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Minimizing secrecy outage probability for primary users in cognitive radio networks

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ABSTRACT

This paper considers a cognitive radio network with a set of secondary users (SUs) who share a spectrum band licensed to a primary user (PU). The PU is assumed to be eavesdropped by a set of eavesdroppers and the SUs are required to interfere with the eavesdroppers to gain their transmission opportunities. We aim to minimize the PU secrecy outage probability under the constraints that the minimum SU ergodic transmission rate and the minimum PU secrecy outage probability reduction are satisfied by optimizing SU scheduling and power allocation. Specifically, it is assumed that unscheduled SUs can send artificial noise to further interfere with the eavesdroppers. Simulation results show that the proposed algorithm outperforms the baseline round-robin scheduling scheme and the existing reference algorithm.

1. Introduction

Cognitive radio (CR) has attracted a lot of research attention due to its high spectrum efficiency by allowing the secondary user (SU) to share the spectrum allocated to the primary user (PU) [1]. In such networks, the degradation of the quality of service (QoS) of the PU shall be limited. Various issues in CR networks have been investigated, such as performance analysis [2,3] and resource allocation [4,5].

This paper is interested in a scenario where the PU is eavesdropped by malicious eavesdroppers (EAVs). In such scenario, the PU secrecy performance is usually measured by secrecy rate or secrecy outage probability, and the existence of the SU shall guarantee that the degradation of the PU secrecy QoS is acceptable. In this context, the works in [6,7] investigated the PU secrecy rate and the secrecy outage probability with the interference from the SU. However, the PU secrecy QoS was not protected under the interference from the SU in [6,7]. In [8], the power allocation problem for the SU was investigated under the constraint that the probability of non-zero PU secrecy rate is above a certain threshold. In [9], the PU and the SU secrecy rates were maximized under the minimum signal to interference and noise ratio (SINR) constraint at the PU. In [10], the PU secrecy rate was maximized under the constraints that the PU secrecy outage probability is under a certain threshold and the SU throughput is above a certain level. Note that the works in [8–10] did not clearly restrict the impact of the SU on the PU secrecy performance. Notably, in [11], we proposed to guarantee the PU secrecy QoS by restricting the increase of the PU secrecy outage probability due to SU transmission being zero and proposed a joint SU scheduling and power allocation scheme to maximize the SU ergodic transmission rate. Further in [12], we considered to maximize the SU ergodic secrecy rate with SUs also facing security threats from EAVs. Note that in [11,12], exactly one SU was assumed to be scheduled for information transmission and other SUs were assumed to be silent.

This paper extends the work in [11] to consider that the PU is greedy and the unscheduled SUs can transmit artificial noise to further interfere with the EAVs. Specifically, we consider that the PU is greedy and requires the SU to minimize the PU secrecy outage probability as low as possible. In order to guarantee the QoS of the SU, the SU ergodic transmission rate is required to be higher than a certain level. In order to guarantee the QoS of the PU, the PU secrecy outage probability is required to be reduced by a certain value compared to the case without the SU transmission. We assume that at most one SU can be scheduled for information transmission while other unscheduled SUs are transmitting artificial noise to interfere with the EAVs. Under the above setups, we propose a joint SU scheduling and power allocation algorithm based on dual optimization. It is shown that our proposed algorithm significantly outperforms the baseline round-robin scheduling scheme and the scheme in [11].

The rest of the paper is organized as follows. The system model is given in Section 2. The joint SU scheduling and power allocation algorithm is proposed in Section 3. Section 4 verifies the proposed algorithm using simulations. Section 5 concludes the paper.

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2. System model and problem formulation

We consider a CR network with K uplink SUs and one cognitive base station (CBS) sharing a narrow spectrum band with a pair of PU transmitter (PTx) and PU receiver (PRx) who is eavesdropped by N EAVs. The sets of SUs and EAVs are denoted by $\mathbb{K}$ and $\mathbb{N}$, respectively. All the channels are assumed to be block fading and the channel power gains from PTx to PRx, PTx to the CBS, PTx to EAV $n \in \mathbb{N}$, SU $k \in \mathbb{K}$ to the CBS, SU $k \in \mathbb{K}$ to PRx, and SU $k \in \mathbb{K}$ to EAV $n \in \mathbb{N}$ are denoted by h_p,h_{ps},h_{pe}^n,h_s^k,h_{sp}^k and $h_{se}^{k,n}$, respectively. The noise power is denoted as σ^2. The channel state information (CSI) on all the channel power gains is assumed to be available at the SUs. Thus, the result obtained in this paper can serve as a performance upper bound for the case of imperfect CSI. Practically, the values of h_p,h_{ps},h_s^k and h_{sp}^k can be obtained by proper signaling among the CBS, the SUs and the PU as proposed in [13], while the values of h_{pe}^n and $h_{se}^{k,n}$ can be obtained by assuming that the EAVs are known users in the network and are momentarily active, or can be obtained by deploying wireless sensors close to the EAVs and letting them feed the estimated channel power gains back to the SUs.

When the SUs are not present, the PU secrecy rate and the PU secrecy outage probability are given by [11]

$$C_{wos} = \left(\log_2\left(1 + \frac{p_p h_p}{\sigma^2}\right) - \log_2\left(1 + p_p \max_{n\in\mathbb{N}} \frac{h_{pe}^n}{\sigma^2}\right)\right)^+, \tag{1}$$

and

$$\varepsilon_p = \Pr(C_{wos} < R_p), \tag{2}$$

respectively, where p_p denotes the transmit power of the PU, R denotes the predefined target PU secrecy rate, $(\cdot)^+$ denotes $\max(\cdot,0)$, and $\Pr(\cdot)$ denotes the probability. Note that the value of ε_p is fixed if p_p,R, the distribution of h_p and h_{pe}^n are provided.

When the SUs are present, at most one SU is scheduled to transmit information to the CBS while the other SUs are transmitting artificial noise to interfere with the EAVs to improve the PU secrecy outage probability. We assume that the information signals transmitted by the scheduled SU are treated as interference at the PU and the EAVs. We also assume that the artificial noise transmitted by the unscheduled SUs can be canceled at the PU and the CBS but cannot be canceled at the EAVs. Since all the SUs can be used to send artificial noise when no SU is scheduled for information transmission, we denote SU 0 as a virtual SU and schedule it for information transmission if all the actual SUs are sending artificial noise. Since SU 0 is virtual, the channel power gains related to it are zero. In what follows, SU 0 is considered to be included in the SU set $\mathbb{K}$.

Suppose that SU k is scheduled to transmit information to the CBS with transmit power p_s^k. Let P_{max} denotes the maximum transmit power limit of the SUs. In order to interfere the EAVs as much as possible, the unscheduled SUs are assumed to transmit the artificial noise at their maximum power P_{max}. Then, the PU secrecy rate with scheduled SU k can be written as

$$C_{ws}^k = \left(\log_2\left(1 + \frac{p_p h_p}{\sigma^2 + p_s^k h_{sp}^k}\right) - \log_2\left(1 + \max_{n\in\mathbb{N}} \frac{p_p h_{pe}^n}{\sigma^2 + P_{max}\sum_{l\neq k, l\in\mathbb{K}} h_{se}^{l,n} + p_s^k h_{se}^{k,n}}\right)\right)^+. \tag{3}$$

Let ρ^k denote the binary SU scheduling index. Specifically, $\rho^k = 1$ indicates that SU k is scheduled for information transmission and vice versa. The PU secrecy outage probability can be then calculated as

$$\varepsilon_p^c = \Pr\Big(\sum_{k\in\mathbb{K}} \rho^k C_{ws}^k < R_p\Big). \tag{4}$$

In order to persuade the PU to let the SUs share its spectrum, the PU secrecy outage probability with the SUs is required to be reduced to a desired target level, as given by $\varepsilon_p^c \leqslant \varepsilon_p - \triangle\varepsilon_p$, where $\triangle\varepsilon_p$ is the PU secrecy outage probability reduction. Define $\varepsilon_0 = \varepsilon_p - \triangle\varepsilon_p$. We term the constraint $\varepsilon_p^c \leqslant \varepsilon_0$ as the minimum PU secrecy outage probability reduction constraint. Besides, to provide a satisfactory QoS for the SUs, the SU ergodic transmission rate is required to be higher than a desired threshold, as given by

$$C_s = E\left\{\sum_{k\in\mathbb{K}} \rho^k \log_2\left(1 + \frac{p_s^k h_s^k}{\sigma^2 + p_p h_{ps}}\right)\right\} \geqslant R_s, \tag{5}$$

where $E\{\cdot\}$ denotes the expectation and R denotes the predefined target SU ergodic transmission rate.

Our aim is to minimize the PU secrecy outage probability by optimizing SU scheduling and power allocation under the aforementioned constraint. The optimization problem is formulated as

$$\text{(P1)}: \min_{\{\rho^k\},\{p_s^k\}} \varepsilon_p^c \tag{6}$$

$$\text{s.t. } \varepsilon_p^c \leqslant \varepsilon_0, \tag{7}$$

$$C_s \geqslant R_s, \tag{8}$$

$$0 \leqslant p_s^k \leqslant P_{max}, \forall\, k \in \mathbb{K}, \tag{9}$$

$$\sum_{k\in\mathbb{K}} \rho^k = 1, \tag{10}$$

$$\rho^k \in \{0,1\}, \forall\, k \in \mathbb{K}, \tag{11}$$

The constraint in (10) indicates that one and only one SU (including the virtual SU) is scheduled for information transmission at one time.

3. Joint user scheduling and power allocation

The problem (P1) may be infeasible due to the conflicting constraints in (7) and (8). To solve (P1), we can first solve (P1) without the constraint in (7) and then check whether the constraint in (7) is satisfied. The problem (P1) is solved if the constraint in (7) is satisfied and is infeasible if the constraint in (7) is violated. It is noted that if the problem (P1) is infeasible, we can make it feasible by either decreasing $\triangle\varepsilon_p$ or R_s to make the constraint in (7) or the constraint in (8) more relaxed.

In what follows, we assume that the constraint in (7) is inactive and derive the optimal solution for (P1). The following indicator function is introduced as

$$\chi_p^k = \begin{cases} 0, & C_{ws}^k \geqslant R_p \\ 1, & C_{ws}^{k,m} < R_p \end{cases}. \tag{12}$$

Then, the expression of can be rewritten as $\varepsilon_p^c = E\{\sum_{k\in\mathbb{K}} \rho^k \chi_p^k\}$.

Although the problem (P1) is nonconvex, by relaxing ρ^k as $0 \leqslant \rho^k \leq 1$, the time-sharing condition can be verified to be satisfied for (P1) [14]. Thus, (P1) can be solved by the Lagrange duality method [15]. The Lagrangian function is written as

$$L(\{\rho^k\},\{p_s^k\},\mu) = E\{\sum_{k\in\mathbb{K}} \rho^k \chi_p^k\} - \mu\left(E\left\{\sum_{k\in\mathbb{K}} \rho^k \log_2\left(1 + \frac{p_s^k h_s^k}{\sigma^2 + p_p h_{ps}}\right)\right\} - R_s\right), \tag{13}$$

where μ is the non-negative dual variable associated with the constraint in (8). The Lagrange dual function is written as

$$G(\mu) = \min_{\{\rho^k\},\{p_s^k\}} L(\{\rho^k\},\{p_s^k\},\mu) \tag{14}$$

$$\text{s.t. } 0 \leqslant \rho^k \leq 1, \forall\, k \in \mathbb{K}, \tag{15}$$

and constraints (9)–(10).

The above problem can be solved by solving parallel subproblems