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Probabilistic quality-aware routing in cognitive radio networks under dynamically varying spectrum opportunities ☆

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ABSTRACT

In this paper, we introduce a probabilistic routing metric that considers the peculiar characteristics of the operating environment of cognitive radio networks (CRNs). This metric captures the dynamic changes in channel availabilities due to the randomness of primary user's activity and the rich channel diversity due to the fact that a CRN is expected to operate over highly separated frequency channels with different propagation characteristics. Our metric, Probability of Success (PoS), statistically quantifies the chances of a successful cognitive radio (CR) packet transmission over a given channel. Based on the PoS metric, we propose a joint probabilistic routing and channel assignment protocol for multi-hop CRNs that attempts at selecting the path with the maximum probability of success among all possible paths for a given CR source-destination pair. Selecting such a path results in minimizing the number of disruptions to CR packet transmissions, which consequently improves network throughput. Simulation results verify the significant throughput improvement achieved by our protocol compared to reference CRN routing protocols.

1. Introduction

Due to the increasing demand for more radio frequency (RF) spectrum along with the reported under-utilization of the licensed portion of spectrum, the concept of cognitive radio (CR) is suggested to provide efficient spectrum utilization [1]. CR users are allowed to opportunistically access the licensed spectrum only when it is not occupied by licensed Primary Users (PUs). However, CR users should immediately vacate that spectrum if PU activity is detected. Using the unoccupied spectrum licensed bands provides a more efficient utilization to the limited spectrum resources [2–4]. Routing in a multi-hop cognitive radio network (CRN) is a very challenging problem and still an open issue. In particular, the presence of licensed PUs introduces new challenges in path selection, channel assignment, and power allocation. These challenges make their routing protocols fundamentally different from traditional multi-channel multi-radio protocols.

In recent years, many routing protocols for CRNs have been proposed and evaluated [5–12]. Commonly, these protocols pay more attention to either select the best quality channel or the channel with the maximum average spectrum-availability time. We note that, in a CRN, both spectrum-availability time and required transmission time can significantly impact network connectivity and routing. Specifically, spectrum-availability time can cause a significant degradation in CRN performance when the average spectrum-availability time of an assigned channel is smaller than the required transmission time over that channel. Worse yet, in multi-hop CRNs, this issue becomes crucial when multiple links are involved. The diverse channel quality and spectrum availability can be used more efficiently to improve network performance if the

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cognitive routing protocol design considers them. To this end, we propose a probabilistic routing protocol for multi-hop CRN, namely Maximum Probability of Success (MaxPoS) protocol.

1.1. Motivation

To illustrate the idea of MaxPoS, we consider the simplified example shown in Fig. 1. We assume that there exists only one path from the CR source $\mathcal{C}_S$ to the CR destination $\mathcal{C}_D$. In this example, we consider an environment in which three PU networks and one CRN coexist. Each PU network m operates over a frequency channel m, where $m = 1, 2, 3$. Assume that, for channel m, the OFF period $T_{OFF}^{(m)}$ follows an exponential distribution with mean μ_m (i.e., $P_r\left[T_{OFF}^{(m)} \geqslant t\right] = e^{-t/\mu_m}$). Each edge, in Fig. 1a, consists of multiple links where the number of links equals to the number of common available data channels between any two neighboring CR users n_i and n_j. Each link in Fig. 1b has its link state indicated by the duple $\left(T_{tr}^{(m)},\ \mu_m\right)$, where $T_{tr}^{(m)}$ and μ_m are the required transmission time, (refer to (2)), and the average spectrum-availability time over link m, respectively. In this example, we assume that there exist three common available data channels between any two neighboring CR users. Note that the packet transmission is successful if the OFF period of the selected channel is greater than the required transmission time over that channel (i.e., $T_{OFF}^{(m)} \geqslant T_{tr}^{(m)}$). When CR users employ the MinTT protocol, transmissions $\mathcal{C}_S \rightarrow X,\ X \rightarrow Y$, and $Y \rightarrow \mathcal{C}_D$ select channels 3, 1, and 3, respectively. In this case, the probability of successful transmission $\mathcal{C}_S \rightarrow \mathcal{C}_D$ is $(e^{-(0.08/0.1)})(e^{-(0.01/1)})(e^{-(0.01/0.1)}) = 0.4025$. When the MaxASA protocol is employed, transmissions $\mathcal{C}_S \rightarrow X,\ X \rightarrow Y$, and $Y \rightarrow \mathcal{C}_D$ select channel 3. In this case, the probability of successful transmission $\mathcal{C}_S \rightarrow \mathcal{C}_D$ is $(e^{-(1/1)})(e^{-(0.01/1)})(e^{-(0.2/1)}) = 0.2982$. However, transmission $\mathcal{C}_S \rightarrow \mathcal{C}_D$ has much better chance of proceeding successfully if both average spectrum availability and channel quality are exploited during channels selection. Hence, when MaxPoS is employed, transmissions $\mathcal{C}_S \rightarrow X, X \rightarrow Y$, and $Y \rightarrow \mathcal{C}_D$ select channels 2, 1, and 3, respectively. In this case, the probability of success for transmission $\mathcal{C}_S \rightarrow \mathcal{C}_D$ is $(e^{-(0.1/0.9)})(e^{-(0.01/1)})(e^{-(0.01/0.1)}) = 0.8016$.

1.2. Contribution

In this paper, we introduce a novel probabilistic routing metric that jointly considers the average spectrum-availability time of idle channels and the required CR transmission time over those channels. This metric aims at maximizing the Probability of Success (PoS) for a given CR transmission, which consequently improves network throughput. In the course of our analysis, we analytically derive a closed-form expression for the PoS based on a stochastic model of PU activities under Rayleigh fading channel model. Based on the introduced metric, we then propose an efficient probabilistic routing protocol, called MaxPoS. MaxPoS computes the path with the maximum PoS for a given CR source-destination pair. The proposed protocol involves path discovery, path selection, path maintenance, and channels assignment along the selected path. To show the effectiveness of our MaxPoS routing protocol, we describe two reference routing protocols, namely, the Minimum Transmission Time (MinTT) and the Maximum Average Spectrum-Availability Time (MaxASA) protocols. The former uses the minimum transmission time as the only routing metric while the latter uses the maximum average-spectrum availability time as the only routing metric. In our performance evaluation, we conduct simulations over a multi-hop CRN. The simulation results demonstrate that the MaxPoS protocol can significantly improve CRN throughput compared to the MinTT and MaxASA protocols under different network scenarios.

1.3. Organization

The rest of this paper is organized as follows. Section 2 gives an overview of related work. In Section 3, we introduce our system model and assumptions. In Section 4, we introduce a novel probabilistic routing metric and formulate our routing

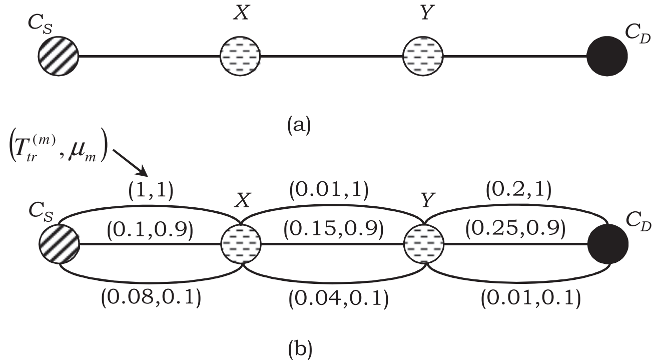

Fig. 1. Path representation in CRN: (a) edge-based. (b) Link-based.