efforts in MANET routing protocols have focused on reliable path evaluation ([1], [4], [5], [9], [10], [11]).

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Intuitively, path lifetime should be estimated on the basis of constituent links' lifetimes. Therefore, after a path is established, Residual (or remaining) Link Lifetime (RLL) ([2]) is introduced as a significant metric to capture or predict the remaining availability of the path.

A number of published works have investigated the link lifetime estimation with different parameters involved in the prediction ([2], [3], [12], [13], [15]). In [3], relative distance between connected nodes is sampled periodically to determine a projected trajectory, which is then used to calculate expected RLL based on a proposed method defined as Mobile-Projected Trajectory (MPT) algorithm. In [2], a new algorithm for RLL prediction is presented with Unscented Kalman Filter (UKF) being employed, in which periodically sampled relative distance between two nodes of a link is also taken into account as the main estimation parameter.

Examining statistical properties of RLL has been focused in the literature ([1], [6], [7]) and plays an important role, nowadays, in providing more appropriate criterions for realistic link and path reliability evaluation ([5], [9], [14]). In [7], further conclusion was validated based on [6], where path lifetime is given as a function of the sum of the inverses of expected links' lifetimes along the path. However, mutual independence of links' RLL is assumed, which is not accurate, since, intuitively, adjacent links' RLLs depend on each other due to the common nodes shared by these links. In [1], the independence assumption is relaxed to a milder requirement that as the hop distance between links increases, dependence of links' RLL will decrease asymptotically. Although the so called "mixing condition" in [1] provides a more general metric for the link and path duration prediction, the statistical estimation is still limited to cases where a path features large number of long hops. In [5], the *Probability Density Function (pdf)* of Link Residual Life and Path Duration are formulated in a detailed analytical model with the typical simplifying assumption that all nodes are assigned with a same constant velocity, which, however, generating a great limitation realistically and indicating a degraded dependence between neighboring links' RLL. [9] and [14], practically, aim at extending link or path duration prediction in VANETs and airborne networks respectively, whereas similar assumptions and limitations appear in theoretical analysis. RLL dependence is highlighted in [8] and is considered in mean path duration estimation through piecewise deterministic Markov process (PDMP) modeling. However, the assumption of discrete sets of node mobility vectors (velocities and directions) has to be made for numerical analysis.

In this letter, the correlation between neighboring links' residual lifetime is fully investigated. A formulation process is proposed to quantify the joint probability density function of RLLs in terms of two adjacent links. Contrary to the existing methods (e.g., [1], [6], [7]), the formulating process does not neglect the dependence between neighboring links' RLLs, which is particularly meaningful when the links are short. In particular, the formulation proposed here avoids the assumptions mentioned above, which, therefore, can be applied

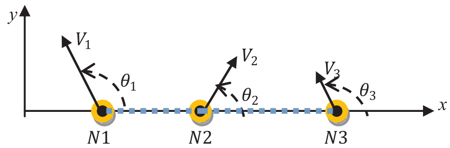

Fig. 1. A simple three-node model.

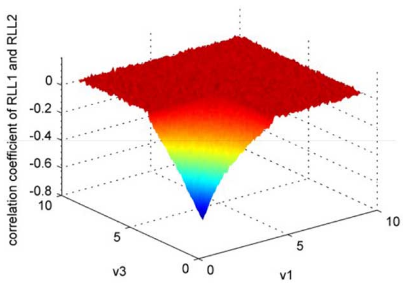

Fig. 2. ρ_{RLL_1,RLL_2} for the three nodes moving independently.

in more general scenarios and for paths with small number of short hops.

The rest of the letter is organized as follows. Section II demonstrates the importance of the neighboring links' dependence for RLL analysis. In Section III, we propose a formulation process to quantify the joint probability density function of two neighboring links' RLLs. Comparison of the formulation with simulation results is provided in Section IV to demonstrate the accuracy of the formulation. Finally, Section V concludes the letter.

II. Correlation of RLLs of Neighboring Links

To demonstrate the effect of correlation on RLLs of adjacent links, we consider here a simple example in Fig. 1 of three mobile nodes, N1, N2, and N3, which create two links, N1-to-N2 (*link 1*) and N2-to-N3 (*link 2*). The underlying mobility model is general, allowing a node i to move with any velocity, V_i, and direction θ_i.

We assume the *protocol model* [16], in which a link between two nodes exists if the distance between the two nodes is smaller than some critical radius, *R,* and we define the *residual link lifetime* (RLL) of a link as the remaining time until the link ceases to exist for the first time. (However, we note that, by expressing a relationship between any reception condition and *R,* our results can be easily expressed as a function of any such a reception condition, rather than *R.*) Throughout this letter, all distances are in units of meters and speed in units of m/sec. The initial distance between the nodes N1 and N2 is 20 and between N2 to N3 is 10. Node N2 moves with constant velocity $V_2 = 5$ and with uniformly distributed angle ($\theta_2 \sim U\,(0, 2\pi)$). The velocities of nodes N1 and N3 are independent with $V_1, V_3 \in [1, 10]$ and $\theta_1, \theta_3 \sim U\,(0, 2\pi)$. The maximal transmission range is assumed to be $R = 500$.

For sample values of V_1, V_3 and $\theta_1, \theta_2, \theta_3$, chosen randomly and independently, the simulation is repeated 10,000 times and the RLL values of link 1 and link 2, RLL_1 and RLL_2, respectively, are measured. Then, the correlation $\rho_{RLL_1,RLL_2} = \frac{Cov(RLL_1,RLL_2)}{\sqrt{Var(RLL_1)\cdot Var(RLL_2)}}$ is calculated. Fig. 2 shows the results. As shown in the graph, even when the nodes of the two adjacent links move independently, there is still a sizeable correlation between the two RLLs, especially when the velocities of all the three nodes are comparable and small.

This simple example demonstrates the importance of taking into consideration the correlation of the RLLs in prediction of the overall residual path lifetime.

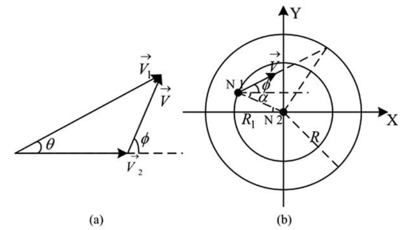

Fig. 3. The mobility model.

III. Joint PDF of RLLs of Two Neighboring Links

The goal of this letter is to derive a formula for the joint *pdf* of the links' RLL, taking into the consideration the dependence between adjacent links. We emphasize that, contrary to the algorithm proposed in [1], we do not limit our derivation to cases of large number of hops and long hop distance.

We first derive the formula for the RLL of the link between N1 and N2. Figs. 3(a) and (b) illustrate the basic mobility model of the two nodes. The coordinate system is fixed on N2, with the x-axis parallel to direction of $\overrightarrow{V_2}$. We assume that the RLLs estimation is performed at time $t = 0$ and we assume that during the RLL estimation, both $\overrightarrow{V_1}$ an $\overrightarrow{V_2}$ dremain constant. At $t = 0$,node N1 is at the distance $R_1 (R_1 < R)$ and at the angle $\alpha (\alpha \sim U\,(0, 2\pi))$ from the origin (note that α is measured clockwise from the negative X-axis). Assume that at time t_1 the distance between N1 and N2 is greater than R, so that the link between the two nodes breaks. Then, $RLL_1 = t_1$.

At time $t = 0$,the value of the velocity $\overrightarrow{V_1}$is randomly distributed $(V_1 \sim U\,(V_{min}, V_{max}),\ 0 \le V_{min} \le V_{max})$. So, we label $V_d = V_{max} - V_{min}$ and the *pdf* of V_1 as $f_{V_1}(v_1) = 1/V_d, V_{min} \le v_1 \le V_{max}$. Furthermore, the angle of $\overrightarrow{V_1}$ is labeled as θ, where $\theta \sim U\,(-\pi, \pi)$, $f_\theta\,(\vartheta) = 1/2\pi$. Since the speed and the angle of $\overrightarrow{V_1}$are independent:

$$f_{V_1,\theta}\left(v_1, \vartheta\right) = 1/2\pi V_d,\ V_{min} \le v_1 \le V_{max}. \tag{1}$$

We label as the relative speed between $\overrightarrow{V_1}$ and $\overrightarrow{V_2}$ and denote as the angle between $\vec{V}$ and x-axis, $\phi \in (-\pi, \pi)$.

$$\vec{V} = \overrightarrow{V_1} - \overrightarrow{V_2};\ V = \left|\overrightarrow{V_1}\right| = \sqrt{V_1^2 + V_2^2 - 2V_1V_2cos\theta} \tag{2}$$

The values of V_1, V_2, θ determine ϕ. Four cases need to be considered:

Case 1: If $(\theta \epsilon [0, \pi)) \cap (V_1cos\theta - V_2 > 0)$ then

$$0 \le \phi < \frac{\pi}{2};\ \phi = arctan\left(\frac{V_1sin\theta}{V_1cos\theta - V_2}\right) \tag{3}$$

Case 2: If $(\theta \epsilon [0, \pi)) \cap (V_1cos\theta - V_2 \le 0)$ then

$$\frac{\pi}{2} \le \phi < \pi;\ \phi = \pi + arctan\left(\frac{V_1sin\theta}{V_1cos\theta - V_2}\right) \tag{4}$$

Case 3: If $(\theta \epsilon [-\pi, 0)) \cap (V_1cos\theta - V_2 > 0)$ then

$$-\frac{\pi}{2} < \phi < 0;\ \phi = arctan\left(\frac{V_1sin\theta}{V_1cos\theta - V_2}\right) \tag{5}$$

***Case 4*:** If $(\theta\epsilon[-\pi,0))\cap(V_1cos\theta-V_2\leq 0)$ then

$$-\pi\leq\phi\leq-\frac{\pi}{2};\phi=-\pi+arctan\left(\frac{V_1sin\theta}{V_1cos\theta-V_2}\right)\qquad(6)$$

Next, we derive $f_{V,\phi|V_2(v,\varphi|v_2)}$ from $f_{V_1,\theta|V_2}(v_1,\vartheta|\,V_2)$. Firstly, relations between these two probability density functions are given as follows:

$$f_{V,\phi|V_2(v,\varphi|v_2)}=\frac{f_{V_1,\theta|V_2}(v_1,\vartheta|\,v_2)}{J}=\frac{f_{V_1,\theta}(v_1,\vartheta)}{J};\qquad(7)$$

since V_1 and θ are independent of V_2, and where

$$J=\begin{vmatrix}\frac{\partial v}{\partial v_1} & \frac{\partial v}{\partial\vartheta}\\ \frac{\partial\varphi}{\partial v_1} & \frac{\partial\varphi}{\partial\vartheta}\end{vmatrix}.$$

Next, we calculate the Jacobian as

$$\frac{\partial v}{\partial v_1}=\frac{v_1-v_1cos\vartheta}{\sqrt{v_1^2+v_2^2-2v_1v_2cos\vartheta}};\ \frac{\partial v}{\partial\vartheta}=\frac{v_1v_2sin\vartheta}{\sqrt{v_1^2+v_2^2-2v_1v_2cos\vartheta}}$$

$$\frac{\partial\varphi}{\partial v_1}=\frac{-v_2sin\vartheta}{\sqrt{v_1^2+v_2^2-2v_1v_2cos\vartheta}};\ \frac{\partial\varphi}{\partial\vartheta}=\frac{v_1^2-v_1v_2cos\vartheta}{\sqrt{v_1^2+v_2^2-2v_1v_2cos\vartheta}}$$

$$J=\frac{v_1}{\sqrt{v_1^2+v_2^2-2v_1v_2cos\vartheta}}=\frac{v_1}{v}=\frac{\sqrt{v^2+v_2^2+2vv_2cos\varphi}}{v}$$

Thus we get:

$$f_{V,\phi|V_2(v,\varphi|v_2)}=\frac{v}{2\pi V_d\sqrt{v^2+v_2^2+2vv_2cos\varphi}}.\qquad(8)$$

As defined before α, represents the original direction of Node 1 relative to Node 2 (as shown in Fig. 3(b)). Furthermore, as indicated before, α is uniformly distributed and is independent of $\overrightarrow{V_2}$, $\overrightarrow{V}$, and ϕ. Thus, we have:

$$f_\alpha(\alpha)=\frac{1}{2\pi}=f_{\alpha|V_2}(\alpha|\,v_2),\quad 0\leq\alpha\leq 2\pi\qquad(9)$$

$$f_{\alpha,V,\phi|V_2}(\alpha,v,\varphi|\,v_2)=f_{\alpha|V_2}(\alpha|\,v_2)\cdot f_{V,\phi|V_2}(v,\varphi|\,v_2)$$
$$=\frac{v}{4\pi^2V_d\sqrt{v^2+v_2^2+2vv_2cos\varphi}}\qquad(10)$$

According to Fig. 3(b),

$$RLL_1=\frac{R_1cos(\phi+\alpha)+\sqrt{R^2-R_1^2sin^2(\phi+\alpha)}}{V}\qquad(11)$$

Assuming, without loss of generality, that $\alpha=0$,

$$RLL_1=\frac{R_1cos(\phi)+\sqrt{R^2-R_1^2sin^2(\phi)}}{V}\qquad(12)$$

$$F_{RLL_1|V_2}(\tau_1|\,v_2)=P(RLL_1\leq\tau_1|\,V_2)$$
$$=P\left(\frac{R_1cos(\phi)+\sqrt{R^2-R_1^2sin^2(\phi)}}{V}\leq\tau_1|\,V_2\right)$$
$$=P\left(V\geq\frac{R_1cos(\phi)+\sqrt{R^2-R_1^2sin^2(\phi)}}{\tau_1}\middle|\,V_2\right)\qquad(13)$$
$$=\int_{-\pi}^{\pi}\int_{\frac{R_1cos(\phi)+\sqrt{R^2-R_1^2sin^2(\phi)}}{\tau_1}}^{v_2+V_{max}}f_{V,\phi|V_2}(v,\varphi|\,v_2)\,dvd\varphi$$
$$=\int_{-\pi}^{\pi}\int_{\frac{R_1cos(\phi)+\sqrt{R^2-R_1^2sin^2(\phi)}}{\tau_1}}^{v_2+V_{max}}\frac{v}{2\pi V_d\sqrt{v^2+v_2^2+2vv_2cos\varphi}}dvd\varphi$$

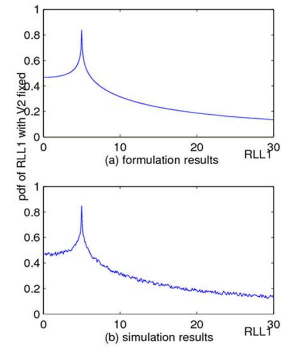

Fig. 4. Comparison of formulation with simulation results for eq. (15).

$$f_{RLL_1|V_2}(\tau_1|\,v_2)=\frac{dF_{RLL_1|V_2}(\tau_1|\,v_2)}{d\tau_1}=$$
$$\frac{d}{d\tau_1}\int_{-\pi}^{\pi}\int_{\frac{R_1cos(\phi)+\sqrt{R^2-R_1^2sin^2(\phi)}}{\tau_1}}^{v_2+V_{max}}\frac{v}{2\pi V_d\sqrt{v^2+v_2^2+2vv_2cos\varphi}}dvd\varphi\qquad(14)$$
$$\int_{-\pi}^{\pi}\frac{d}{d\tau_1}\left(\int_{\frac{R_1cos(\phi)+\sqrt{R^2-R_1^2sin^2(\phi)}}{\tau_1}}^{v_2+V_{max}}\frac{v}{2\pi V_d\sqrt{v^2+v_2^2+2vv_2cos\varphi}}dv\right)d\varphi$$

Next, we use the Leibniz integral rule on (14) to obtain:

$$f_{RLL_1|V_2}(\tau_1|\,v_2)=$$
$$\int_{-\pi}^{\pi}\frac{\left(R_1cos\varphi+\sqrt{R^2-R_1^2sin^2\varphi}\right)^2}{2\pi V_d\tau_1^2\sqrt{\left(R_1cos\varphi+\sqrt{R^2-R_1^2sin^2\varphi}\right)^2+v_2^2\tau_1^2+2v_2\tau_1cos\varphi\left(R_1cos\varphi+\sqrt{R^2-R_1^2sin^2\varphi}\right)}}d\varphi\qquad(15)$$

Formulation of $f_{RLL_2|V_2}(\tau_1|\,v_2)$ can be derived by following the same process. Then, we obtain the joint *pdf* of RLL_1 and RLL_2 as:

$$f_{RLL_1,RLL_2|V_2}(\tau_1,\tau_2|\,v_2)=f_{RLL_1|V_2}(\tau_1|\,v_2)\cdot f_{RLL_2|V_2}(\tau_2|\,v_2).$$

Removing the condition, we obtain $f_{RLL_1,RLL_2}(\tau_1,\tau_2)$ as:

$$f_{RLL_1,RLL_2}(\tau_1,\tau_2)=\int_{V_{min}}^{V_{max}}f_{RLL_1,RLL_2|V_2}(\tau_1,\tau_2|\,v_2)\cdot f_{V_2}(v_2)dv_2\qquad(16)$$

IV. Simulation Results

We use numerical analysis to evaluate and compare equation (15) with simulation results of $f_{RLL_1|V_2}(\tau_1|\,v_2)$. Fig. 4 shows the comparison for $V_2=10$, $V_d=10$, $R_1=50$ and $R=100$, demonstrating, demonstrating excellent match between the formulation and the simulation results.

A. Further Discussion on Dependence of Neighboring Links' RLL

In this section, we evaluate the effect of correlation on the accuracy of residual path lifetime estimation. In other words, we evaluate the error in the residual path lifetime, if the formula

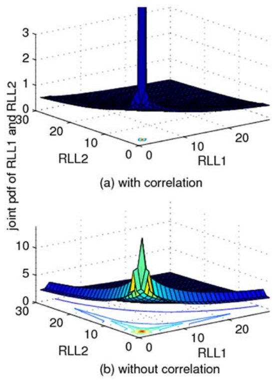

Fig. 5. Joint pdf of RLL_1 and RLL_2 ($R_1 = R_2 = 70$).

TABLE I
COMPARISON OF CDF VALUES

T	$P_1(RPL \geq T)$	$P_2(RPL \geq T)$
2	**0.79**	**0.95**
5	**0.71**	**0.87**
10	**0.62**	**0.75**
15	**0.49**	**0.69**
20	**0.25**	**0.40**

(16) is approximated by a formula that neglects the correlation between RLL_1 and RLL_2; i.e.,

$$f_{RLL_1,RLL_2}(\tau_1, \tau_2) = f_{RLL_1}(\tau_1) \cdot f_{RLL_2}(\tau_2) \tag{17}$$

As a representative comparison, we show in Fig. 5 the $f_{RLL_1,RLL_2}(\tau_1, \tau_2)$ for the case of $R_1 = R_2 = 70$. Evident from the figure is the difference in these two functions. The disparity increases as the values of R_1 and R_2 decrease. As a point of reference, we consider the values of the *pdf* $f_{RLL_1,RLL_2}(\tau_1, \tau_2)$ for $RLL_1 = 0$ and $RLL_2 = 30$. For $R_1 = R_2 = 80$, the value of the *pdf* based on (17) is nearly four times as large as the (accurate) value based on equation (16). For $R_1 = R_2 = 10$, the value of the *pdf* based on (17) is almost ten times as large as the (accurate) value based on equation (16).

Based on these and numerous other results that we have obtained, we conclude that especially for short links, the correlation between adjacent links must be taken into account in RLL evaluation in order to guarantee the accuracy of path lifetime prediction.

To further demonstrate the importance of the correlation, we compare the (complementary) *cdf* of the *Residual Path Lifetime (RPL)* for a selected set of values, as shown in Table I. In this example, the path is composed of two links, and we evaluate the probability that the path will remain up (i.e., both links are up) for time larger than *T,* where $T \in \{2, 5, 10, 15, 20\}$. In the table, $P_1(RPL \geq T)$ is evaluated using equation (16), while $P_2(RPL \geq T)$ is evaluated using equation (17). The results were obtained for $R = 100$, $R_1 = R_2 = 10$, $V_{min} = 5$, and $V_{max} = 15$.

As is clearly evident from the table, neglecting the correlation between the two links causes overestimation of the probability of the path's survival for all the values of T.

In summary, by disregarding the correlation between adjacent links on a path, the lifetime of a path is overestimated. Relying on an overestimated path lifetime would cause frequent path breakage, interrupting the end-to-end connectivity, and degrading the communication's QoS.

V. CONCLUSION

In this letter, we provided formulation of the statistical properties of the MANETs' links lifetime, while taking into consideration the dependence between adjacent links. The goal of this letter was to propose a model for evaluation of path availability without the simplifying assumptions adopted in previous works. First, through an example, we showed the significance of the dependence between neighboring links. Then, we derived a formula for the joint probability density function of two neighboring links' RLLs. Finally, based on the comparison of simulation and formulation results, the accuracy of the proposed scheme is demonstrated. Further, we evaluated, for an exemplary case, the error in the residual path lifetime as the result of ignoring the dependence of neighboring links.

Our results will allow more effective and efficient path selection protocols in MANET, leading to improved network quality of service.

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