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An Analytical Framework for The Charaterization of Link Dynamics in MANETs

Invited Paper

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Abstract— We present an analytical framework and statistical models to accurately characterize the lifetime of a wireless link in a mobile ad hoc network (MANET). We show that the lifetime of a link can be computed through a two-state Markov model and that the analytical solution follows closely the results obtained through discrete event simulations. The proposed framework has widespread application in the modeling of medium access control protocols, routing protocols, clustering, and the optimization of MANETs.

I. INTRODUCTION

Mobile wireless ad hoc network (MANET) has created intensive interests for its unique features of flexible deployment, autonomous network, and potential applications such as tactical deployment in the battlefield. Mobility brings opportunities to MANETs as well as creates challenges. Constant movements of nodes in MANETs result in a highly dynamic network topology. Meanwhile, communication links undergo frequent link breakages and protocol stacks of MANET need to adapt to this dynamic environment. In particular, clustering and routing algorithms are key to the success of MANET but an efficient design of them necessitate a thorough understanding of link behavior in MANETs.

Interestingly, as critical as the problem of characterizing link behavior is for the performance of the protocol stack of a MANET, no such analytical model exists to accurately characterize link lifetime as a function of node mobility, which is a defining attribute of MANETs! As a result, link behavior in MANETs has been analyzed mostly through simulations, and analytical modeling of channel access and routing protocols for MANETs have

not represented the temporal nature of MANET links accurately. For example, the few analytical models that have been developed for channel access protocols operating in multihop ad hoc networks have either assumed static topologies (e.g., [1]) or focused on the immediate neighborhood of a node, such that nodes remain neighbors for the duration of their exchanges (e.g., [2]). Similarly, most studies of routing-protocol performance have relied exclusively on simulations, or had to use limited models of link availability (e.g., [3]) to address the dynamics of paths impacting routing protocols (e.g., [4]).

This paper provides the most accurate analytical model of link behavior in MANETs to date, and characterizes link behaviors as a function of node mobility. The importance of this model is twofold. First, it enables investigation of many questions regarding fundamental tradeoffs in throughput, delay and storage requirements in MANETs, as well as the relationship between many protocol-design choices (e.g., packet length) and network dynamics (e.g., how long links last in a MANET). Second, it enables the development of analytical models for channel access, clustering and routing schemes operating in MANETs by allowing such models to use link lifetime expressions that are accurate with respect to simulations based on widely-used mobility models.

Recently, Samar and Wicker [5], [6] presented an analytical evaluation of link dynamics. They also provided an example of how an analytical formulation of link dynamics can be incorporated into the protocol design task. However, Samar and Wicker assume that communicating nodes maintain constant speed and direction in order to evaluate the distribution of link lifetime. This simplification overlooks the case in which either of the communicating nodes change speed or direction while the nodes are in transmission range of each other. As a result, the results predicted by Samar and Wicker's model can deviate from

reality greatly, being overly conservative and underestimating the distribution of link lifetime [5], [6], especially when the ratio R/v between the radius of the communication range R to the node speed v becomes large, such that nodes are likely to change their velocity and direction during an exchange.

The rest of the paper is organized as follows. Section II describes the network and mobility models that is used to characterize link behavior. Section III describes the proposed analytical framework and presents our results on link lifetime. We present a two-state Markovian model that precisely reflects the movements of nodes inside the circle of transmission range and builds an analytical framework to accurately evaluate the distribution of link lifetime. Simulation results are provided in section IV to illustrate the accuracy of our analytical model. Finally, section V provides our concluding remarks.

II. SYSTEM MODEL

We consider a square network consistent with several prior analytical models of MANETs [7], [8], [9], as depicted in Fig. 1. The entire network is of size $L \times L$ and there are n nodes initially randomly deployed in the square network.
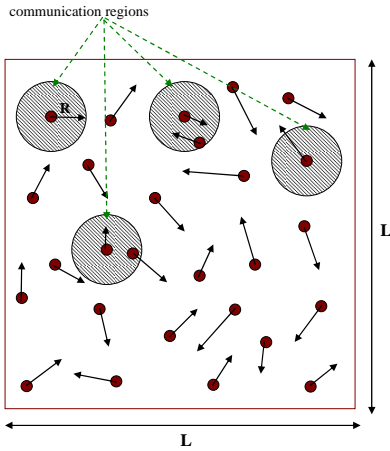

Fig. 1. Model of network structure

Nodes are mobile and initially equally distributed over the network. The movement of each node is unrestricted, i.e, the trajectories of nodes can be anywhere in the network. The model of node mobility in the network is the same as that used in prior work [10], [11], [12], which is also known as random direction mobility model (RDMM) [13], [14]. Node movement is independent and identically distributed (iid) and can be described by a continuous-time stochastic process. The continuous movement of nodes is divided into mobility epochs during which a node moves at constant velocity, i.e., fixed speed

and direction. But the speed and direction varies from epoch to epoch. The time duration of epochs is denoted by a random variable τ, assumed to be exponentially distributed with parameter λ_m. Its complementary cumulative distribution function (CCDF) $F_m(\tau)$ can be written as [12].

$$F_m(\tau) = exp(-\lambda_m \tau)$$

The direction during each epoch is assumed to be uniformly distributed over $[0, 2\pi)$ and the speed of each epoch is uniformly distributed over $[v_{min}, v_{max}]$, where v_{min}, v_{max} specify the minimum and maximum speed of nodes respectively. Speed, direction and epoch time are mutually uncorrelated and independent over epochs. Furthermore, when a node reaches the network boundary, the node is reflected back with respect to the normal edge of the network boundary and the speed is kept unchanged.

The stationary node distributions of the location and direction have been shown to be uniform for an arbitrary direction, speed and travel time distributions, irrespective of the boundaries being reflected or wrapped around [15]. The minimum speed v_{min} can be zero and it stands for the case where nodes can stop and rest for a while during movements.

Communication between nodes is allowed only when the distance between the two communicating nodes is less than R and can be performed reliably. The communication between any two nodes within that communication circle satisfies the minimum SNIR (signal to noise and interference ratio) requirement with certain outage probability in the wireless fading environment.

A typical communication session is illustrated in Fig. 2 and detailed here. Assume that a node m_a becomes active at time t_0. After being active, node m_a starts to detect beacon signals for a duration Δ_b. Because no active nodes except node m_a is inside the communication circle that is centered at node m_a with radius R, it detects no beacon signal. Clearly, the communication circle for node m_a moves as the node moves. At time $t_0 + \Delta_b$, node m_a starts to send out beacon signals with a period of δ_b ($< \Delta_b$) and waits for responses from other nodes. Suppose that another active node m_b enters the communication circle at time $t_1 > t_0 + \Delta_b$, while node m_a is still moving and sending out a beacon signal. Node m_b detects the beacon signal from node m_a within the time interval $(t_1, t_1 + \delta_b)$. After receiving the beacon signal, node m_b immediately sends out the IND-DATA signal to indicate its presence and readiness to start data communication. Assume that node m_a starts the data transfer (denoted by DATA) to node m_b at time t_2 ($> t_1$) after receiving the IND-DATA signal from node m_b. After node m_b successfully received

the data packet, it sends out the acknowledgment (ACK) to confirm reception of the packet or the data acknowledge response (ACK-DATA) when node m_b wants to confirm reception of the packet and the intention to transmit data to node m_a. When two or more nodes simultaneously enter into communication circle, a MAC layer protocol is required to resolve the potential contention. However, this is beyond the scope of this paper, and we only consider the case of communication sessions without collision.
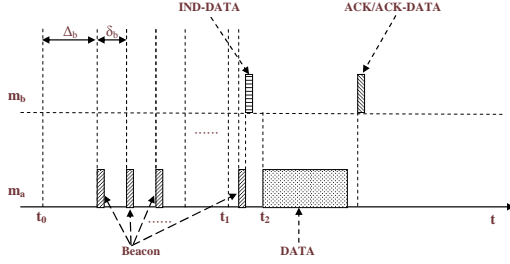

Fig. 2.   A typical communication session

III. LINK LIFETIME

A bidirectional link exists between two nodes if they are within communication range of each other. In this paper, we do not consider unidirectional links, given that the vast majority of channel access and routing protocols use only bidirectional links for their operation. Hence, we will refer to bidirectional links simply as links for the rest of this paper.

Using the example in Fig. 2, the link between nodes m_a and m_b is broken when the distance between node m_a and node m_b is greater than R or node m_b moves out of the communication circle for node m_a. When a data packet starts at time t_2, the positions of node m_b could be anywhere inside the communication circle. In general, their location should follow the stationary spatial distribution of the random direction mobility model and thus can be considered as uniformly distributed.

Let B ($bits/s$) be the transmission rate of a data packet, L_p be the length of the data packets, and t_2+T_L denote the moment that node m_b is moving out of the communication circle. A data packet can be successfully transferred only if nodes m_a and m_b stay inside their communication circle during the whole communication session of the data packet, that is,

$$L_p/B \ \leq \ T_L \tag{1}$$

where T_L is the link lifetime (LLT) denoting the maximum possible data transfer duration. Statistically, T_L specifies the distribution of residence time that measures

the duration of the time, for node m_b, starting from a random point inside the communication circle with equal probability, to continuously stay inside the communication circle before finally moving out of it. Furthermore, its (CCDF) is denoted by $F_L(t)$

$$F_L(t) = P(T_L \geq t) \tag{2}$$

The link outage probability P_{L_p} associated with a particular packet length L_p can be evaluated as

$$P_{L_p} = P(T_L \leq \frac{L_p}{B}) = 1 - F_L(\frac{L_p}{B}) \tag{3}$$

A. Distribution of Relative Velocity

Fig. 3 shows the transmission zone of a node (say node m_a) which is a circle of radius R centered at the node. The figure shows another node (say node m_b) starting DATA communication with node m_a at time t_2. As shown in the left side of the figure, at time t_2, node m_a is moving at speed v_a of direction θ_a while node m_b moves at speed v_b and direction θ_b.
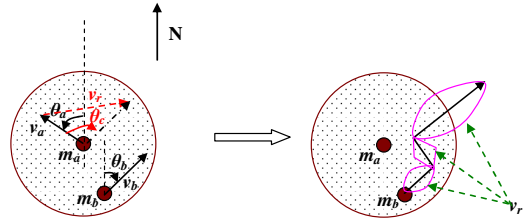
Fig. 3.   Graphical Illustration of Relative Velocity

Alternatively, if we consider node m_a as static, node m_b is then moving at their *relative speed* v_r and direction θ_c. An example of resulting trajectories of node m_b moving at relative velocity is given in the right side of Fig. 3. Recall that both θ_a and θ_b are uniformly distributed within $[0, 2\pi)$ and it can be concluded that composite direction $\theta_c = \theta_b - \theta_a$ is also uniformly distributed within $[0, 2\pi)$. And the relative speed v_r can be expressed as

$$v_r = \sqrt{v_a^2 + v_b^2 - 2v_a v_b \cos \theta_c} \tag{4}$$

Conditioning on v_a and v_b and noting the symmetric property of θ_c, the distribution of v_r can be computed as

$$p(v_r) = E_{\{v_a, v_b\}}(p(v_r|v_a, v_b)) \tag{5}$$

$$p(v_r|v_a, v_b) = p(\theta_c)|\frac{d\theta_c}{dv_r}|$$
$$= \frac{1}{\pi}|\frac{d}{dv_r}(arccos(\frac{v_a^2 + v_b^2 - v_r^2}{2v_a v_b}))|$$
$$= \begin{cases} g(v_r, v_a, v_b), & |v_a - v_b| \leq v_r \leq v_a + v_b \\ 0, & others \end{cases} \tag{6}$$

where $g(x,y,z) = \frac{2}{\pi}\frac{x}{\sqrt{2(x^2y^2+x^2z^2+y^2z^2)-x^4-y^4-z^4}}$.

In particular, if both nodes move at the same speed $v = v_a = v_b$, we will have

$$p(v_r|v) = \begin{cases} \frac{2}{\pi}\frac{1}{\sqrt{4v^2-v_r^2}}, & v_r \in [0, 2v] \\ 0, & others \end{cases} \quad (7)$$

B. Distribution of Link Lifetime (LLT)

The essence of modeling link dynamics in MANETs consists of evaluating the distribution of LLT, because it reflects the link dynamics resulting from the motions of nodes. LLT measures the duration of time for a node to continuously stay inside the communication range of another node. In our model, this range is a circle.

Clearly, different mobility models and parameters lead to different LLT distributions, and the main challenge in modeling LLT consist of making the problem tractable and relevant. In the RDMM model, we assume that the direction of the node is uniformly distributed within $[0, 2\pi)$ at the moment when a data packet starts (e.g., t_2), and node m_a (or m_b) will keep moving in the same direction for a time duration of τ_a (or τ_b), where the duration τ_a (or τ_b) is exponentially distributed with parameter λ_m. Let $\tau = \min\{\tau_a, \tau_b\}$, which implies that the relative velocity v_r will change at the end of τ. Its CCDF $F_m(\tau)$ can then be described as

$$F_m(\tau) = exp(-2\lambda_m\tau) \quad (8)$$

We also know that the relative movement of nodes consists of a sequence of mobility epochs. Let A_s be the starting point of the current mobility epoch and its position be uniformly distributed over the communication circle. The end point of the current epoch is denoted by A_d, and A_d may be anywhere in the cell, i.e., inside or out of the communication circle. In the case that A_d is located inside the communication circle, it serves as the starting point (i.e., new A_s) for the next epoch and the whole process is repeated. In the evaluation of LLT, the repeating procedure ends when the final A_d is out of the communication circle.

As illustrated in Fig. 4, the procedure for evaluating the LLT can be modeled as a two-state Markovian process. The residence state S_0 represents the scenario where the end point A_d of current epoch is located inside the communication circle, while the departing state S_1 refers to the complementary scenario where A_d will be out of communication circle. Compared to the model by Samar and Wicker [5], [6], in which only the last scenario (i.e., state S_1) is considered, the two-state Markovian model reflects the motion of nodes more accurately, which leads to better results in evaluating link dynamics.
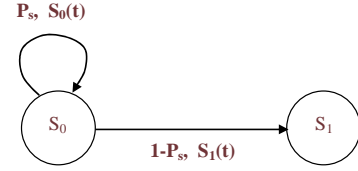
Fig. 4. Two-state Markovian model for LLT evaluation

Let P_s be the *residence probability*, which denotes the probability that A_d is located inside the communication circle of A_s. The probability distribution function (PDF) $S_0(t)$ specifies the distribution of sojourn time of mobility epochs when a node stays in state S_0. Correspondingly, the PDF $S_1(t)$ is used to measure the distribution of departing times when nodes move out of communication circles and switch to the state S_1.

Before eventually moving out of the communication circle, i.e., being switched to the departing state S_1, nodes may stay at the residence state S_0 multiple times. Let N_i be the integer variable counting the number of times for a node to remain in state S_0, and $\{S_{0,0}, \ldots, S_{0,N_i-1}\}$ be the associated random variables that specify the duration of time of mobility epochs for each return.

Clearly, $\{S_{0,0}, \ldots, S_{0,N_i-1}\}$ are random variables of the same distribution but correlated. However, to make our problem more tractable, we assume that $\{S_{0,0}, \ldots, S_{0,N_i-1}\}$ are statistically i.i.d random variables of distribution $S_0(t)$. Our simplifying assumption makes the final result slightly deviated from the real situation when the residence probability becomes larger. However, as we will see later, our model still provides a good approximation, even with a large residence probability.

We define S_1 as the random variable measuring the departing time of distribution $S_1(t)$. We can evaluate conditional link life time $T_L(N_i)$ and $P(N_i = K)$ as

$$T_L(N_i) = \sum_{i=0}^{N_i-1} S_{0,i} + S_1 \quad (9)$$

$$P(N_i = K) = P_s^K \quad (10)$$

The characteristic function $U_{T_L}(\theta)$ for the LLT T_L can now be evaluated as

$$\begin{aligned} U_{T_L}(\theta) &= E(e^{j\theta T_L}) \\ &= \sum_{k=0}^{\infty} E(e^{j\theta(\sum_{i=0}^{k-1} S_{0,i}+S_1)})P(N_i = k) \\ &= \sum_{k=0}^{\infty} U_1(\theta)U_0(\theta)^k P_s^k \end{aligned}$$

$$= \frac{U_1(\theta)}{1 - U_0(\theta)P_s} \tag{11}$$

where $U_0(\theta)$ and $U_1(\theta)$ are the characteristic functions of $S_0(t)$ and $S_1(t)$, respectively.

When the communication circle is small with respect to the network size and nodes' speed, A_d will be mostly located out of the communication circle of A_s. Consequently, we have $P_s \ll 1$. Given that $U_0(\theta)$ is the characteristic function of $S_0(t)$, one has $|U_0(\theta)| \leq 1$. Finally, it is clear that $|U_0(\theta)P_s| \ll 1$. Therefore, Eq. (11) can be approximated as

$$U_{T_L}(\theta) \approx U_1(\theta) \tag{12}$$

For clarification purposes, we call Eq. (11) as the Exact LLT (ES-LLT), which is based on the two-state Markovian model. The approximation in Eq. (12) is called Approximated LLT (AS-LLT), and it reflects the scenario considered by Samar and Wicker [5], [6]. As we will see later, the analytical expression for AS-LLT is the same as the expression in [5], [6], except for a normalization factor.

To evaluate the LLT T_L, we need to evaluate P_s, $S_0(t)$, and $S_1(t)$. Let z_d denote the least distance to be traveled by node to move out of the communication circle, starting from the position A_s with the direction and speed v being kept unchanged. A graphical illustration of z_d is presented in Fig. 5. The probability P_s can now be evaluated through z_d as

$$P_s = E_{z_d}(P_s(z_d)) = \int_{z_d} P_s(z_d)p(z_d)dz_d \tag{13}$$

$$P_s(z_d) = \int_{v_r} P(\tau \leq \frac{z_d}{v_r})p(v_r)dv_r$$

$$= \int_{v_r} (1 - F_m(\frac{z_d}{v_r}))p(v_r)dv_r$$

$$= \int_{v_r} (1 - exp(-2\lambda_m z_d/v_r))p(v_r)dv_r \tag{14}$$

where $P_s(z_d)$ is the conditional probability of P_s on z_d. $p(z_d)$ is PDF of z_d and the evaluation of z_d directly follows from [16] being calculated as

$$p(z_d) = \begin{cases} \frac{2}{\pi R^2}\sqrt{R^2 - (\frac{z_d}{2})^2}, & \text{for } 0 \leq z_d \leq 2R \\ 0, & \text{elsewhere} \end{cases} \tag{15}$$

where R specifies the radius of the communication circle.

$S_0(t)$ is the PDF of the time duration for nodes to return to state S_0. Conditioning on z_d and assuming that

Fig. 5. Graphical Illustration of z_d.

the starting time is at time 0, $S(t)$ is the probability of the node m_b changing its relative velocity at time t on condition that A_d is located inside the communication circle. Therefore,

$$S_0(t) = E_{z_d}(S_0(t|z_d)) \tag{16}$$

$$S_0(t|z_d) = \frac{1}{P_s}P(t = \tau, z_d \geq v_r\tau|z_d)$$

$$= \frac{1}{P_s}2\lambda_m e^{-2\lambda_m t}\int_0^{\min\{V_m,\frac{z_d}{t}\}} p(v_r)dv_r \tag{17}$$

where $S_0(t|z_d)$ is the conditional PDF on z_d and V_m is the maximum speed of v_r.

$S_1(t)$ can be evaluated in much the same way as we have done for $S_0(t)$. Conditioning on z_d and assuming that the starting time is at time 0, $S_1(t)$ is simply the probability of the node m_b moving out of the communication circle at time t with relative velocity being kept constant. Similar to the above case, we have

$$S_1(t) = E_{z_d}(S_1(t|z_d)) \tag{18}$$

$$S_1(t|z_d) = \frac{1}{1 - P_s}P(t = \frac{z_d}{v_r}, z_d \leq v_r\tau|z_d)$$

$$= \frac{1}{1 - P_s}P(\tau \geq t)p(v_r = \frac{z_d}{t})|\frac{d}{dt}(\frac{z_d}{t})|$$

$$= \frac{1}{1 - P_s}exp(-2\lambda_m t)p_{v_r}(\frac{z_d}{t})\frac{z_d}{t^2} \tag{19}$$

where $S_1(t|z_d)$ is the conditional PDF on z_d using Jacobian transformation. An alterative way to evaluate $S_1(t)$ is as follows: Let's define v_{s_1} to be the conditional relative velocity associated with state S_1 such as $p(v_{s_1}) = p(v_r|S_1)$ and it should be noted that the distribution of v_{s_1} can be greatly different from the distribution of $p(v_r)$. We can then compute $S_1(t)$ as

$$S_1(t) = E_{v_{s_1}}(S_1(t|v_{s_1})) \tag{20}$$

$$S_1(t|v_{s_1}) = \frac{1}{1 - P_s}P(t = \frac{z_d}{v_{s_1}}, z_d \leq v_{s_1}\tau|v_{s_1})$$

$$= \frac{1}{1 - P_s}P(\tau \geq t)p(z_d = v_{s_1}t)\frac{d}{dt}(v_{s_1}t)$$

$$= \begin{cases} \frac{4e^{-2\lambda_m t}}{\pi(1-P_s)}\frac{v_{s_1}}{2R}\sqrt{1 - (\frac{v_{s_1}t}{2R})^2}, & 0 \leq t \leq \frac{2R}{v_{s_1}} \\ 0, & \text{elsewhere} \end{cases} \tag{21}$$

where $S_1(t|v_{s_1})$ is the conditional PDF of $S_1(t)$ on v_{s_1}. A detailed examination of Eq. (20) reveals that it shares the same core analytical expression of link lifetime distribution of Eq. (15) in [6], with the only exception that a normalization factor $e^{-2\lambda_m t}/(1 - P_s)$ accounts for the probability of nodes leaving for state S_1. It implies that the AS-LLT formula, solely relying on $S_1(t)$, gives the same link lifetime distribution as in [6].

IV. EXAMPLES

We now compare the results predicted by our analytical model with simulations. In the simulations, we assume that every node is moving at the same constant speed and only its direction is changed according to the RDMM model. The simulation with variable speeds can be obtained by averaging the results from every speed with respect to the distribution of speed v. The cell size is chosen as $4km \times 4km$ (i.e., $L = 4km$). Three different speeds are simulated $v \in \{0.1L, 0.5L, 2.5L\}(km/h)$, covering from slower to faster speeds. Similar to [17], parameter λ_m in the RDMM model is set to $\lambda_m = 4$, indicating that on average nodes change their velocity at every $\frac{1}{4}$ hour.

When determining the radius R of the communication circle, due to the interference constraint from neighbor nodes and to achieve the maximum possible parallel communications, the radius should satisfy $\pi R^2 * \frac{n}{2} \le L^2$ [18]. Two different values of $R \in \{100m, 10m\}$ are simulated, representing the cases of large communication circle and the small one, or in another words, the cases of the moderate node density ($n = \Theta(1000)$) and the dense node density ($n = \Theta(100000)$). Combining with three different speed setups, we simulate six scenarios and present their results below.

TABLE I

RESIDENCE PROBABILITY P_s.

Radius (m) (R)	Speed v (km/h)		
	$v = 2.5L$	$v = 0.5L$	$v = 0.1L$
$R = 10$	$P_s = 0.014$	0.053	0.180
$R = 100$	$P_s = 0.092$	0.287	0.651

Table I describes the residence probability P_s for all six scenarios. It can be observed that, as shown in Eq. (16) and (18), the characteristics of mobility are governed by the relative radius (ReR) $\frac{R}{v}$, the ratio between the radius R of communication circle and speed v. For this reason, we will use the ReR value ($\frac{R}{v}$) to differentiate our simulations, i.e., $\frac{R}{v} \in \{0.001, 0.005, 0.01, 0.025, 0.05, 0.25\}$. As shown in Table I, the residence probability increases

with ReR, indicating that it is more likely for nodes with larger ReR to stay inside the communication circle.

From Figs. (6) and (7), it can be observed that the theoretical derivation for $S_0(t)$ and $S_1(t)$ in Eq. (16) and (18), accurately describe the mobility characteristics of nodes and exhibit good match with all the simulations.
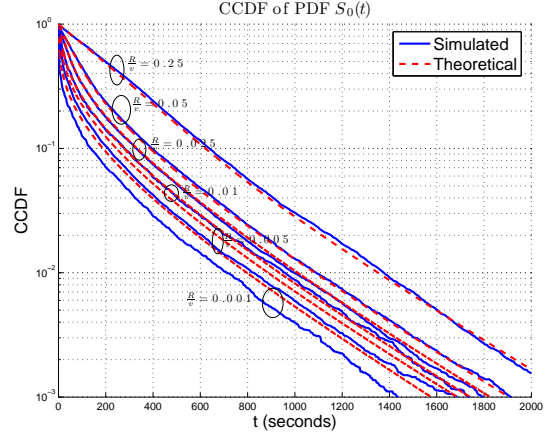

Fig. 6. $S_0(t)$: Simulated vs. Theoretical.
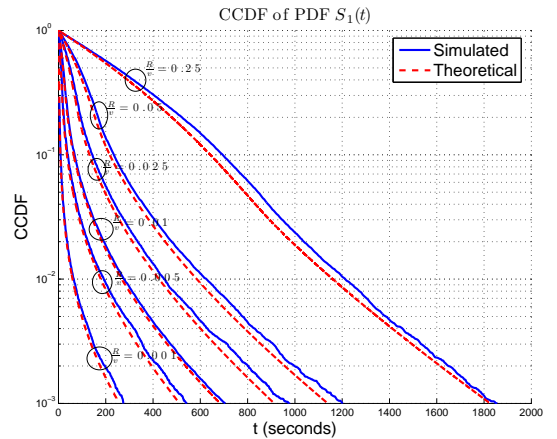

Fig. 7. $S_1(t)$: Simulated vs. Theoretical.

Fig. 8 presents the results for link lifetime ES-LLT and AS-LLT predicted by our analytical model and obtained by simulations. The results confirm that the two-state Markovian model is a powerful tool to accurately model link dynamics of link lifetime distribution as a function of node mobility. It can be also observed that the ES-LLT formula, obtained from the Markovian model, shows good matches with the simulations in all scenarios. On the other hand, the AS-LLT formula with the simplified assumptions corresponding to the model by Samar and Wicker [5], [6] gives good approximations to the simulations only for small values of ReR ($\frac{R}{v}$) and greatly deviates from the simulations when ReR becomes large, i.e., larger residence probability P_s and larger possibility for nodes to stay inside communication circle.
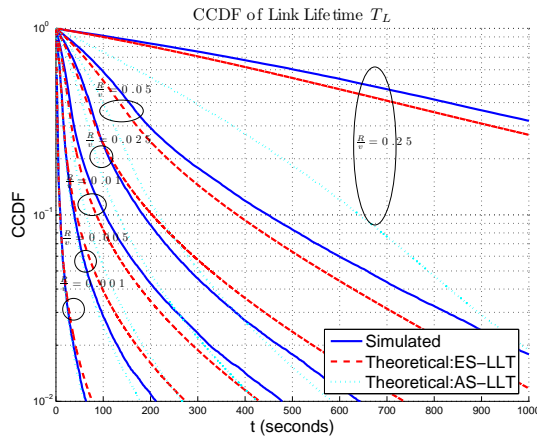
Fig. 8. Link Lifetime T_L: Simulated, ES-LLT(Markovian), AS-LLT.

In summary, the Markovian model (ES-LLT formula) is a much more accurate model than the AS-LLT formula [5], [6] and shows close approximations to all simulations, in contrast to the AS-LLT formula that gives good approximation only when ReR is relatively small.

Our two-phase Markov model can be generalized to evaluate other networks with the two building blocks $S_0(t)$ and $S_1(t)$ adapted for the specific network and mobility models. For example, it can be applied to MANET with static infostation or MANETs with restricted mobility[19].

V. CONCLUSIONS

We have presented an analytical framework for the characterization of link behavior in MANETs. Given the existence of prior attempts to incorporate link dynamics in the modeling of routing and clustering schemes [4], [20], [21], we believe that this new framework will find widespread use by researchers interested in the analytical modeling and optimization of channel access and routing protocols in MANETs. The advantage of our framework is that it accurately describes link dynamics as a function of node mobility.

ACKNOWLEDGEMENT

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