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Analytical framework for the characterization of the link properties in multi-hop mobile wireless networks

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ABSTRACT

The maintainability of connectivity in multi-hop mobile wireless networks is a complex task to achieve, for which various factors must be taken into account in order to avoid link failures. In addition to the bandwidth limitation, node mobility and interference are two aspects that impact directly the reliability of the communication link, leading generally to loss of wireless link connectivity. In this paper, we develop an analytical framework which determines the link and path lifetime in multi-hop mobile wireless networks. Through this model, we derive an analytical model of the link and path lifetime by taking into consideration both node mobility and interference. We find that the probability density function (PDF) of the duration of a link in presence of interference can be approximated by an exponential distribution with parameter λ which relies the transmission range *R*, the average speed $\bar{V}$, the Signal-to-Interference-Plus-Noise-Ratio (*SINR*) threshold β, the path loss exponent α, and the maximum number of interfering nodes *N*. We extend this model to evaluate the *PDF* of the link lifetime by taking into account both interference and mobility of the linked nodes. We conclude that the *PDF* of the overall link lifetime can be approximated by a Rayleigh distribution that is in harmony with several previous simulation based-studies. Furthermore, some properties of wireless links and multi-hop paths are evaluated and several simulations are carried out in order to investigate the multi-hop wireless network connectivity and the associated performance.

1. Introduction

Communication between mobile nodes in multi-hop wireless networks is carried out by a set of wireless links between node pairs which require routing over multi-hop paths. The nature of the wireless medium is unreliable and can be subject to errors due to the unpredictability of the environment and the limited bandwidth of wireless channels. Moreover, nodes are free to move randomly and can enter and leave the network dynamically. In this case, link breakage can occur when nodes move out of the transmission range of each others [1].

Aside from node mobility, interference is an inherent characteristic of wireless multi-hop networks [2]. Communications between nodes are achieved through a single channel and therefore potentially interfere with each other [3]. In this case, nodes that are located inside the transmission area of the receiver can produce interference, because mobile nodes in multi-hop wireless networks do not have a separate interface for each operation of data transmission and all stations must switch the channel regulatory. Consequently, transmission to the intended node can be impacted by interferences from nodes located in the transmission area of the receiver.

Achieving network performance requires a deep comprehension of link properties [4]. Many random factors such as node mobility, propagation environment and interference should be considered in the characterization of wireless links in such environment characterized by dynamic movement of nodes and interference. To the best of our acknowledge, the link lifetime was usually determined by the node mobility, however, this paper deals with the effect of the interference, radio channels as well as the node mobility on wireless link lifetime. Our motivation is to give an accurate estimation of the lifetime probability density function due to both linked nodes mobility and interference for multi-hop wireless networks.

The rest of the paper is organized as follows. Section 2 contains a literature overview on the characterization of link duration in multi-hop wireless networks and associated properties. We describe in Section 3 our approach to modeling the lifetime of wireless links and multi-hop paths by taking into consideration both linked nodes mobility and interference. In Section 4, we present the distribution of link lifetime due to interference by using a

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discrete-time Markov chain for modeling the link state at each time step. The section contains also numerical simulations carried out to validate our analytical framework. We then give in Section 5 the link and multi-hop path lifetime properties in the presence of interference. The derivation and validation of the link lifetime distribution due to both linked nodes mobility and interference is presented in Section 6. Finally, Section 7 concludes the paper.

2. Related work

2.1. Link properties in multi-hop wireless networks

Ensuring end-to-end connectivity in multi-hop wireless networks is a critical issue because, several factors such as node mobility, propagation environment and interference have an impact on the link characteristics and can often involve a link breakage [5]. Obviously, the characterization of the link properties such as link lifetime is the key element to achieve efficiency and network performance. Accordingly, several works have investigated the link lifetime estimation. Some of them have been limited to simulation-based approaches in order to provide empirical distribution of link and multi-hop path lifetime to evaluate the network connectivity [6–8].

Some other works have focused on analysis-based studies, the authors of [9] show that the path duration *PDF* can be approximated by an exponential distribution, they take into account the node relative speed, the node transmission range, and the number of hops in the path. Moreover,[10] and [[11]] show that the link lifetime has a peak roughly at the transit time of two mobiles crossing each others transmission range. These studies are based on mobility models such as Random Waypoint [12], Random Walk [13], Gauss–Markov [14] and their variants. In other work,[15] highlights that these models are not realistic and have a significant impact on the distribution of nodes, their speeds and their directions in comparison with their steady states. Link analysis based on such models is helpful to understand the impact of mobility models on the wireless link performance [16]. The authors of [17] indicate that the link lifetime decreases when the node speed increases and the link breakage can occurs only when, at least, one of the linked nodes is moving.

Other studies propose analytical methods to provide insights concerning link behaviors and properties including link availability [18], link lifetime and link residual time [9,10]. In this context,[19] proposes an analytical approach to determine the probability distribution of the link lifetime under the combined assumptions of the radio transmission model and the distribution model of nodes distance. However, this approach requires a previous known of the node speed. In [20], the authors examine the use of mobility prediction to anticipate topology changes. Nonetheless, the presented approach is based on communicating the current positions and velocities to all the neighbor nodes. In recent works,[21] studies the link properties by considering that the nodes speed follows a normal distribution and [22] examines many predictors in urban which require knowledge of the location of the node and the path loss. Moreover,[23] shows that the link duration for two nodes is determined by the relative speed and the distance during which the link is connected.

Besides the previously mentioned works, the authors of [24] provide an approximation of the distribution of the link lifetime due to linked nodes mobility. In this study, time is divided into equal length time steps Δt and a distance transition probability matrix is used in order to model the distance after every discrete time step based on a smooth mobility model [15]. The main result is an approximation of the link lifetime due to linked nodes mobility by an exponential distribution with parameter $\frac{\bar{V}}{R_e}$, where $\bar{V}$ is the mean of speed and R_e the effective transmission range (*ETR*) which is used in order to capture the effect of radio propagation.

Many issues related to the link behavior are largely explored in the literature. However, the limitations of existing works on link properties are due to interference which was ignored in these analysis and the use of random mobility models which cannot capture the steady state of the network topology and can cause multiple channel availabilities that affect the link-level quality. In this context, the purpose of our study is to develop an analytical framework in order to investigate characteristics related to link properties by taking into account both linked nodes mobility and interference.

2.2. Contributions

The analysis presented in this paper aims to determine the distribution of the overall link duration by considering both interference and linked nodes mobility. The main idea is to separate link failures caused by linked nodes mobility and interference. For this purpose, we consider the model developed in [24] in which the link lifetime due to linked nodes mobility is approximated by an exponential distribution with parameter $\frac{\bar{V}}{R}$ and in this paper, we aim to determine the link lifetime due to interference.

In this context, we develop an analytical approach to determine the probability that a transmission is successfully received by a node in the presence of interference from a given number of nodes. Starting from modeling the relative distances between nodes, we calculate the probability that the *SINR* is greater than a certain threshold β in the presence of L active interfering nodes. Moreover, we use a transition probability matrix for modeling the link state in the presence of interference after every discrete time step.

The main contribution is the approximation of the link lifetime due to interference by an exponential distribution, and the overall link lifetime due to mobility and interference by a Rayleigh distribution. These results are used to evaluate the link properties such as the average link lifetime and the residual link lifetime. The main application is as a component of network design algorithm, for example, for routing and performance evaluation.

3. Basic framework

In this section, we present our approach for modeling the lifetime of wireless links and multi-hop paths. The link lifetime is the period of time between the establishment of the link until its breakage due to a failure. We classify the link lifetime into two main classes. Link duration in which the failure is caused by movement of the linked nodes and link lifetime in which the failure is due to interference.

Results of [24] show that the lifetimes of links follow an exponential distribution. In fact, this study does not take into account interference and considers the mobility of linked nodes as the only factor which causes link failures. The purpose of this work is to evaluate link properties by taking into account both linked nodes mobility and interference.

We denote by $d_{u,v}$ the distance between the node-pair (u, v) where u is the sender node and v is the receiver node. The corresponding relative distance after k time steps is denoted by $d_{u,v}^{(k)}$. And let $SINR_{u,v}^{(k)}$ be the Signal-to-Interference-Plus-Noise-Ratio at the k^{th} time steps (the duration of the time step is denoted by Δt). The mathematical formulations of $d_{u,v}^{(k)}$ and $SINR_{u,v}^{(k)}$ are given in the next section.

Definition 1. The link lifetime due to linked nodes mobility, denoted by $T_{link,mvt}$, is the period of time between the establishment