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Coverage probability in cognitive radio networks powered by renewable energy with primary transmitter assisted protocol

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ABSTRACT

This paper studies the opportunistic spectrum access (OSA) of the secondary users in a large-scale overlay cognitive radio (CR) network powered by renewable energy to improve both the energy and spectral efficiency of data transmission. Particularly, with energy harvesting module and energy storage module, the primary transmitters (PTs) and secondary transmitters (STs) are assumed to be able to collect ambient renewables and store them in batteries for future use. Upon harvesting sufficient energy, the corresponding PTs and STs (denoted by eligible PTs and STs) are then allowed to access the spectrum according to their respective medium access control (MAC) protocols. For the primary network, an Aloha type of MAC protocol is considered, under which the eligible PTs make independent decisions to access the spectrum with probability ρ_p. For the secondary network, a threshold-based Opportunistic spectrum access (OSA) scheme, namely the primary transmitter assisted (PTA) protocol, is investigated, under which an eligible ST is allowed to access the spectrum only if the maximum signal power of the received pilots sent from the active primary transmitters (PTs) is lower than a certain threshold N_{ta}. By applying tools from random walk theory and stochastic geometry, and assuming infinite battery capacity for energy storage module, we characterize the transmission probabilities of PTs and STs, respectively. With the obtained results of transmission probability, we then evaluate the coverage (transmission non-outage) performance of the overlay CR network powered by renewable energy. Simulations are provided to validate our analysis.

1. Introduction

Renewable energy harvesting [1,2], envisioned as a promising alternative to the traditional fossil fuel based power generation, provides an effective way of improving energy efficiency in wireless networks. By powering mobile networks with renewable energy sources, the energy costs and potentially harmful effects to the environment caused by CO_2 emissions can be significantly reduced. Further, with stand-alone renewable energy harvesters, the self-sustained wireless networks can be flexibly deployed without relying on the infrastructure of the powerline.

Along with energy efficiency, another important issue in the design of wireless networks is the maximization of spectral efficiency. Particularly, the dilemma between the physical scarcity of spectrum resources and the underutilization of the

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licensed frequency bands has imposed new challenges for the next generation wireless networks. To address such difficulty, concepts of cognitive radio (CR) [3,4] and opportunistic spectrum access (OSA) [5,6] are proposed as effective approaches to improve the spectrum utilization efficiency. The basic idea of OSA in CR networks is to enable the unlicensed secondary users to access the licensed spectrum by detecting and exploiting the spectrum holes [7] available in the primary network. As such, with OSA, the underutilized spectrum in the primary network can be effectively and efficiently reused by the secondary network.

In this paper, we consider a large-scale renewable energy powered CR network to improve both the energy and spectral efficiency of data transmission. Particularly, the renewable energy harvesting module endows the PTs and STs with self-sustaining capability, and therefore potentially enables a perpetual operation of CR network without the need of external power supply. On the other hand, the OSA allows the dynamic access of STs, which thereby effectively exploits the spectrum holes in the primary network. It is worth noting that, in general, such large-scale renewable energy powered CR network can be considered as an attractive alternative for various types of future mobile networks, including ultra-dense cellular networks [8], D2D networks [9], and wireless caching networks [10].

Several attempts have been made on exploiting energy harvesting in CR networks [11,12]. In [11], Park et al. developed a kind of myopic spectrum access policy to maximize the throughput of the renewable energy powered secondary transmitter under the assumption of perfect spectrum sensing. Further, in [13] and [14], Park et al. explored the impact of spectrum sensing error and temporal correlation of the primary traffic on the achievable throughput of the energy harvesting secondary transmitter, respectively. In [15], Pappas et al. studied the maximum stable throughput region for a simple cognitive radio network in which the primary transmitter harvests ambient energy while the secondary transmitter is powered by reliable on-grid energy source. In [16], Yin et al. investigate the optimal cooperation strategy of secondary users powered by renewable energy to maximize the achievable throughput of the CR network. Further, in [17], Yin et al. considered a generalized multi-slot spectrum sensing paradigm with secondary users powered by renewable energy, and jointly optimize the save-ratio, sensing duration, sensing threshold as well as fusion rule while keeping primary transmissions sufficiently protected. In [12], Chung et al. characterized the optimal sensing duration and energy detectors sensing threshold to maximize the average throughput of the energy-harvesting CR network. It is worth noting that in [11,12], the studied CR networks contain only one primary link and one secondary link. As such, the size of CR networks studied in [11,12] is relatively small. Further, it is worth noting that [11,12] do not consider the impact of the locations of PTs and STs on the performance of the CR network.

In this paper, different from [11,12], we consider a large-scale overlay CR network powered by renewable energy and assume that the locations of PTs and STs are distributed as Poisson point processes. Both the PTs and STs are assumed to be able to collect ambient renewables and store them in batteries for future use. With sufficient energy stored in the batteries, the corresponding PTs and STs (denoted by eligible PTs and STs) are then allowed to access the spectrum according to their respective medium access control (MAC) protocols. For the primary network, an Aloha type of MAC protocol is considered, under which the eligible PTs make independent decisions to access the spectrum with probability ρ_p. For the secondary network, a threshold-based Opportunistic spectrum access (OSA) scheme, namely the primary transmitter assisted (PTA) protocol, is investigated, under which an eligible ST is allowed to access the spectrum only when the maximum signal power of the received pilots sent from the active primary transmitters (PTs) is lower than a predefined threshold N_{ta}. By applying tools from random walk theory [18] and stochastic geometry [19], the transmission probabilities of PTs and STs are analyzed under the assumption that the battery capacity is infinite. Further, based on the obtained results of transmission probability, the coverage (transmission non-outage) performance in the overlay CR network powered by renewable energy is characterized. Simulations are provided to validate our analysis.

It is worth noting that in this paper, we mainly focus on the case that PTs and STs are equipped with battery of infinite capacity. However, our results can be easily extended to the finite battery capacity case. Particular, for PTs and STs with finite battery capacity, the battery overflow phenomenon may occur and thereby the harvested energy has to be discarded due to battery saturation. As such, how to effectively characterize the distribution of the overflowed renewable energy is the major challenge to be tackled in the finite battery capacity case. We may investigate this issue in our future work.

The remainder of this paper is organized as follows. The system model is described in Section 2. The transmission probabilities of PTs and STs are characterized in Section 3. The coverage performance of the primary and secondary networks is analyzed in Sections 4 and 5, respectively. Simulation results are presented in Section 7. Finally, we conclude the paper in Section 7.

Notations of selected symbols used in this paper are summarized in Table 1.

2. Model and metric

2.1. System model

We consider an overlay CR network in which two wireless networks, namely the primary network and the secondary network, coexist and share the same spectrum on $\mathbb{R}^2$. The PTs are licensed nodes with a higher priority to access the spectrum, while the STs are allowed to transmit only if they are detected to be in the spatial holes of the primary network. The locations of the PTs and STs are assumed to follow two independent HPPPs with density μ_0 and λ_0, respectively. For each PT, the intended PR is located at a distance of d_p away in a random direction. Similarly, for each ST, the intended SR is