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Strategic behavior and admission control of cognitive radio systems with imperfect sensing☆

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ABSTRACT

This paper conducts the game-theoretic analysis of the behavior of secondary users (SUs) in a cognitive radio (CR) system with a single primary user (PU) band and sensing failures. It is assumed that the sensing errors occur only when an SU is being served by the PU band. It may incorrectly detect there is no PU accessing to the band (called *misdetection*), or it may wrongly sense that there is an incoming PU but in fact it is not true (called *false alarm*). When a misdetection occurs, the PU will be blocked and the ongoing SU will drop into a retrial pool called orbit in which it can retry for service after some random time. When a false alarm occurs, the ongoing SU will drop into the retrial orbit. That is, both errors will degrade the quality of service of the system. First, we investigate how the arriving SUs make decisions on whether to join or balk the system which can be studied as a non-cooperative game. We obtain the equilibrium behavior of SUs who want to maximize their benefit in a selfish distributed manner. Second, we derive the socially optimal strategies of SUs from the perspective of the social planner. To use the PU band more efficiently, an appropriate admission fee imposed on each joining SU is proposed based on the gap between the equilibrium strategy and the socially optimal strategy. Finally, theoretic results are validated by numerical analysis and the effect of various parameters on the behavior of SUs is illustrated.

1. Introduction

To utilize the wireless spectrum resources more efficiently, the concept of cognitive radio (CR) was first introduced by Mitola [1] in which the spectrums can be shared among different users. Indeed, a great number of studies have shown that the utility of the spectrum is very low under conventional static spectrum access strategies [2]. As the increasing demand from users but the decreasing amount of dedicated spectrum, more and more network users have to choose dynamic spectrum access (DSA) which has been considered as a viable solution to alleviate this spectrum scarcity and improve radio communication efficiency. It allows the secondary users (SUs) to use the unoccupied spectrum in an opportunistic way so that it will not cause harmful interference to the primary users (PUs). Therefore, spectrum sensing plays an important role in CR as it allows the SUs to differentiate between the spectrum used and the spectrum holes which are unused.

Spectrum sensing performed by a secondary user to detect the presence of PUs is a fundamental requirement in CR networks and many detection techniques have been proposed in the literature. However, due to unreliable channel and signal interference, sensing failures always occur which negatively impact the performance of primary users as well as other secondary users. These sensing failures can be classified into two types [3,4], i.e., false alarms and misdetections, which increase the amount of interference to the PUs and the overlooked spectrum holes in the system. In [3–6,8–11], the authors took imperfect sensing into account. In [3], the probability of collision to primary users increases with the probability of miss-detection and the probability of successful secondary communications decreases with the primary traffic arrival rate were obtained. Suliman et al. [5] extended the analysis in [3] to capture the effect of the false alarm rate on the operation of CR networks. In [4], the multiple-channel CR system with unreliable spectrum sensing was discussed and the authors employed a two-dimensional continuous-time Markov chain model to analyze the system. While a discrete-time Markov chain is used to model a CR system with imperfect sensing in [6,7]. In [8], the performance of a multichannel CR network with spectrum handover enabled by SUs and imperfect spectrum sensing was studied. A novel spectrum access mechanism [9] was proposed to alleviate the negative effects of imperfect

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spectrum sensing under a time-slotted cognitive setting with buffered primary and secondary users. Homayouni and Ghorashi [10] considered the issue of sub-banding the secondary users' channel in CR networks considering unreliable spectrum sensing. Recently, Akin and Gursoy [11] focused on channel sensing which impacted the estimation method to obtain channel state information. However, these works neglected the random access or competition between different SUs and the admission control of these users.

In CR systems, in most cases there is no centralized controller to regulate channel access. Hence, a rational SU behaves strategically relying on local information and has to adapt to the environment quickly. Game-theoretic analysis of spectrum sharing criteria has been proposed, see [12–14]. Several studies in the literature [15–19] considered the decentralized behavior of SUs and adopted queueing-game approach to investigate the interactions between PUs and SUs in the CR networks. Jagannathan et al. [15] illustrated SUs utilizing the spectrum holes in the unobservable case but they did not consider the optimization strategy. Li and Han [16] and Do et al. [17] investigated the socially optimal strategy of SUs in a CR base station. In [18], both SUs and PUs were assumed to leave the base station when a collision happened. However, spectrum sensing is assumed to be perfect in these works.

Recently, Wang et al. [20] proposed a constant retrial model characterizing the behavior of arriving SUs. However, the retrial rate is a constant which is independent of the number of SUs in the orbit which means only the head customer in the queue can retry for accessing to the server. In this paper we focus on the game-theory based equilibrium behavior among all SUs. More specifically, each arriving SU decides whether to join the system or not according to the expected sojourn time until it gets service finally. This paper overcomes the limitations of the first-come-first-served (FCFS) discipline used in [15–18]. Evidently it is not realistic to assume a queue with FCFS discipline in wireless environments. When the PU band is sensed unavailable, an SU will enter the retrial orbit and retry after some period of time. The SU will finish transmission if there is no PU arriving with perfect sensing. While with sensing failures, the amount of interference to the PUs and the overlooked spectrum holes increase, the SU will spend more time to complete information transmission.

Comparing with the existing related works in CRNs, our major contributions of this paper are as follows. First, we construct a random access CR system with imperfect sensing and a retrial queueing mechanism is used to character the SUs' repeated transmissions due to the interruption by PUs and the spectrum sensing failures. We successfully formulate the competition problem among SUs as a non-cooperative queueing game with no information level. Imposed by a reward-cost structure, we derive the equilibrium and socially optimal strategies for all SUs. Furthermore, we observe that it is possible for the administrator of CR system to impose an appropriate admission fee on SUs who decide to join the system. By this treatment, the gap between equilibrium strategy and socially optimal strategy will be eliminated and it can make the SUs behave in a socially way.

The paper is organized as follows. Section 2 we gives the model description and assumptions. In Section 3 we derive the average sojourn time for the arriving SUs who decide to enter the CR system. They are not informed of the system's information. The SUs' behavior with PUs' interruptions are studied and the equilibrium joining probabilities and socially optimal strategies of SUs are obtained. Based on the gap between individual strategy and social strategy, we propose an appropriate admission fee to coincide these two strategies with each other. Section 5 illustrates the effect of various performance measures on the system by analytical and numerical comparisons. Finally, in Section 6, we give some necessary conclusions.

2. Model description

We focus on a cognitive radio system with a single PU band that opportunistically used by SUs, which means that the PU band can transmit either one PU packet or one SU packet at one time. This PU band can be regarded as a server. As PUs have high priorities to use the PU band, a PU will get service immediately whenever there is an SU being served or the PU band is in an idle state. The server resumes to be shared by SUs until the PU completes transmissions. We characterize this process of PUs' interruptions and SUs' corresponding reactions by a retrial queueing system [21].

The primary SUs and PUs arrive to the system according to a Poisson process with rate λ_s and λ_p respectively. The service times that SUs and PUs complete transmissions are exponentially distributed with rate μ_s and μ_p respectively. We assume that each arriving SU accesses to the PU band with a probability and if the server is sensed free, the SU starts service immediately. Otherwise, both the entering SU who senses the server unavailable and the SU who is squeezed out by PUs during service will enter the retrial pool. When the PU band becomes idle, the SUs in the retrial orbit will try their luck to access to the PU band repeatedly and the retrial times are assumed as a Poisson process with intensity θ. The repeated request of an SU will disappear when it completes transmission. We assume that the SU arrivals and PU arrivals, service times for SUs, service times for PUs and retrial times are mutually independent.

With perfect detection of primary users, the quality-of-service experienced by PUs will not be affected by SUs. However, in practice, sensing failures always inevitably happen and it has effects on both PUs and SUs. One kind of disruption events may occur to a PU during transmission when an arriving SU senses the PU band incorrectly and miss-senses that the PU band is idle. A second type of disruption events to a PU may occur when an ongoing SU transmits through the PU band and it incorrectly detect there is no PU accessing to the PU band. We refer to such detection errors as class-A and class-B misdetection events, respectively. In this paper, we shall only consider class-B misdetection events. So when a misdetection event occurs, the PU will be blocked and the ongoing SU will drop into the retrial orbit. On the other hand, an ongoing SU may incorrectly sense that the PU band is busy when in fact the band is idle. We refer this type of error as a false alarm event. When a false alarm event happens, the ongoing SU will drop into the retrial orbit immediately. We denote by p_m and p_f the probabilities of misdetection and false alarm respectively.

Every arriving SU who wants to get service at the CR system can decide whether or not to join the system. We will consider the unobservable case that SUs do not know the information (i.e., whether the PU band is available or not and the total SUs in the retrial orbit) about the system. After each service completed, an SU will get a reward of R units. And the cost for waiting in the system is charged by C units per time unit. All SUs want to maximize their own benefit and they are neutral. They will make decisions on joining or balking according to their assessment on the reward against the costs.

For convenience, some important notations used are listed in Table 1. Denote by $\eta = (1 - p_m - p_f)\lambda_p, \xi = p_m\lambda_p + p_f\mu_s$, $\mu_s' = (1 - p_m - p_f)\mu_s$.

Based on the queueing-game theory (see [22]) we describe SUs'

Table 1
Important notations in this paper.

Symbol	Meaning
R	Reward for each service
C	Cost per time unit
λ_s	Arrival rate for primary SUs
λ_p	Arrival rate for primary PUs
μ_s	Transmission rate for SUs
μ_p	Transmission rate for PUs
θ	Retrial rate for SUs
p_m	The probability of misdetection
p_f	The probability of false alarm
p	Admission fee