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Multi-leader multi-follower Stackelberg model for cognitive radio spectrum sharing scheme

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ABSTRACT

Radio spectrum is one of the most scarce and variable resources for wireless communications. Therefore, the proliferation of devices and rapid growth of wireless services continue to strain the limited radio spectrum resource. Cognitive Radio (CR) paradigm is a promising technology to solve the problem of spectrum scarcity. In this paper, a new fair-efficient spectrum sharing scheme is proposed for cognitive radio networks. Based on the multiple-leader multiple-follower Stackelberg game model, the proposed scheme increases opportunistic use of the licensed radio spectrum. To adaptively use the spectrum resource, control decisions are coupled with one another; the result of the each user's decisions is the input back to the other user's decision process. Under widely diverse network environments, this adaptive feedback process approach can provide an effective way of finding a suitable solution. The simulation results demonstrate that the proposed scheme has excellent network performance, while other schemes cannot offer such an attractive performance balance.

1. Introduction

The emergence of new wireless technologies has created huge demand of radio spectrum. However, radio spectrum is a naturally limited and expensive resource around the world. Due to the limitation of radio spectrum, wireless communication networks suffer from the scarcity in spectrum resource [1,2]. Although almost all the spectrum has been allocated, the actual utilization measurement clearly shows that many portions of the radio spectrum are not used for a significant amount of time [3]. It becomes obvious that the present fixed frequency allocation strategy cannot accommodate the new emerging multimedia services. To avoid the inefficiency of spectrum usage, opportunistic or dynamic spectrum access strategy has been considered an effective solution for wireless networks [1–3].

For decades, research has been done to solve the problem of spectrum scarcity in a very dynamic environment. Cognitive Radio (CR) is widely regarded as one of the most promising technologies for improving the utilization of spectrum resources. CR is a paradigm for wireless communication that unlicensed users may access and use the spectrum when it is idle from licensed users. Therefore, the increased spectrum utilization in CR networks is achieved through spectrum sharing between licensed and unlicensed users [2]. For the proper spectrum sharing in CR systems, the spectrum trading process should be modeled effectively. Nowadays, the main idea of game theory has emerged as an effective way of designing the CR trading process [4].

Game theory is a field of applied mathematics that provides an effective tool in modeling the interaction among independent decision makers. It can describe the possibility to react to the actions of the other decision makers and analyze the situations of conflict and cooperation in real world. The rational decision makers, referred to as 'players'

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in a game model, try to maximize their expected benefits through strategy set. Many applications of game theory are related to economics, but it is also a powerful tool to model a wider range of telecommunications and network management [5–7].

Stackelberg games are a class of games in game theory; it is initially proposed by the German economist von Stackelberg in 1934 to explain some economic monopolization phenomena [8]. In a Stackelberg game, one player acts as a leader and the rest as followers, and the main goal is to find an optimal strategy for the leader, assuming that the followers react in such a rational way that followers optimize their objective functions given the leader's actions. Therefore, it can be the static bilevel optimization model [9]. In 1984, Sherali further extended the classical Stackelberg model by considering multiple leaders [10]. Multi-leader Stackelberg Game (MSG) model assumed the existence of more than one leader, with each leader's actions do not precipitate responses from other leaders. About MSG models, there are many applications in the field of economics, engineering and science. In particular, MSG model has some attractive features to understand the behavior of self-regarding and independent CR users [10–12].

Motivated by the above discussion, we propose a new MSG based spectrum sharing scheme that solves the joint problem of licensed and unlicensed users in CR networks. The main challenge is to use spectrum as efficiently as possible while ensuring fairness. To achieve this design goal, the proposed scheme consists of two different algorithms; leader-level algorithm for the licensed users and follower-level algorithm for unlicensed users. In the leader-level algorithm, licensed users make their decisions based on the egalitarian bargaining solution [13]. The result of licensed users' decision is the input back to the follower-level algorithm. In the follower-level algorithm, unlicensed users make their decisions by using the non-cooperative game [6,9]. Therefore, control decisions of two algorithms are hierarchically interconnected and can cause cascade interactions. By using this dynamics of feedback loop, licensed and unlicensed users can be interacting with one another and make their decisions in a way to reach an efficient network equilibrium.

The important features of the proposed scheme are: (i) ability to provide the relevant tradeoff between efficiency and fairness, (ii) a well-balanced network performance between licensed and unlicensed users, (iii) dynamically adjustable approach by considering the current network conditions, (iv) low complexity of decision mechanisms to make it practical for real network operations, and (v) adaptive feedback interactive process to approximate an efficient network equilibrium.

Recently, several Stackelberg game models for CR networks have been presented. The *Resource Pricing with Stackelberg Approach* (*RPSA*) scheme [2] investigated the resource allocation problem in CR networks. By using the Stackelberg model, this scheme solved the pricing process of licensed users and got the Nash equilibrium point. In addition, the *RPSA* scheme introduced a control parameter to quantify the negative impact. Therefore, licensed users can guarantee their services by keeping this parameter below a predefined threshold. The *Power Control and Channel Allocation* (*PCCA*) scheme in [4] suggested a game theoretical approach that allowed master–slave cognitive radio pairs to update their transmission powers and frequencies, simultaneously. Based on the Stackelberg game model, licensed frequency user became a leader and transmitted a virtual price for using the licensed frequency band. This approach was developed by constructing utility functions, which were potential functions. The *Distributed Optimization for Cognitive Radio* (*DOCR*) scheme [12] was designed as a Stackelberg game based hierarchical framework to optimize the CR network performance. By using a simple pricing function for licensed users, the *DOCR* scheme was implemented as a distributed algorithm to converge the Stackelberg equilibrium. In addition, the power allocation methods for unlicensed users had been derived, and the price for licensed users had been calculated. All the earlier work has attracted a lot of attention and introduced unique challenges. Compared to these schemes, the proposed scheme attains better performance for wireless network managements.

This paper is organized as follows. Section 2 presents the related work about wireless network spectrum sharing schemes based on the game theory. Section 3 describes the proposed algorithms in detail. In Section 4, performance evaluation results are presented along with comparisons with the schemes proposed in [2,4,12]. Finally, concluding remarks are given in Section 5.

2. Related work

Recently, several spectrum sharing schemes based on the game theory have been presented in research literature. The *Rate and Power Control* (*RPC*) scheme [14] is a control algorithm based on game model for wireless communication. This scheme introduced the classic form of non-cooperative power control model as a new framework. By considering the joint transmission rate and power control issues, the Nash equilibrium solution for either the transmit rate or the transmit power is achieved in the cognitive radio. In addition, a pricing function that relates to both transmit rate and power is introduced for improving the Pareto efficiency and fairness of the obtained Nash equilibrium solution.

The *Game based Power Control* (*GPC*) scheme [15] can regulate the transmitter power to meet the different SINR requirements and enhance the total throughput effectively. The *GPC* scheme adopted the game theory for power control modeling in cognitive radio system, and developed a new sigmoid efficiency function with non-liner pricing only related with user's SINR. In addition, non-cooperative power control game created by Goodman is applied for decentralized users. This approach is very suitable for cognitive radio system because of its regardless of the modulation of users' RAT.

The *Cognitive Radio Power Control* (*CRPC*) scheme in [16] is a multi-antenna cognitive radio power control algorithm with the idea of game theory. In this scheme, every user improves the transmitting power selfishly not considering other users, and other users choose the corresponding strategies. This interactive and repeated process is actually