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Fast efficient spectrum allocation and heterogeneous network selection based on modified dynamic evolutionary game

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ABSTRACT

Dynamic evolutionary game has attracted a lot of attention in cognitive network because it can adaptively learn during the strategy under changing conditions adopting replicator dynamics equation. But the information required by the original replicator dynamics equation is large. In this paper, we provide a modified replicator dynamics equation, which can adaptively converge to the desired stable state with faster speed. Noted that, the necessary information transmission in the evolutionary process is much less than that of the original replicator dynamics equation. Moreover, we apply the modified dynamics equation to (i) opportunistic spectrum access with multiple primary users selling free spectrum opportunities to multiple secondary users; (ii) heterogeneous network selection. Simulation results show that the evolving time is cut down greatly and equal maximal payoff is obtained. Besides, the proposed method is robust even if there is large time delay in the process of information transmission.

1. Introduction

Recently, many researchers pay much attention to many applications of complex networks [1]. Now, we are interested in the applications of game theory in the wireless networks. FCC (Federal Communications Commission) recently reports that the spectrum utility is only 15%–85% in most time and most region [2]. FCC is considering to admit the cognitive radio (CR) users to opportunistically access the idle spectrum with the aid of cognitive radio technology. The CR users need to satisfy some conditions about their locations when they access the same spectrum [3–6]. Spectrum sensing and spectrum management are the key technologies in the cognitive radio networks. CR users have to first sense the spectrum and then access the idle spectrum in order to avoid the interference with the authorized users (or, the primary radio (PR) users). Research shows that the collaboration of the CR users can improve the detection probability of PR users [7,8]. There are many different dynamic cognitive behaviors in cognitive networks, in this paper, we focus on the dynamic spectrum access and heterogeneous network selection. The objective of this opportunistic spectrum access trading is to maximize the revenue of primary users and the satisfaction of secondary or cognitive radio (CR) users. Given the fixed spectrum price and the size of spectrum share to CR users, the CR users can adapt their strategies to buy the frequency spectrum and maximize their payoff. The authors in [9] presented the use of a genetic algorithm model as a solution approach to the dynamic spectrum allocation problem. Recently, much research has done to increase

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spectrum efficiency based on game theory [10–22]. The authors in [10] presented two game-theoretical mechanism design methods to suppress cheating and collusion behavior of selfish users. Various auction and pricing methods were proposed for the efficient spectrum allocation, such as auction games for interference management [11,12]. In [13], the authors proposed a model for the strategic interaction of legitimate and malicious users based on repeated graphical games with incomplete information. A game theoretical overview for dynamic spectrum sharing was presented in [14] and the authors in [15] modeled the spectrum allocation in wireless networks with multiple selfish legacy spectrum holders and unlicensed users as multi-stage dynamic games and proposed an efficient pricing-based distributive collusion-resistant dynamic spectrum allocation approach to optimize the overall spectrum efficiency. [16] provided non-exhaustive methodologies for characterizing equilibria in wireless games in terms of existence, uniqueness, selection, and efficiency. [17] discussed distributed resource allocation schemes in which each transmitter determines its allocation autonomously, based on the exchange of interference prices. [18] modeled the evolution and the dynamic behavior of secondary users as evolutionary game and the competition among the primary users as a noncooperative game. In [19], quality-of-service (QoS) performance in a cognitive radio system involving primary and secondary users was analyzed by using a Markov chain. The authors in [22] showed many challenging unsolved resource allocation problems in the emerging field of cognitive radio networks fit naturally either in the game theoretical paradigm or in the more general theory of Variational Inequality.

In [23], a hierarchical radio resource management framework was designed to support a seamless handoff between a WLAN and a cellular network. The authors in [24] proposed an admission control scheme for a vertical handoff in an integrated WLAN and CDMA cellular network. Due to the users to access different types of wireless networks is a dynamic competitive behavior. Shortly, in [25], population evolution algorithms were presented for network selection in heterogeneous networks, which required a centralized controller to exchange the information. They further adopted reinforcement-learning to reach evolutionary equilibrium without any interaction with other users. There are a lot of networks selection references based on game theory [26–29].

In most of the existing cooperative spectrum sharing schemes, evolutionary game theory is adopted widely, such as [18,25,30]. This is because evolutionary game provides an excellent method by exploring different actions, adaptively learning during the strategy under changing conditions and environments using replicator dynamics. But in the original replicator dynamics equation, there are many messages need to transmit, which require a central controller in general case. Sensing a licensed frequency band also consumes a certain amount of energy and time which may alternatively be diverted to data transmissions. Moreover, the free spectrum may be recalled once the primary users are busy. So many papers provide different distributed methods to enhance the spectrum efficiency.

In this paper, we modify the original replicator dynamic equation in the evolutionary game theory. Only a neighbor's payoff need to transmit in the improved dynamic equation instead of the average payoff. Using the property of the evolutionary equilibrium, the desired stable state with identical optimal payoff is obtained. And we apply this modified dynamic equation to two specific issues—spectrum bands reuse and heterogeneous network selection.

The rest of this paper is organized as follows. In Section 2, we present the modified dynamic equation and the convergence analysis after a brief overview of evolutionary game theory. The detailed applications based on the modified dynamic equation of spectrum access and network selection are shown in Sections 3 and 4, respectively. Simulation results are given in Section 5. Finally, Section 6 concludes the paper.

2. Dynamic evolutionary game

2.1. Evolutionary stable strategy

Evolutionary game theory provides a good way to process the strategic uncertainty by learning during the strategic interactions. Evolutionary Stable Strategy (ESS) is widely adopted in evolutionary game theory, which is "a strategy such that, if all members of the population adopt is, then no mutant strategy could invade the population under the influence of natural selection" [31]. Even if a small part of players may not be rational and take out-of-equilibrium strategies, ESS is still a locally stable state. We use the expected payoff as an individual fitness, and use $\pi(p, \hat{p})$ to denote the payoff of an individual using strategy p against another individuals using strategy $\hat{p}$. Then, the formal definition of an ESS is given as [31]:

Definition 1. A strategy p^* is an ESS if and only if, for all $p \neq p^*$,

(1) $\pi(p, p^*) \leq \pi(p^*, p^*)$, (equilibrium condition)

(2) if $\pi(p, p^*) = \pi(p^*, p^*)$, $\pi(p, p) < \pi(p^*, p)$ (stability condition).

Condition (1) states that p^* is the best response strategy to itself and is hence a Nash Equilibrium (NE). Condition (2) is interpreted as a stability condition.

Since the spectrum allocation game is played repeatedly and evolves over time, even if new secondary users change their strategies, we hope the stable state is not altered. Hence, a stable strategy which is robust to mutants using different strategies is especially preferred. So, we adopt evolutionary game theory to analyze the behavior dynamics of the players and further derive the ESS as the secondary users' optimal collaboration strategy in cooperative spectrum sharing.

2.2. Original replicator dynamics

The key concept of evolutionary game is replicator dynamics, which describes the evolution of strategies with time. During the process, the percentage (or population share) of players using a certain pure strategy may change. It is important to recall the original replicator dynamics in the paper.