Computer Networks 57 (2013) 1863–1879

Contents lists available at SciVerse ScienceDirect

Computer Networks

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

Proportional and double imitation rules for spectrum access in cognitive radio networks ☆

Stefano Iellamo [a], Lin Chen [b], Marceau Coupechoux [a,*]

[a] Telecom ParisTech, CNRS LTCI, 46 Rue Barrault, Paris 75013, France
[b] University Paris-Sud XI, CNRS, LRI, 91405 Orsay, France

ARTICLE INFO

Article history:
Received 29 June 2012
Received in revised form 7 March 2013
Accepted 8 March 2013
Available online 26 March 2013

Keywords:
Cognitive radio networks
Resource allocation
Population game
Learning

ABSTRACT

In this paper, we tackle the problem of opportunistic spectrum access in large-scale cognitive radio networks, where the unlicensed Secondary Users (SUs) access the frequency channels partially occupied by the licensed Primary Users (PUs). Each channel is characterized by an availability probability unknown to the SUs. We apply population game theory to model the spectrum access problem and develop distributed spectrum access policies based on imitation, a behavior rule widely applied in human societies consisting of imitating successful behaviors. We develop two imitation-based spectrum access policies based on the basic Proportional Imitation (PI) rule and the more advanced Double Imitation (DI) rule given that a SU can only imitate the other SUs operating on the same channel. A systematic theoretical analysis is presented for both policies on the induced imitation dynamics and the convergence properties of the proposed policies to the Nash equilibrium. Simple and natural, the proposed imitation-based spectrum access policies can be implemented distributedly based on solely local interactions and thus is especially suited in decentralized adaptive learning environments as cognitive radio networks.

1. Introduction

Cognitive radio [1], with its capability to flexibly configure its transmission parameters, has emerged in recent years as a promising paradigm to enable more efficient spectrum utilization. Spectrum access models in cognitive radio networks can be classified into three categories, namely exclusive use (or operator sharing), commons and shared use of primary licensed spectrum [2]. In the last model, unlicensed Secondary Users (SUs) are allowed to access the spectrum of licensed Primary Users (PUs) in an opportunistic way. In this case, a well-designed spectrum access mechanism is crucial to achieve efficient spectrum usage.

In this paper, we focus on the generic model of cognitive networks consisting of multiple frequency channels, each characterized by a channel availability probability determined by the activity of PUs on it. In such a model, from the SUs perspective, a challenging problem is to coordinate with other SUs in order to opportunistically access the unused spectrum of PUs to maximize its own payoff (e.g., throughput); at the system level, a crucial research issue is to design efficient spectrum access protocols achieving optimal spectrum usage and load balancing on the available channels.

We tackle the spectrum access problem in large-scale cognitive radio networks from an evolutionary game theoretic angle. We formulate the spectrum access problem, show the existence of a Nash Equilibrium (NE) and develop distributed spectrum access policies based on imitation, a behavior rule widely applied in human societies consisting of imitating successful behavior. We study the system

☆ This work is supported by the project TEROPP (technologies for TERminal in OPPortunistic radio applications) funded by the French National Research Agency (ANR).

* Corresponding author. Tel.: +33 1 45 81 75 88; fax: +33 1 45 81 31 19.
E-mail addresses: stefano.iellamo@telecom-paristech.fr (S. Iellamo), chen@lri.fr (L. Chen), marceau.coupechoux@telecom-paristech.fr (M. Coupechoux).

1389-1286/$ - see front matter © 2013 Elsevier B.V. All rights reserved.
http://dx.doi.org/10.1016/j.comnet.2013.03.008

dynamics and the convergence of the proposed policies to the NE when the SU population is large. Simple and natural, the proposed spectrum access policies can be implemented distributedly based on solely local interactions and thus is especially suited in decentralized adaptive learning environments as cognitive radio networks.

In our analysis, we develop imitation-based spectrum access policies where a SU can only imitate the other SUs operating on the same channel. More specifically, we propose two spectrum access policies based on the following two imitation rules: the Proportional Imitation (PI) rule where a SU can sample one other SU; the more advanced adjusted proportional imitation rule with double sampling (Double Imitation, DI) where a SU can sample two other SUs. Under both imitation rules, each SU strives to improve its individual payoff by imitating other SUs with higher payoff. A systematic theoretical analysis is presented for both policies on the induced imitation dynamics and the convergence properties of the proposed policies to the NE.

The key contribution of our work in this paper lies in the systematical application of the natural imitation behavior to address the spectrum access problem in cognitive radio networks, the design of distributed imitation-based channel access policies, and the theoretic analysis on the induced imitation dynamics and the convergence to an efficient and stable system equilibrium. In this paper, we extend the results of [3], where it is assumed that SUs are able to immediately and uniformly imitate any other SU. This assumption makes the theoretical analysis straightforward from the literature on imitation. We assume here that SUs can only imitate SUs on the same channel and obtain a delayed information, as a result of which significant changes should be done in terms of policy design and theoretical analysis.

The rest of the paper is structured as follows. Section 2 discusses related work in the literature. Section 3 presents the system model and Section 4 presents the formulation of the spectrum access game. Section 5 describes the proposed imitation-based spectrum access policies and motivates the choices of proportional and double imitation rules as basis of our policies. In Section 6, we study the system dynamics and the convergence of our algorithms. Section 7 discusses the assumptions of our network model. Section 8 presents simulation based performance evaluation, where our schemes are compared to another decentralized approach called Trial and Error. Section 9 concludes the paper.

2. Related Work

The problem of distributed spectrum access in cognitive radio networks (CRN) has been widely addressed in the literature. A first set of papers assumes that the number of SUs is smaller than the number of channels. In this case, the problem is closely related to the classical Multi-Armed Bandit (MAB) problem [4]. Some recent work has investigated the issue of adapting traditional MAB approaches to the CRN context, among which Anandkumar et al. proposed two algorithms with logarithmic regret, where the number of SUs is known or estimated by each SU [5]. Contrary to this literature, we assume in our paper a large population of SUs, able to share the available bandwidth when settling on the same channel.

Another important thrust consists of applying game theory to model the competition and cooperation among SUs and the interactions between SUs and PUs (see [6] for a review). Several papers propose for example algorithms based on no-regret learning (e.g. [7,8]), which are not guaranteed to converge to the NE. Besides, due to the perceived fairness and allocation efficiency, auction techniques have also attracted considerable research attention and resulted in a number of auction-based spectrum allocation mechanisms (cf. [9] and references therein). The solution proposed in this paper differs from the existing approaches in that it requires only local interactions among SUs and is thus naturally adapted in the distributed environments as CRNs.

Due to the success of applying evolutionary [10] and population game theories [11] in the study of biological and economic problems [11], a handful of recent studies have applied these tools to study resource allocation problems arisen from wired and wireless networks (see e.g. [12,13]), among which Shakkottai et al. addressed the problem of non-cooperative multi-homing of users to WLANs access points by modeling it as a population game [14]. Authors however focus on the system dynamics rather than on the distributed algorithms as we do in this paper. Niyato et al. studied the dynamics of network selection in a heterogeneous wireless network using the theory of evolutionary game [15]. The proposed algorithm leading to the replicator dynamics is however based on a centralized controller able to broadcast to all users the average payoff. Our algorithms are on the contrary fully distributed. Coucheney et al. studied the user-network association problem in wireless networks with multi-technology and proposed an algorithm based on Trial and Error mechanisms to achieve the fair and efficient solution [13].

Several theoretical works focus on imitation dynamics. Ackermann et al. investigated the concurrent imitation dynamics in the context of finite population symmetric congestion games by focusing on the convergence properties [16]. Berenbrik et al. applied the Proportional Imitation Rule to load-balance system resources by focusing on the convergence speed [17]. Ganesh et al. applied the Imitate If Better rule[1] (see [19] for a review on imitation rules) in order to load-balance the service rate of parallel server systems [18]. Contrary to our work, it is assumed in [17,18] that a user is able to observe the load of another resource before taking its decision to switch to this resource.

As it is supposed to model human behavior, imitation is mostly studied in economics. In the context of CRN, specific protocol or hardware constraints may however arise so that imitation dynamics are modified, as we show it in this paper. Two very recent works in the context of CRN are [20,21], which have the same goals as ours. In [20], authors propose a distributed learning algorithm for spectrum access. User decisions are based on their accumulated experience and they are using a mixed strategy. In [21], imitation is also used for distributed spectrum access. However, the proposed scheme relies on the existence of

[1] Imitate If Better (IIB) is a rule consisting in picking a player and migrating to its strategy if the latter has yielded a higher payoff than the achieved one. IIB is called Random Local Search in [18].