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Coexistence in heterogeneous spectrum through distributed correlated equilibrium in cognitive radio networks

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ABSTRACT

Coexistence protocols enable collocated cognitive radio networks (CRNs) to share the spectrum in an opportunistic manner. These protocols work under the assumption that all spectrum bands provide the same level of throughput. This assumption is however limited in scope because channel conditions as well as the licensee's usage of allocated channels can vary significantly with time and space. Under these circumstances, CRNs are expected to have a preference over the choice of available channels which can lead to an imbalance in contention for disparate channels, degraded quality of service, and an overall inefficient utilization of spectrum resource. In this paper, we analyze this situation from a game theoretic perspective and model the coexistence of CRNs with heterogeneous spectrum as a non-cooperative, repeated spectrum sharing game. We derive three solutions for the game; (1) pure and (2) mixed strategy Nash Equilibria as well as (3) centralized and distributed correlated equilibria which are derived using linear programming and a channel selection learning algorithms, respectively. We also analyze each of these solutions from the perspective of fairness and efficiency. To that end, we utilize the concept of *price of anarchy* to measure the efficiency of these solutions under selfish behavior from CRNs.

1. Introduction

The TV white space (TVWS) channels in the 54–698 MHz frequency range have been made available by the Federal Communications Commission (FCC) [1] for secondary unlicensed access. This is because of a realization that the gap between the demand and supply of wireless spectrum resource is ever increasing and fixed spectrum allocation is causing its severe under-utilization [2]. Strict requirements are placed on the Secondary Users (SUs) of the spectrum which is otherwise allocated to licensees called primary users (PUs), to continuously sense the spectrum and vacate it when the presence of the PU is detected and not to cause them any interference. This type of spectrum access is intuitively called Dynamic Spectrum Access (DSA). Cognitive Radio Network (CRN) is a paradigm that meets precisely this communication criterion and utilizes DSA to enable secondary, unlicensed access to TVWS spectrum bands in an opportunistic and non-interfering basis [1].

DSA allows CRNs to ensure that their use of spectrum does not cause interference to PUs while at the same time all spectrum opportunities are utilized to the maximum. The decision to select a specific channel for DSA is usually made by a central entity in the CRN such as its base station or some algorithm that enables all SUs in the

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CRN to reach a consensus in a distributed manner. IEEE 802.22 wireless regional area network (WRAN) [3] is an example of a CRN in which the base station controls all the operation including the choice of spectrum bands for communication. Regardless of how a decision to utilize a specific channel is made, every entity in the CRN is bound to abide by that decision. However, reaching a consensus is non-trivial in the case of multiple, collocated and independent CRNs in a given region, all of whom compete for access to the same set of available channels. This situation is called self-coexistence in the context of CRNs which employ coexistence protocols to deal with such situations.

1.1. Problem definition

Most coexistence protocols work under the assumption that all spectrum bands afford the same level of throughput and do not take into consideration the fact that these channels can be heterogeneous. The heterogeneity of channels can be in the sense that they may vary in their characteristics such as signal to noise ratio (SNR) or bandwidth. Furthermore, a channel whose PU remains idle for most of the time may be more attractive to a CRN as compared with a channel with high PU spectrum usage. This would entail that channels can have an associated *quality* parameter and CRNs may have a preference over the set of available channels for secondary access. Without any incentive for altruism, all CRNs would want to gain access to the highest quality channels making it a conflict condition. Therefore, *in the absence of any mechanism to enforce fairness in accessing varying quality channels, ensuring coexistence with fair spectrum allocation and efficient spectrum utilization for CRNs is likely to become a very difficult task*.

Game theory provides an elegant means to model strategic interaction between agents which may or may not be cooperative in nature. It has been applied to numerous areas of research involving conflict, competition and cooperation in multi-agent systems which also encompass wireless communications. Therefore, by leveraging the mechanisms of game theory, we model the heterogeneous spectrum sharing in CRNs as a repeated, non-cooperative anti-coordination game in which collocated CRNs in a given region are its players, as shown in Fig. 1. The payoff for every player in the game is determined by the quality of the spectrum band to which it is able to gain access.

In a preliminary version of this paper [15], we presented a study of various game theoretic solutions for the problem of self-coexistence in the context of heterogeneous spectrum resources. In this paper, we provide a detailed discussion on the problem and its proposed solution. We also present a detailed mathematical analysis on fairness and efficiency of the solution through the concept of *price of anarchy* which is an analysis tool that measures a system's degradation in the presence of selfish behavior from its entities. We also confirm our findings through detailed simulations.

1.2. Contribution

In this paper, we have formulated a heterogeneous spectrum sharing anti-coordination game to come up with a solution that results in fair and efficient utilization of the spectrum resources. Specifically, we have made the following contributions:

- As potential solutions for the heterogeneous spectrum sharing game, we have derived the game's pure and mixed strategy Nash Equilibria (PSNE and MSNE respectively) as well as its Correlated equilibrium (CE).
- We have analyzed the game's solutions in the context of fairness and efficiency and demonstrated that the traditional solution concepts of Nash Equilibria (NE) are either inefficient or unfair. We also show that the strategies in CE are optimal as well as fair while sharing heterogeneous spectrum resource.
- Finally, to show that CE is scalable, we have demonstrated how CE can be achieved in a 2-player as well as an N-player game with centralized as well as a distributed approach using linear optimization and channel selection learning algorithm, respectively.

2. Related work

In this section, we provide an overview of some of the works carried out in the domain of self-coexistence in CRNs as well as application of the game theoretic solution concept of correlated equilibrium in the context of communication networks.

A game theoretic approach based on correlated equilibrium has been proposed in [4] for multi-tier decentralized interference mitigation in two-tier cellular systems. Zheng et al. [5] propose a multi-cell resource allocation game for efficient allocation of resources in orthogonal frequency division multiple access (OFDMA) systems based on throughput, inter-cell interference and complexity. The subcarriers are considered as players of the game while the base station acts as the provider of external recommendation signal needed for achieving correlation of strategies of players.

The solution concept of Nash equilibrium has been adopted for distributed spectrum management, relay selection and queuing in [6, 7] for interference-limited cooperative wireless networks. The authors have proposed a distributed best-response algorithm to develop a Branch and Bound-based algorithm solving the associated social problem. Huang and Krishnamurthy [8] model the competition among multiple femtocell base stations for spectrum resource allocation in an OFDMA LTE downlink system as a static non-cooperative game. The correlated equilibrium of the game is derived through a distributed resource block access algorithm which is a variant of the No-Regret learning algorithm. CRNs with SUs having variable traffic characteristics are considered in [9] to tackle the problem of distributed spectrum sensing by modeling it as a cooperative spectrum sensing game for utility maximization. The authors have proposed another variant of the no-regret learning algorithm called neighborhood learning (NBL)