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Adaptive energy-efficient spectrum probing in cognitive radio networks

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ABSTRACT

In cognitive radio networks, secondary users must constantly probe the spectrum to promptly detect the arrival and the departure of primary users (PUs). However, spectrum probing is an energy-consuming process. This indicates the tradeoff between the frequency of spectrum probing and the delay of detecting the PU state change, and highlights the need for energy-conscious spectrum-probing strategies. In this paper, we provide a theoretical framework to find the optimal spectrum-probing methods that minimize the probing delay under a constraint on energy consumption in real stochastic environments. Moreover, we design a practical, sub-optimal adaptive-probing strategy that self-learns the behavior of the PU's dynamics and exploits the proposed optimal probing method. Specifically, we find that the most widely used spectrum-probing scheme, *i.e.*, periodic probing, is not optimal when the arrival rate of the PU state change is not constant or when the distribution of PU channel occupancy/vacancy is not uniform. On the other hand, the derived optimal and adaptive strategies can adapt to the dynamics of PUs and adjust the probing intervals based on the time-varying arrival rate of the PU state changes or the non-uniform distribution of PU channel occupancy/vacancy. Our simulation results show that the optimal spectrum-probing strategies and adaptive-probing methods perform much better and consume much less energy than periodic probing in realistic environments.

1. Introduction

In a cognitive radio network, licensed users or primary users (PUs) allow unlicensed users or secondary users (SUs) to access the licensed spectrum opportunistically when PUs are not transmitting. To allow for the coexistence of PUs and SUs, an important condition is that SUs can monitor channels and promptly detect the arrival of PUs, avoiding harmful interference to the transmission of PUs. Moreover, when PUs transit from active to dormant states, SUs should be able to sense the availability of the spectrum as soon as possible to effectively use the precious channel resource. Therefore, how fast an SU can respond to the arrival and the departure of PUs is an important metric to the design of cognitive radio networks. For example, IEEE 802.22 specifies that SUs should be able to detect the appearance of PUs within 2 s with low probabilities of misdetection and false alarm [27].

This work focuses on when an SU should schedule its channel scans to detect the PU state change in a timely manner. Traditionally, the term "spectrum sensing" is used to specify the underlying physical and MAC techniques that detect channel opportunities [1,25,13]. To avoid confusion, in this paper we apply the term "spectrum probing" to specifically refer to a scheduling strategy that an SU uses to constantly probe the spectrum to discover transmission opportunities [3,7].

Spectrum probing is an energy-consuming process. Each probe consumes a certain amount of energy [1]. As a result, it is not desirable to have an SU keep probing the spectrum all the time when PUs are present. One way to conserve energy is to prolong the time interval

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between spectrum probes. However, this would add to the latency for SUs to discover channel opportunities. Therefore, frequent spectrum probing can be energy inefficient, whereas infrequent spectrum probing can lead to the long delay to respond to the PU state change. That is, there is obviously a tradeoff between the frequency of spectrum probing (*i.e.*, energy consumption) and the delay of detecting the arrival or the departure of PUs.

In cognitive radio networks, the most widely used probing method is periodic probing that SUs scan the spectrum at a constant interval. In our previous work [3], we have shown that for a single SU, periodic probing is an optimal method. That is, given the same power budget on spectrum probing, periodic probing can achieve the minimum delay in detecting the PU state change. The optimality of periodic probing, however, relies on two key assumptions: (1) The arrival rate of the PU state change is constant, and (2) the distribution of PU channel occupancy or vacancy is uniform. It is clear that these two assumptions are not valid in real environments [24,4]. First, the arrival rate of the PU state change is time-varying [24]. Taking TV channels as an example, PUs are much less active late at night than in the daytime. Second, real measurements demonstrate that the PU channel occupancy/vacancy distribution is not uniform [4]. In this paper, we attempt to investigate the following problems: In real stochastic environments, is periodic probing still the optimal energy-efficient scheme? If not, what is the optimal spectrum-probing strategy?

It is obvious that if an SU has exact information regarding PUs' arrival and departure times, then this SU can respond to PUs' state changes immediately, and there is no need for spectrum probing. Similarly, as we will show in this paper, if an SU has some knowledge on the pattern of PUs' dynamics, then it is possible to design optimal spectrum-probing strategies that outperform those without such information. In most realistic cases, however, an SU has no prior knowledge on the behavior of PUs. Hence, the following questions arise: If an SU is totally blind to the behavior of PU's dynamics at the beginning, is it possible for the SU to self-learn the behavior of the PU while probing the spectrum? And if so, how can the SU utilize such self-learned knowledge to enhance its spectrum-probing strategy?

The goals of our work are twofold: to provide a theoretical framework on the optimal spectrum-probing strategy that an SU can use to effectively and efficiently detect the PU state change in real environments; and to design a practical and efficient adaptive spectrum-probing method that an SU can self-learn/estimate the dynamics of the PU while probing and update the probing strategies to reduce the delay of detecting PU state changes. To achieve these goals, we formulate an optimization problem that minimizes the delay to detect the PU state change given a constraint on energy consumption. Equivalently, the derived optimal strategy minimizes energy consumption given the delay performance constraint. We discover that under realistic conditions, the periodic probing scheme is not optimal and cannot adapt to the dynamic behaviors of PUs. On the other hand, our proposed optimal strategy adaptively chooses the probing intervals based on the time-varying arrival rate of the PU state change or the non-uniform distribution of PU channel occupancy/vacancy. As a result, a smart SU should probe the channels more frequently for the time slots when the PU changes its state more frequently or with a higher probability. For example, an SU can probe the spectrum at large intervals late at night and use more energy for probing in the daytime to catch the dynamics of TV channels. Through simulation study, we find that the optimal spectrum-probing scheme performs much better than periodic probing. For example, our simulation results show that depending on the environmental conditions and the parameter setting, the energy saving in spectrum probing can be as much as 29–82% if we switch the spectrum-probing method from periodic probing to the proposed optimal scheme. Although the optimal scheme requires the knowledge on the arrival rates of the PU state change or the distribution of PU channel occupancy/vacancy, our theoretical results can provide the performance bounds and aid in the design of practical adaptive energy-efficient spectrum-probing strategies.

We further design an adaptive spectrum-probing method for SUs that are totally blind to the behavior of the PU's dynamics at the beginning. Such an adaptive method estimates the arrival rates of the PU state changes in real time and exploits the structure of the optimal-probing strategy. Through extensive simulation study, we find that the proposed adaptive probing performs much better than periodic probing and is indeed sub-optimal. Moreover, we discover that with our simulation setting, the performance of different estimators only has a minor effect on the performance of adaptive probing. Hence, a simple estimator can work well with our adaptive probing method.

The remainder of this paper is structured as follows. Section 2 discusses the related work. Section 3 introduces the system model and problem definition. Section 4 revisits the optimality of periodic probing under certain conditions. Sections 5 and 6 derive and evaluate the optimal probing scheme when the arrival rate of the PU state change is not constant, and when the distribution of PU channel occupancy/vacancy is not uniform, respectively. Section 7 designs an adaptive-probing method when an SU is totally blind to the dynamics of the PU at the beginning. Finally, Section 8 concludes this paper.

2. Related work

Spectrum sensing in cognitive radio networks is an active research topic. For example, many physical and MAC spectrum-sensing techniques have been designed, including energy detection, matched filter detection, and cyclostationary feature detection [1,25]. Spectrum sensing schemes that use hybrid detection techniques have also been proposed to improve the detection accuracy. For example, a two-stage detection scheme based on energy detection and feature detection is proposed in [15] whereas the two-stage scheme in [16] combines both energy detection and cyclostationary detection. In this paper, we investigate the delay performance of spectrum probing schemes, and specifically focus on how SUs in a cognitive