Scientific Research

Link Availability Prediction for Cognitive Radio Ad Hoc Networks

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Abstract

One critical issue for routing in cognitive radio ad hoc networks (CRAHNs) is how to select a reliable path for forwarding traffic. This is because mobility may cause radio links to break frequently. The reliability of a path depends on the availability of those links that constitutes the path. In this letter, we present a novel approach to predict the probability of the availability of the link between two cognitive radio nodes. The prediction is achieved by estimating the link activation and spectrum activation probabilities. Our prediction is verified by simulation and proved to be accurate. This study can provide reliability assurance on dynamic routing for cognitive radio ad hoc networks.

Keywords

1. Introduction

Cognitive radio (CR) was proposed to make use of the existing wireless spectrum opportunistically without causing harmful interference or collisions to the primary users (PUs) [1]. Cognitive radio ad hoc networks (CRAHNs) are networks with mobile CR devices working without the support of any fixed infrastructure or central administration. Since the topology of a CRAHN can change rapidly and unpredictably, efficient routing is difficult to achieve in CRAHNs. Routing path in CRAHNs may break frequently due to dynamic network topology. If any single link of a path breaks, then this path needs to be either locally repaired by finding another link if possible or globally replaced with a new path by rerouting. Route repair or rerouting will induce more energy consumption, waste the scarce radio resources, and degrade end-to-end network performance such as throughput and delay [2]. Thus, an optimal path in CRAHNs should first be stable and reliable to avoid frequent

rerouting operations. The stability of a path depends on the availability of all links constituting this path.

A large number of prediction models, such as [2]-[8], are available for link availability prediction in the classical MANETs. In these networks, a link is considered to be available if the two nodes associated with this link are within the transmission range of each other. However, in CRAHNs, a link should also satisfy another requirement that the two nodes associated with this link have to have a common available spectrum channel to use. Thus, the prediction models for MANETs are not suitable for the link availability estimation in CRAHNs.

Two link availability prediction models for CRAHNs are proposed in [9] and [10]. In [9], a time period T_p that the link between two CR nodes will stay available and its corresponding probability $L(T_p)$ is predicted. Another time period $\hat{T}_p$ until either CR node of the link moves into the interference area of a PU and its corresponding probability $L(\hat{T}_p)$ are also predicted. After that, the link availability is revealed by the combination of $\left[T_p, L(T_p)\right]$ and $\left[\hat{T}_p, L(\hat{T}_p)\right]$. In their work, each predicted time period is determined by velocities of CR nodes and the node distance. In [10], the link availability is predicted in a fixed time interval. However, in reality, the link availability during flow transmitting time (traffic flow duration) is most important to routing. Therefore, unlike the previous work that predicting time period, we concentrate on predicting link availability throughout the traffic flow duration. The main contribution of this paper is a method to predict how the CR node mobility and PU activities affect the link stability throughout the traffic flow duration. By using the prediction method presented in this paper, a more stable routing path could be selected in order to avoid frequent link failure.

The rest of this paper is structured as follows. Section 2 describes the system model. A link-availability prediction scheme is presented in Section 3. The results given by this estimation are compared with simulation results in Section 4. Finally, Section 5 concludes this paper.

2. System Model

Since cognitive radio users (CUs) are considered to have lower priority and belong to secondary users of the spectrum allocated to PUs, CUs have to sense the spectrum to detect PU activities. Spectrum availability is only affected by PU activities in the scenario that the interference area of PUs is large enough to cover the CRAHN. In this letter, we study how the spectrum availability due to PU activities affects the network performance in CRAHNs.

We consider a cognitive radio ad hoc networks consisting of *n* cognitive radio users and *m* primary users. The PUs, who coexist in an overlapping region with the CUs, hold licenses for specific spectrum channels, and they are only allowed to utilize their assigned channel [2]. As CUs do not have any licensed spectrum, they can only opportunistically use the idle channels.

We denote the set of CR nodes as $CU = \{CU_1, CU_2, \cdots, CU_n\}$ and the set of PUs as $PU = \{PU_1, PU_2, \cdots, PU_m\}$. We assume that PU_i hold licenses for spectrum channel Ch_i. The channel Ch_i is busy when PU_i arrives and uses it. Only when PU_i is not present, the channel Ch_i can be used by CUs. Assume that the arrival rate of PU_i to its assigned channel follows Poisson distribution with mean $\lambda_{p,i}$. Note that PU activities and CU movements are independent of each other.

In this letter, we consider that CUs move in random walk mobility model. Based on this model, the movement of a CU consists of a sequence of random length intervals called *mobility epochs*. During a mobility epoch, a node moves in a constant direction at a constant speed. The speed and direction of each node varies randomly from epoch to epoch. Mobility epoch durations are exponentially distributed. Speed, direction and epoch length are uncorrelated. Besides, the mobility of the CUs are independent with each other.

The mobility epoch is illustrated in **Figure 1**. The speed v_i and direction θ_i of node CU_i during each epoch are uniformly distributed over the ranges of $(v_{\min}, v_{\max})$ and $(0, 2\pi)$, respectively. The mobility epoch duration of node CU_i is exponentially distributed with mean $1/\lambda_{c,i}$. When the epoch starts, the initial position of CU_i is at (x_i, y_i), the initial position of CU_j is at (x_j, y_j) and the initial distance between CU_i and CU_j is d_0. After time period t during the mobility epoch, the position of CU_i can be expressed as $(x_i + v_i t \cos\theta_i, y_i + v_i t \sin\theta_i)$. Then, the distance d_t after time period t can be expressed as

$$d_t = \sqrt{\alpha t^2 + \beta t + d_0^2} \tag{1}$$

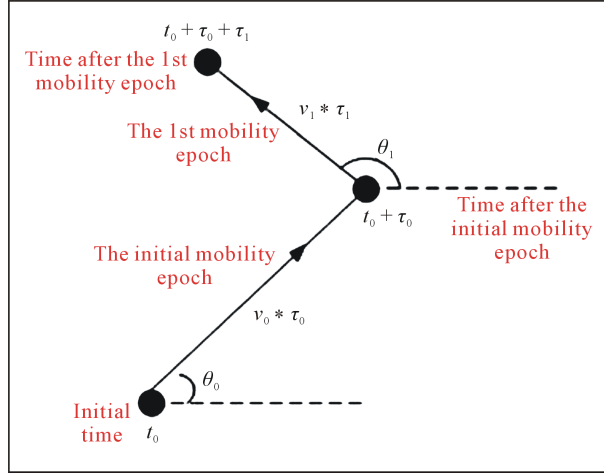where, $\alpha = v_i^2 + v_j^2 - 2v_i v_j \cos(\theta_i - \theta_j) \geq 0$;

Figure 1. Radom mobility epoch model.

$$\beta = 2(x_i - x_j)(v_i \cos\theta_i - v_j \cos\theta_j) + 2(y_i - y_j)(v_i \sin\theta_i - v_j \sin\theta_j).$$

3. Link Availability Estimation

Let t_0 denote the initial time instant and T_f denote the traffic flow duration time. And the link from CU_i to CU_j on channel Ch_k is denoted by $e_{i,j}^k$. In this section, we propose a link availability estimation method to predict the link availability from t_0 to $t_0 + T_f$.

Before explaining the method for estimating the link availability grade, the definition of link availability is provided in what follows:

Definition 1. A link between two nodes CU_i and CU_j with transmission range R is defined to be link connected at time instant t, when the distance between both nodes is such that $d_{i,j}(t) \le R$. **Figure 2** shows a simple example in which the link between nodes CU_i and CU_j is connected initially but then become deactivated after a mobility epoch. The probability of link connected from t_0 to $t_0 + T_f$ is defined as *link connection probability* and denoted by $\mathcal{F}_{i,j}(T_f)$.

Definition 2. A link between two nodes CU_i and CU_j is defined to be spectrum available on channel Ch_k at time instant t, when the channel Ch_k is available for the link to use at time instant t. That is, Ch_k is not utilized by its licensed user at time t. We denote the probability of spectrum availability from t_0 to $t_0 + T_f$ by $\mathcal{H}_{i,j}^k(T_f)$.

Definition 3. A link between two nodes CU_i and CU_j is defined to be available on channel Ch_k at time stant t if the link is both link connected and spectrum available.

Definition 4. A link between two nodes CU_i and CU_j is defined to be available on channel Ch_k during time t_0 to $t_0 + T_f$, if the link is continuously available from t_0 to $t_0 + T_f$. The probability of link continuously available from t_0 to $t_0 + T_f$ is defined as *link availability* and denoted by $\mathcal{L}_{i,j}^k(T_f)$.

Link availability is dependent on link connection probability and spectrum availability probability. Link connection probability is affected by CUs' movement. We neglect the spectrum contention among CUs. We assume that spectrum availability is only dependent on PU activity. And as mentioned earlier, CU movement and PU activity are independent of each other. Thus, for a link $e_{i,j}^k$, its link availability $\mathcal{L}_{i,j}^k(T_f)$ is given by

$$\mathcal{L}_{i,j}^k(T_f) = \mathcal{F}_{i,j}(T_f)\mathcal{H}_{i,j}^k(T_f). \tag{2}$$

It is easy to calculate $\mathcal{H}_{i,j}^k(T_f)$, which is equal to the probability that PU_k will not arrive to use channel Ch_k from t_0 to $t_0 + T_f$. Given the Poisson arrival process with parameter $\lambda_{p,k}$, then the probability of zero arrivals to the licensed channel Ch_k is given by

$$\mathcal{H}_{i,j}^k(T_f) = \frac{(\lambda_{p,k}T_f)^0 \, \mathrm{e}^{-\lambda_{p,k}T_f}}{0!} = \mathrm{e}^{-\lambda_{p,k}T_f}. \tag{3}$$

However, it is difficult to give an accurate calculation for $\mathcal{F}_{i,j}(T_f)$ because of the difficulties in estimating
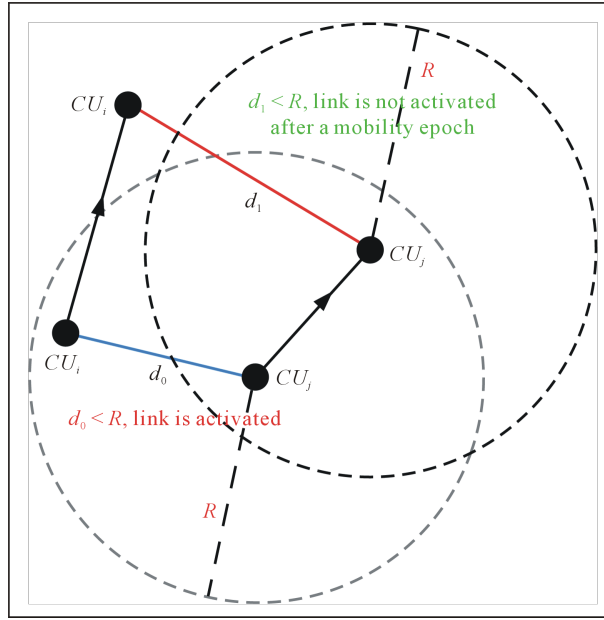
Figure 2. Link mobility and activation example.

the movement of CR users. In the following, we discuss an estimation method for $\mathcal{F}_{i,j}(T_f)$.

Since the mobility epoch lengths of CUs follow exponential distribution, the process for a node to change its velocity is Poisson with a mean rate equal to the reciprocal of the mean epoch [5]. According to the assumption that the movement of each CR user is independent, then the probability for X changes in velocities (or consist of $X + 1$ mobility epochs) to happen to a link $e_{i,j}^m$ is denoted as $C(X, T_f)$ and given by

$$C(X, T_f) = \frac{(\lambda T_f)^X e^{-\lambda T_f}}{X!} \qquad (4)$$

where $\lambda = \lambda_{c,i} + \lambda_{c,j}$.

A mobility epoch to a link is a time period during which both nodes associated with this link will not change their velocities. Let $L_{i,j}^X(T_f)$ denote the probability that link $e_{i,j}^m$ can be still continuously available with X changes in velocities happening within T_f. Let τ_k denote the time duration of the kth mobility epoch, where $k \in \{0, 1, \cdots, X\}$ and $T_f = \sum_{k=0}^{X} \tau_k$. Then, the probability that link $e_{i,j}^m$ will be continuously activation within T_f is expressed as

$$\mathcal{F}_{i,j}(T_f) = \sum_{X=0}^{\infty} C(X, T_f) L_{i,j}^X(T_f). \qquad (5)$$

The link connection state of a link $e_{i,j}^m$ at the end of a mobility epoch can be regarded as a random variable, whose state space is $(0,1)$, where 0 corresponds to link activation and 1 corresponds to not activation. Let $\mathcal{F}_{i,j}(\tau_k)$ denote the link activation probability during the kth mobility epoch given that the link $e_{i,j}^m$ is connected during the last mobility epoch. Then, the state transition matrix of the kth mobility epoch is defined as

$$
M(\tau_k) = \begin{array}{c} 0 \\ 1 \end{array}\!\!\begin{pmatrix} \overset{0}{\mathcal{F}_{i,j}(\tau_k)} & \overset{1}{1 - \mathcal{F}_{i,j}(\tau_k)} \\ 0 & 1 \end{pmatrix}.
$$

For a initially activated link $e_{i,j}^m$, we have the initial vector $I_s = (1, 0)$. The final vector can be derived as $I_{T_f} = (y_0, y_1) = I_s \prod_{k=0}^{X} M(\tau_k)$. Then, $L_{i,j}^X(T_f)$ is expressed as

$$L_{i,j}^X(T_f) = y_0 = \prod_{k=0}^{X} \mathcal{F}_{i,j}(\tau_k). \qquad (6)$$

Lemma 1. If a link is connected at the initial and at the end of a mobility epoch, then the link is continuously connected during this mobility epoch.

Proof. Let $d(\Delta t)$ denote link distance after an epoch of Δt. Given the initial distance of a link is d_0 and both nodes associated with this link will not change their velocities during Δt, according to (1), $F(\Delta t)$ can be expressed as

$$F(\Delta t) = d(\Delta t)^2 = \alpha \Delta t^2 + \beta \Delta t + d_0^2.$$

where α and β are constant, and $\alpha \geq 0$.

Then, $F''(\Delta t) = \alpha \geq 0$. Accordingly, the function $F(\Delta t)$ is convex downward. Let d_1 denote the link distance at the end of the mobility epoch. And thus, $F(\Delta t) \leq \eta d_0^2 + (1-\eta) d_1^2$, where $0 \leq \eta \leq 1$.

If a link is available at the initial and at the end of a mobility epoch, then d_0 and d_1 both satisfy the link activation requirement ($d_0 \leq R$ and $d_1 \leq R$). Therefore, $F(\Delta t) = d(\Delta t)^2 \leq \eta d_0^2 + (1-\eta) d_1^2 \leq R^2$, which represents that the link distance satisfies the link activation requirement all the time during the mobility epoch. □

Let t_k denote the initial time of the kth mobility epoch. Also let $A_{i,j}(\tau_k)$ denote the probability that link $e_{i,j}^m$ is activated at $t_k + \tau_k$ given it is activated at t_k. According to Lemma 1, then the problem of calculating continuous link activation probability $\mathcal{F}_{i,j}(\tau_k)$ can be obtained by calculating the non-continuous link activation probability $A_{i,j}(\tau_k)$.

It is easy to calculate $A_{i,j}(\tau_0)$ because initial distance between nodes v_i and v_j and the velocities of them are known. Based on the known information, the value of α and β in Equation (*6) can be determined.

Assuming that $F(T_0) = \alpha T_0^2 + \beta T_0 + d_0^2 = R^2$, then $T_0 = \dfrac{\sqrt{\beta^2 - 4\alpha(d_0^2 - R^2)} - \beta}{2\alpha}$. If $\tau_0 \leq T_0$, then $A_{i,j}(\tau_0) = 1$; if otherwise, $A_{i,j}(\tau_0) = 0$.

However, for the mobility epochs after the initial epoch, the velocities and link distance are not known. Therefore, according to the conclusion from [3], then

$$A_{i,j}(\tau_k) = 1 - \Phi\left(\frac{1}{2}, 2, \frac{-4R^2}{\varphi_{i,j}}\right)$$

$$\varphi_{i,j} = 2\tau_k \left(\frac{\sigma_i^2 + \delta_i^2}{\mu_i} + \frac{\sigma_j^2 + \delta_j^2}{\mu_j}\right)$$

4. Numerical Result

In this section, the correctness of the proposed approach is verified via computer simulations. The simulated environment is a two dimensional space (500, 500), which represents an area of size 500 meters by 500 meters. CR nodes are randomly moving in the 2-D space according to the random-walk based mobility model, where a node moves with a direction uniformly and a speed uniformly from 0 to $v_{\max}$ with exponentially distributed epochs. The maximum transmission range of each node is 300 meters, and the transmission rate is 2 Mb/s. Then we statistically calculated the probability that the link was continuously available for t seconds based on all the experimental results. Each curve shown in **Figure 3** is a result of 15,000 independent experiments.

In **Figure 3**, each plot is composed of two curves: simulation results and estimation results. As shown in the figure, the estimation results are very close with the simulation results, implying that our research can be applied to predict link availability in actual mobile environments. We can also observe that in a high dynamic environment (high speed of CR nodes or high arrival rate of primary users), link availability drops quickly as t increases. For example, when the maximum velocity is 5 m/s, as time goes by, link availability drops more quickly than the situation when the maximum velocity is 2 m/s. Similarly, as shown in **Figure 3**, when the arrival rate of primary users is 0.02, as time goes by, link availability drops more quickly than the situation when the arrival rate is 0.01. Therefore, the ability of predicting link availability for a short period of time is very important for CRAHNs, especially in a highly dynamic network environment.

5. Conclusion and Future Work

In this letter, we develop a mathematical model for link availability estimation in cognitive radio ad hoc networks with a random walk mobility model. Our approach is to predict the probability that the link will be
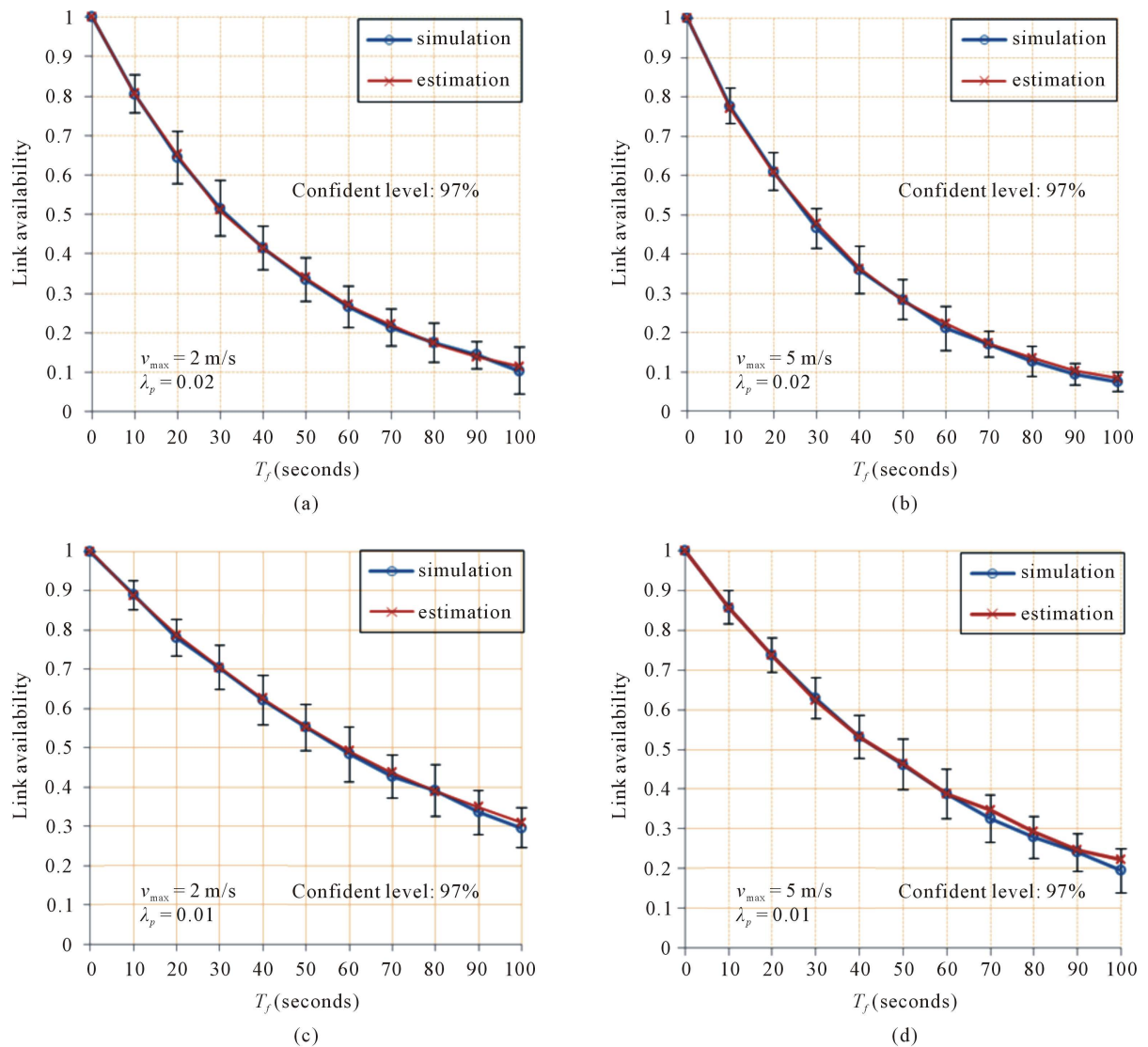
Figure 3. Simulation and predicted results.

continuously available during traffic flow duration. Simulation results reveal that our proposed link availability estimation approach can accurately predict link availability. Our work can provide reliability assurance on dynamic routing for cognitive radio ad hoc networks. The transmission range is assumed to be the same in all directions in this paper. To make it more practical, our future work is to develop an irregular transmission model to predict more comprehensive link availability.

Funding

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