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A hybrid view of mobility in MANETs: Analytical models and simulation study ☆

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ABSTRACT

We study the effects of node mobility on the wireless links and protocol performance in mobile ad hoc networks (MANETs). First we examine the behavior of links through an analytical framework and develop statistical models to accurately characterize the distribution of lifetime of such wireless links in MANETs. We compute the lifetimes of links through a two-state Markov model, and use these results to model multi-hop paths and topology changes. We show that the analytical solution follows closely the results obtained through discrete-event simulations for two mobility models, namely, random direction and random waypoint mobility models. Finally, we present a comprehensive simulation study that combines the results from the findings in simulations with the analytical results to bring further insight on how different types of mobility translate into protocol performance.

1. Introduction

The communication protocols of mobile ad hoc networks (MANET) must cope with frequent changes in topology due to node mobility and the characteristics of radio channels. From the standpoint of medium access control (MAC) and routing, node mobility and changes in the state of radio channels translate into changes in the state of the wireless links established among nodes, where typically a wireless link is assumed to exist when two nodes are able to decode each other's transmissions.

The behavior of wireless links is critical to the performance of MAC and routing protocols operating in a MANET. However, no analytical model exists today that accurately characterizes the lifetime of wireless links, the paths they form from sources to destinations, and topology changes resulting from dynamic link behaviors, as a function of node mobility. As a result, the performance of MAC and routing protocols in MANETs have been analyzed through simulations, and analytical modeling of channel access and routing protocols for MANETs have not accounted for the temporal nature of MANET links and paths. For example, the few analytical models that have been developed for channel access protocols operating in multi-hop 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]). Accordingly, there is a strong motivation to investigate analytical modeling of link dynamics and its generalization to the distribution of multi-hop paths and topology changes.

This paper provides the most accurate analytical model of link and path behavior in MANETs to date, and characterizes the behavior of links and paths as a function of node mobility. The importance of this model is twofold. First, it enables the investigation of many questions regarding fundamental tradeoffs in throughput, delay and storage requirements in MANETs, as well as the relationship between many crosslayer-design choices (e.g., information packet length) and network dynamics (e.g., how long links last in a MANET). Second, it enables the development of new analytical models for channel access, clustering and routing schemes 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] pioneered the analytical evaluation of link dynamics, and provided new insight on the importance of an analytical formulation of link dynamics in the optimization of the protocol design. However, Samar and Wicker assumed 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 one of the

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communicating nodes changes its speed or direction while the nodes are in transmission range of each other. Consequently, the results predicted by Samar and Wicker's model could 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 first contribution of this paper is to provide a two-state Markov model that better describes the mobility patterns of communicating nodes. Section 2 describes the network and mobility models used to characterize link and path behavior. Section 3 describes the proposed analytical framework and presents our results on link lifetime. Our approach is based on a two-state Markovian model that reflects the movements of nodes inside the circle of transmission range and builds an analytical framework to accurately evaluate the distribution of link lifetime. And the proposed model subsumes the model of Samar and Wicker [5,6] as a special case, and provides a more accurate characterization of the statistics of link lifetime. Section 5 illustrates the accuracy of our analytical model by comparing the analytical results against simulations based on the random direction mobility model (RDMM) and the random waypoint mobility model (RWMM) model.

We extend the analytical results on link dynamics to path dynamics and topology changes in Section 4. These results help to understand the difference in protocol performance obtained in the subsequent simulation study. We argue that, although the end-to-end performance measure such as delay and packet delivery ratio are important, a complementary view of the performance of MAC layer is also essential to obtain a thorough understanding on how mobility influences protocol performance. Although a simulative framework is presented in [7] to incorporate mobility effects into simulations of ad hoc networks, little works has been reported in analyzing the performance evolutions of MAC layer due to nodes' mobility. Section 6 presents a comprehensive simulation study on the mobility induced performance evolution of the MAC layer. To the best of our knowledge, it is the first work to provide such results. Section 7 concludes this paper.

2. System model

Consistent with several prior analytical models of MANETs [8–10], we consider a square network of size $L \times L$ in which n nodes are initially randomly deployed, as depicted in Fig. 1. The movement of each node is unrestricted, i.e, the trajectories of nodes can be anywhere in the network. The model of node mobility falls into the general category of random trip mobility model [11], where nodes' movement can be described by a continuous-time stochastic process and the movement of nodes can be divided into a chain of trips.

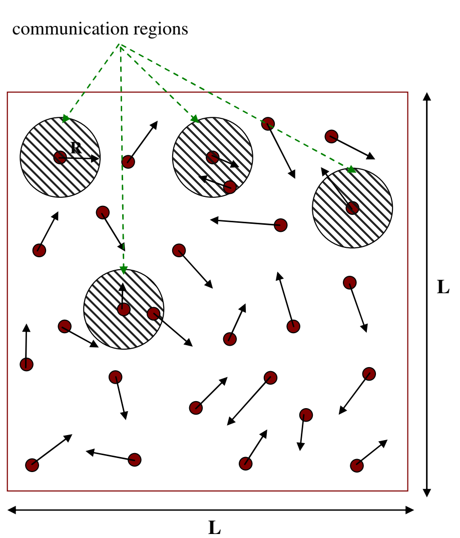

Fig. 1. Model of network structure.

Communication between two nodes is allowed only when the distance between them is less than or equal to R and can be performed reliably. Communication zone of a given node consisting of the circle of radius R satisfies the minimum SINR (signal to interference plus noise ratio) requirement with certain outage probability in the wireless fading environment.

A typical communication session between two nodes involves several control and data packet transmissions. Depending on the protocol, nodes may be required to transmit beacons to their neighbors to synchronize their clocks for a variety of reasons (e.g., power management, frequency hopping). Nodes can find out about each other's presence by means of such beacons, or by the reception of other types of signaling packets (e.g., HELLO messages). Once a transmitter knows about the existence of a receiver, it can send data packets that are acknowledged, and the MAC protocol attempts to reduce or avoid those cases in which more than one transmitter sends data packets around a given receiver, which typically causes the loss of all such packets at the receiver. To simplify our modeling of link lifetime, we assume that the proper mechanisms are in place for neighboring nodes to find each other, and that all transmissions of data packets are successful, as long as they do not last beyond the lifetime of the wireless link between transmitter and receiver. Relaxing this simplifying assumption is the subject of future work, as it involves the modeling of explicit medium access control schemes (e.g., [1]).

3. 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.

The wireless link between nodes m_a and m_b is broken when the distance between nodes m_a and m_b is greater than R. When a data packet starts at time t_1, the positions of node m_b could be anywhere inside the communication circle defined by the transmission range of m_a and is assumed as uniformly distributed.[1]

Let B (bits/s) be the transmission rate of a data packet, L_p be the length of the data packet, and $t_1 + T_L$ 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 within their communication range during the whole communication session of the data packet, that is

$$L_p/B \leqslant T_L \quad (1)$$

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 communica-

[1] In mobile ad hoc network, the traffic is generated randomly and nodes are moving randomly. When a node initiate traffic to other nodes, the target node could be anywhere in the network and the relays could also be anywhere in the communication range. Therefore, a uniform distribution assumption naturally fits into the scenario.