Journal of Network and Computer Applications 41 (2014) 379–388

Contents lists available at ScienceDirect

Journal of Network and Computer Applications

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

Joint power control and spectrum access in cognitive radio networks

Qingyang Song, Zhaolong Ning*, Yang Huang, Lei Guo, Xiaobing Lu

School of Information Science and Engineering, Northeastern University, Shenyang 110819, P.R. China

ARTICLE INFO

Article history:
Received 4 July 2013
Received in revised form
21 January 2014
Accepted 12 February 2014
Available online 24 February 2014

Keywords:
Wireless networks
Cognitive radio (CR) networks
Differential evolution (DE)
Power control
Dynamic spectrum access (DSA)

ABSTRACT

Cognitive Radio (CR) is proposed to overcome the problem of spectrum underutilization and congestion caused by the increasing demand of wireless services and applications. It is still a challenge to improve the spectrum efficiency of the secondary network for Secondary (unlicensed) Users (SUs) and avoid imposing interference to the Primary (licensed) Users (PUs). In this paper, we propose a joint power control and spectrum access scheme for the CR network. By addressing the power allocation problem and exploiting a Dynamic Spectrum Access (DSA) scheme (which is based on the power allocation and also aims at improving the secondary network throughput) from a cooperative-game perspective, our joint scheme can improve the throughput of the secondary network and guarantee the SUs' fairness, without imposing overlarge interference to the PUs. Numerical results reflect that, compared with previous studies, our joint power control and spectrum access scheme presents advantages in comprehensive performance (e.g., spectrum efficiency, fairness and throughput). Beyond a theoretical framework, we solve the optimization problem with the Differential Evolution (DE) algorithm which is more feasible to be implemented in practice.

1. Introduction

The rapidly developed wireless services and applications have an increasing demand of spectrum resource which is actually limited (Talay and Altilar, 2013). However, the conventional access policy only allows licensed users, who are called Primary Users (PUs), to utilize pieces of licensed spectrums regardless of whether PUs are active or inactive, which causes spectrum underutilization. In order to address the above problems, the technology of Cognitive Radio (CR) was proposed and advocated, which enables Secondary (unlicensed) Users (SUs) to access and utilize the licensed spectrum. Recently, the US Federal Communications Commission (FCC) also made a decision to permit SUs to access the licensed spectrum without imposing interference to PUs (Salameh and Badarneh, 2013).

In the literature, according to the way that SUs access the licensed spectrum, there are currently three main CR network implementation paradigms: overlay, Underlay Spectrum Sharing (USS), and Opportunistic Spectrum Access (OSA) (Goldsmith et al., 2009). The overlay mode allows SUs to transmit at any power provided that PUs' performances are not degraded. It requires that each SU uses one part of the transmission power to repeat a PU's packets and exploits the other part of power to transmit his own packets with sophisticated processing such as channel coding and network coding (Xin et al., 2010). However, since the SU should get knowledge of the packets of the PU's subsequent transmission, the application scenario for overlay is limited in common CR networks (Zhang and Su, 2011). Therefore, in this paper, our dynamic spectrum access scheme mainly considers the USS and OSA modes.

The USS mode allows SUs to coexist with active PUs and exploits the interference temperature method to constrain the SUs' total power below the PUs' interference threshold, such that each PU's uplink Signal to Interference-plus-Noise Ratio (SINR) can be maintained as an acceptable value (Liang et al., 2011). In our work, we consider that the OSA mode opportunistically utilizes spectrum holes in time domain, which enables the SUs to access the licensed spectrum when the absence of PUs is detected (Song et al., 2012). Obviously, both the USS and OSA modes guarantee PUs' throughput performance at the cost of degrading SUs' Quality of Service (QoS) performance, namely, constraining SUs' transmission powers and access opportunities, which motivates us to improve SUs' performance. Moreover, in practice (e.g., a 24-h period), it has been demonstrated in Yang et al. (2010) that SUs' performance should be improved in dynamic spectrum utilization situations. Thus, in different channel utilization situations, access modes dynamic selection, power optimization, and data transmission duration optimization should be performed to improve SUs' throughput performance. However, to the authors' knowledge, many current works only focus on the single aspect: power or rate control (Han et al., 2007; Zhang and Su, 2011; Fan et al., 2011;

---

* Corresponding author.
E-mail addresses: songqingyang@ise.neu.edu.cn (Q. Song), zhaolongning@gmail.com (Z. Ning), hyocean198927@gmail.com (Y. Huang), guolei@ise.neu.edu.cn (L. Guo), jerrylu0908@gmail.com (X. Lu).

http://dx.doi.org/10.1016/j.jnca.2014.02.005
1084-8045

Yang et al., 2010; Ni and Zarakovitis, 2012), or spectrum access (Pei et al., 2007; Liang et al., 2008; Li et al., 2014), while the joint design has not been adequately investigated. Thus, it is necessary to investigate the joint power control and spectrum access scheme in behalf of the SUs while protecting the PUs' benefits, which is also significant for the design of an adaptive Medium Access Control (MAC) policy in the uplink CR network (Zhang and Su 2011; Liang et al., 2008).

In the context of power control in wireless networks, many previous studies addressed the power allocation problem through non-cooperative games (Han et al., 2007; Zhang and Su, 2011; Fan et al., 2011). In these games, selfish nodes maximize their own utilities without considering other nodes' benefits. However, in CR networks, SUs are motivated to cooperate to enhance their own throughput (Ni and Zarakovitis, 2012), and cooperative games are more suitable for CR networks. It is noted that both spectrum efficiency and fairness, which are the most common metrics in the power control problem, can be handled by the Nash's axioms. Specifically, the Pareto efficiency guarantees that only one power allocation strategy can provide the maximum spectrum efficiency, and the independence of irrelevant alternatives provides the proportional fairness. Therefore, recent works (Yang et al., 2010; Ni and Zarakovitis, 2012) applied the Nash bargaining game to address the power allocation problem. Thus, the power control part in our work still formulates the optimization problem as a cooperative game based on the Nash Bargaining Solution (NBS). Different from the existing approaches, our work exploits the Differential Evolution (DE) algorithm (Storn and Price, 1997), which is a population-based stochastic global optimization algorithm, to solve the NBS-based power control problem. DE is of simple structure, easy use, speediness and robustness than genetic algorithms (Storn and Price, 1997). Further, DE does not require a utility function to be differentiable as in the conventional methods of solving the optimization problems, which relaxes computing complexity and makes DE feasible to be deployed.

In summary, our joint power control and spectrum access scheme addresses the power allocation problem from the perspective of cooperative game and obtains the optimal solution with the DE algorithm; then, based on the results of the power allocation scheme, we optimize the length of sensing slot and adaptively select an access mode to achieve optimal spectrum efficiency under different channel utilization states, where we also demonstrate a comparative study between the performance of our proposed DSA scheme and that of conventional cognitive radio paradigms, as well as the DSA scheme in previous studies.

The remainder of this paper is organized as follows. Section 2 describes the system model of this paper. In Section 3, we discuss the proposed power control scheme. Then, Section 4 discusses our DSA scheme. Section 5 evaluates the proposed joint power control and spectrum access scheme. Finally, conclusions are drawn in Section 6.

2. System model

2.1. Network model

In this paper, a cognitive radio network is considered as a heterogeneous system where the primary network is a TV network and the CR network is a Code Division Multiple Access (CDMA) based cellular network, as depicted in Fig. 1. In the primary network, a Primary Base Station (PBS) broadcasts packets to its stationary PUs through downlink channels over a licensed frequency band. In the CR network, a Secondary Base Station (SBS) communicates with the SUs on dedicated downlink channels without causing interference to the PUs. The distance between the PBS and the SBS is assumed to be so large that there is little interference at the SBS caused by the PBS. In the considered networks, the PBS and SBS respectively coordinate PUs' and SUs' uplink transmissions, and the SBS is responsible to perceive the Pus' states.

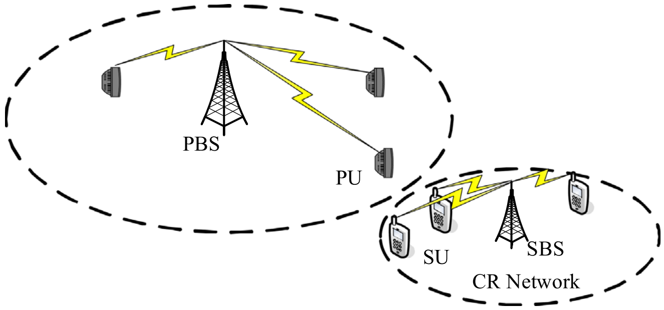

Fig. 1. Example of network model. Some SUs and a SBS comprise the secondary network. To transmit messages to the SBS, the SUs need to opportunistically access or concurrently access the licensed spectrum with the PUs in the primary network.

2.2. Spectrum sensing and data transmission modes

As shown in Fig. 2, the CR network operates on a frame-by-frame basis. The duration of each frame consists of one sensing slot τ and one data transmission slot $T-\tau$, thus periodic spectrum sensing is carried out.

Spectrum holes appear when the licensed frequency band is temporarily not used by the PUs. In the OSA mode, the SUs have to frequently sense the licensed spectrum, and then access the licensed spectrum once the spectrum holes have been detected (Liang et al., 2011). However, in this scheme, frequent spectrum sensing causes overhead, which mitigates network throughput. Different from the OSA mode, the USS mode allows the SUs to share the licensed spectrum with the active PUs, provided the transmission power levels of the SUs are restricted to ensure the interference to the PUs is below tolerable thresholds. Therefore, our work jointly investigates power control and spectrum access in the implementation of the CR technology.

The DSA scheme proposed by our work enables the SUs to perform both the OSA mode and the USS mode, which dynamically chooses the transmission mode according to both spectrum sensing result and expected throughput (which is elaborated in Section 4.3). Power control and spectrum access schemes are developed to maximize the throughput of the cognitive network, which will be elaborated in Sections 3 and 4.

2.3. Licensed channel model

The licensed channel in the primary network is regarded as a Markov process which persistently switches between ON and OFF states (Liang et al., 2008). The ON (or OFF) state represents that the licensed channel is (or is not) occupied by the PUs. That is whether the spectrum holes are available is decided by the PUs' activities. For an alternating renewal channel, let variables λ_1 and λ_0 respectively represent the mean durations of the ON and OFF states, and they follow the exponential distribution. Set the null hypothesis H_0 as "the licensed spectrum is idle", and set the alternative hypothesis H_1 as "the licensed spectrum is busy"; the probability of the licensed channel being idle is given by

$$P(H_0)=\frac{\lambda_0}{\lambda_0+\lambda_1}, \tag{1}$$