Int. J. Electron. Commun. (AEÜ) 68 (2014) 747–755

Contents lists available at ScienceDirect

International Journal of Electronics and Communications (AEÜ)

journal homepage: www.elsevier.com/locate/aeue

Ergodic capacity and outage probability optimization for secondary user in cognitive radio networks under interference outage constraint

Ding Xu[a,*], Qun Li[b]

[a] Wireless Communication Key Lab of Jiangsu Province and Key Lab of Broadband Wireless Communications and Sensor Network Technology, Ministry of Education, Nanjing University of Posts and Telecommunications, Nanjing, China
[b] School of Computer Science & Technology, Nanjing University of Posts and Telecommunications, Nanjing, China

ARTICLE INFO

Article history:
Received 14 October 2013
Received in revised form 9 January 2014
Accepted 24 February 2014

Keywords:
Cognitive radio
Ergodic capacity
Outage probability
Power allocation

ABSTRACT

This paper considers a cognitive radio network where a secondary user (SU) coexists with a primary user (PU). The interference outage constraint is applied to protect the primary transmission. The power allocation problem to jointly maximize the ergodic capacity and minimize the outage probability of the SU, subject to the average transmit power constraint and the interference outage constraint, is studied. Suppose that the perfect knowledge of the instantaneous channel state information (CSI) of the interference link between the SU transmitter and the PU receiver is available at the SU, the optimal power allocation strategy is then proposed. Additionally, to manage more practical situations, we further assume only the interference link channel distribution is known and derive the corresponding optimal power allocation strategy. Extensive simulation results are given to verify the effectiveness of the proposed strategies. It is shown that the proposed strategies achieve high ergodic capacity and low outage probability simultaneously, whereas optimizing the ergodic capacity (or outage probability) only leads to much higher outage probability (or lower ergodic capacity). It is also shown that the SU performance is not degraded due to partial knowledge of the interference link CSI if tight transmit power constraint is applied.

1. Introduction

Motivated by the fact that many parts of the licensed spectrum are used inefficiently under the current traditional spectrum regulation policy, the concept of cognitive radio (CR) is proposed as a promising solution for improving the spectrum efficiency [1]. Secondary users (SUs) in CR networks can coexist with the primary users (PUs) on the same spectrum band in the spectrum sharing model provided that the interference caused by the former to the latter is below a certain threshold [2].

Power allocation for the SU is an important operation not only to ensure that the SU causes acceptable interference to the PU but also to maximize the SU utility. In this regard, many studies on the problem of power allocation for the SU have recently been appeared in the literature. In [3], under the constraint that the outage probability of the PU is not degraded by the SU, the optimal power allocation strategy was proposed to maximize the SU rate. In [4], under the peak/average transmit power and the peak/average interference power constraints, the optimal power allocation strategies to maximize the ergodic capacity and the outage capacity of the SU were derived and it is shown that the SU under the average power constraint achieves higher capacity gain over the peak power constraint. Under the same power constraints, [5] obtained the optimal power allocation to minimize the average bit error rate (BER) of the SU. The authors in [6] proposed the optimal power allocation strategy to maximize the SU rate under the PU rate loss constraint. In their further work [7], the optimal power allocation strategies to maximize the SU ergodic capacity and outage capacity under the PU outage constraint were derived. In [8], the optimal power allocation to maximize the SU throughput under the signal to noise ratio (SINR) constraint with PU's limited cooperation was derived. It is shown in [8] that the SU throughput is greatly increased compared to the non-cooperative case. In [9], a family of power allocation strategies were presented and established that the family can balance the SU rate against the individual PU rate loss constraint. In [10], utilizing opportunistic subchannel access, two power allocation strategies were proposed to maximize the SU rate and the sum rate of the SU and the PU, respectively. Under both the PU and the SU SINR constraints, [11] studied the problem of power allocation to maximize the sum rate of the SU and the PU and provided the solutions for both low and high SINR scenarios. In [12], the authors proposed a distributed power allocation scheme

* Corresponding author.
E-mail address: xuding.bupt@gmail.com (D. Xu).

http://dx.doi.org/10.1016/j.aeue.2014.02.014
1434-8411/

based on Nash bargaining solution and presented theoretic analysis of the convergence of the distributed scheme. In their further work [13], using Stackelberg game theory to model the interaction between the SU and the PU, a price-based power allocation strategy was proposed to maximize the revenues of the SU and the PU. In [14], the optimal power allocation to minimize the outage probability of the SUs was derived for interference-limited cognitive multiple access channels. In [15], a power allocation strategy to maximize the average sum rate of a CR multicast network under the service outage constraint was proposed. It is shown in [15] that the proposed strategy significantly outperforms the conventional scheme.

In this paper, we study the problem of power allocation for the SU to jointly maximize the ergodic capacity and minimize the outage probability of the SU, under the average transmit power constraint and the interference outage constraint to protect the PU transmission. Ergodic capacity is the maximum achievable rate averaged over all the fading states, which is used to measure the performance of the SU on a long-term basis. Outage probability is the probability that the rate is below a predefined target rate (outage capacity), which is a performance metric of the SU on a short-term basis. Different from existing work, such as [4,7,14], which only considered ergodic capacity or outage probability as the performance indicator, this paper takes both ergodic capacity and outage probability of the SU into consideration. The optimal power allocation strategy is then derived assuming that the SU has the perfect knowledge of the instantaneous channel state information (CSI) of the interference link between the SU transmitter and the PU receiver. Besides, to manage more practical situations, we also consider the partial CSI scenario that the SU only knows the distribution of the interference link channel and derive the corresponding optimal power allocation strategy. Simulation results show that our proposed strategies can achieve high ergodic capacity and low outage probability at the same time, while the power allocation strategy optimizing the ergodic capacity (or outage probability) only leads to much higher outage probability (or lower ergodic capacity). It is also shown that, under tight transmit power constraint, the SU performance is not degraded due to partial knowledge of the interference link CSI.

The remainder of the paper is organized as follows. Section 2 introduces the system model. Sections 3 and 4 derive the optimal power allocation strategies with perfect and partial CSI of the interference link, respectively. Section 5 presents the simulation results. Finally, Section 6 concludes the paper.

2. System model

We consider one secondary link coexists with one primary link as in [4,5,7]. The PU and the SU share the same narrow band for transmission. The primary link consists of a PU transmitter (PT) and a PU receiver (PR), while the secondary link consists of a SU transmitter (ST) and a SU receiver (SR). Let g_{ss}, g_{sp} and g_{ps} denote the instantaneous channel gains of the ST-SR link, the ST-PR link and the PT-SR link, respectively. All the channels involved are assumed to be independent block fading channels. The perfect knowledge of g_{ss} and g_{ps} is assumed to be available at the SU[1]. As for g_{sp}, Section 3 assumes that the SU knows g_{sp} perfectly and Section 4 assumes that only the distribution of g_{sp} is known at the SU. The noise power at the SR is assumed to be σ^2.

To protect the PU transmission, the interference outage constraint is applied as

$$Pr(p_s g_{sp} > Q) \le \varepsilon, \tag{1}$$

where p_s is the transmit power the ST, Q is the predefined interference power threshold and ε is the interference outage probability limit. In addition, the transmit power of the ST is also constrained as

$$\mathbb{E}\{p_s\} \le P, \tag{2}$$

where P is the average transmit power limit.

3. Optimal power allocation with perfect CSI

In this section, the problem of power allocation to jointly maximize the ergodic capacity and minimize the outage probability of the SU subject to the average transmit power constraint and the interference outage constraint is studied. The optimization problem is stated as (**P1**)

$$\begin{aligned} &\max_{p_s \ge 0} \quad \mathbb{E}\{\log_2(1+\gamma)\} \text{ and } \min_{p_s \ge 0} Pr(\log_2(1+\gamma) < R) \\ &\text{s.t.} \quad (1), (2), \end{aligned} \tag{3}$$

where $\gamma = p_s g_{ss} / \sigma^2 + P_p g_{ps}$ is the SINR of the SU, P_p is the transmit power of the PU and R is the target rate. The above multi-objective functions in **P1** can be transformed to a single-objective function by applying scalarization methods [16]. To make the two objective functions in (3) comparable, we normalize the ergodic capacity as $\mathbb{E}\{\log_2(1+\gamma)\}/C_{\max}$, where C_{max} is the maximum ergodic capacity under the constraints in (1) and (2) which can be obtained by solving the following problem

$$\begin{aligned} C_{\max} = &\max_{p_s \ge 0} \quad \mathbb{E}\left\{\log_2(1+\gamma)\right\} \\ \text{s.t.} \quad & (1), (2). \end{aligned} \tag{4}$$

Therefore, the two objective functions $\mathbb{E}\{\log_2(1+\gamma)\}/C_{\max}$ and $\Pr(\log_2(1+\gamma) < R)$ are dimensionless quantities within $[0, 1]$, which are comparable. Then **P1** can be reformulated as (**P2**)

$$\begin{aligned} &\min_{p_s \ge 0} \frac{\omega}{C_{\max}} \mathbb{E}\left\{-\log_2(1+\gamma)\right\} + (1-\omega) Pr(\log_2(1+\gamma) < R) \\ &\text{s.t.} (1), (2), \end{aligned} \tag{5}$$

where weight factor ω ($0 \le \omega \le 1$) represents the relative importance of the objective function $\mathbb{E}\{-\log_2(1+\gamma)\}/C_{\max}$ to the objective function $\Pr(\log_2(1+\gamma) < R)$[2]. As for solving the problem in (4) to obtain the value of C_{max}, the same power allocation strategy proposed in what follows to solve **P2** can be used by setting $\omega = 1$ and $C_{max} = 1$ in (5).

For the convenience of later analysis, the following indicator functions are introduced as

$$\chi_o(p_s) = \begin{cases} 1, & \log_2(1+\gamma) < R \\ 0, & \log_2(1+\gamma) \ge R, \end{cases} \tag{6}$$

and

$$\chi_i(p_s) = \begin{cases} 1, & p_s g_{sp} > Q \\ 0, & p_s g_{sp} \le Q. \end{cases} \tag{7}$$

[1] In practice, g_{ss} can be obtained by classic channel estimation technologies, while g_{ps} can be obtained at the SU by measuring the received signal power from PT assuming that the SU knows the transmit power of PT [7].

[2] Note that how to choose the value of ω depends on the preferences for the ergodic capacity and the outage probability.