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Learning solutions for auction-based dynamic spectrum access in multicarrier systems

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ABSTRACT

In this work, we address competition among autonomous cognitive radios (CRs) which are competing for frequency bands, and model their interactions. We design auction mechanisms with and without an entry fee and define utility functions based on the total achieved capacity per unit price. We equip the CRs with a learning algorithm in order to bid more efficiently. Our considered network consists of a central spectrum moderator (CSM) and a number of competing CR pairs. The CSM auctions the available spectrum bands, and each CR bids for them in order to transmit its data. A CR bids for a subcarrier at a value proportional to the achievable capacity for it to transmit on that subcarrier, and the CR is free to dynamically assign portions of its transmit power to available subcarriers in order to maximize its achievable capacity per unit of price. We propose a Dirichlet process-based and a Gaussian process regression-based learning algorithms which make use of the outcomes of the past auctions to learn the bidding behavior of the competing CRs. By learning the bidding behavior of competing CRs, a CR can improve its bidding efficiency by concentrating its transmit power on the subcarriers that it has a higher chance of getting access to. Simulation results show that the proposed nonparametric learning algorithms achieve significantly higher utilities for the CRs than the myopic approach, and both the Dirichlet and the Gaussian processes provide roughly the same level of improvement.

1. Introduction

Dynamic spectrum access (DSA) has received a great deal of attention due to the tremendous growth in the demand for bandwidth-hungry wireless services, and to the poor spectrum utilization efficiency that results from rigid static spectrum management policies. DSA encompasses various approaches to spectrum reform [1], which target to improve the spectrum utilization efficiency by dynamically assigning spectrum to different services based on their requirements [1]. Cognitive radios (CRs) have been proposed to realize such a vision. CRs are intelligent radios that are able to learn from their surroundings and adapt their transmission parameters accordingly [2].

As mentioned above, intelligence and the ability to adapt their transmission parameters to the environment are the desired features of CRs [3], which are achieved by applying learning methods to extract knowledge from its past experiences and observations. Most recent studies about learning in CRs focus on learning about the channel quality or the presence of primary users (PUs) in the

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channels of interest [4–6]. However, learning the behavior of other CRs will also be beneficial, especially in scenarios where the CRs are competing for resources.

Spectrum access can be performed using centralized and/or distributed approaches [7]. In centralized approaches, there exists no competition among CRs. In these approaches, a secondary base station either optimizes the secondary spectrum usage [8,9] or maximizes the achievable throughput [10]. In distributed approaches, autonomous CRs compete or cooperate to make use of the spectrum opportunities. In distributed approaches, game theory is often applied to study the existence of and convergence to an equilibrium for the system [11]. Auction theory is an economics-originated method which has been applied to a wide range of spectrum management applications [12–14].

In this work, we model the secondary spectrum access as a sequence of VCG auctions, where each CR bids for the available OFDM subcarriers, and the auctions are repeated for each time slot. The subcarriers are not identical and each CR values each subcarrier based on its achievable capacity on that specific subcarrier. We classify our auction-based spectrum assignment approach as a semi-centralized approach. Unlike centralized approaches, in this approach the central spectrum moderator (auctioneer) does not need to know the preferences of all CRs and their channel state information (CSI). Hence, the auctioneer does not need to perform high complexity computations to assign the subcarriers to the CRs. Moreover, in this semi-centralized approach, CRs are also taking part in the decision process, and are able to bid on their own preferred subcarriers. Unlike distributed approaches where multiple iterations are required before convergence [15], our proposed auction-based spectrum assignment approach requires the CRs to submit the bid vectors only once at each time slot.

In our proposed auction-based spectrum assignment mechanism, the CRs are able to learn their competitors' behavior and adjust their bids in order to maximize their individual utility, i.e. the achieved capacity per unit of price. Unlike other studies, the CRs have the freedom to divide their limited power (and hence the achievable capacity) over the available subcarriers to increase or decrease their bids on those subcarriers. In other words, a CR is able to increase its bid on the high quality unoccupied subcarriers, by increasing its power on those subcarriers. We formulate the bidding policy as a constrained maximization problem, and having an accurate estimate of others' valuation for subcarriers plays a critical role in our proposed bidding policy. Due to the intractable state space of the learning problem, we adopt nonparametric learning models which are based on the Dirichlet process (DP) and Gaussian process (GP) regression. Both algorithms observe the highest bid of opponent CRs and use it to learn the opponents' biding behavior and predict the opponents' highest bid for the next time slot. We compare the total utility of CRs equipped with DP-based and GP regression-based learning algorithms with that using myopic algorithm as their bidding policy. Myopic approach makes no prediction for the opponents' highest bid and, they bid for subcarriers only based on their maximum achievable capacity given by a water-filling algorithm.

A CR may not gain access to one or some of the subcarriers that it has bid for. Unlike other works, we allow CRs to enhance their utility by recomputing their power assignment after the bid and when subcarrier allocations have been made, i.e., the bidding and transmission processes are two completely different process. For example, a CR that bids for three subcarriers divides its power between the three subcarriers. When the outcome of the auction on each subcarrier is revealed to the CR and it only gains access to two of the subcarriers that it has bid for (it loses one of the auctions), we allow the CR to redistribute its power among the two subcarriers that it has gained access to in order to improve its utility.

A use case for such a learning based auction mechanism would be in the construction of a cognitive radio based backhaul for small cell networks. Licensed Shared Spectrum Access (LSA) has been proposed to enable the regulated shared use of TV white space (TVWS) [16]. It enables the operators to spatially lease/share their underutilized spectrum. One of the key techniques used in LSA is dynamically auctioning the TVWS spectrum resources to support backhaul transmission for small cell eNodeBs [17]. The proposed mechanism can also be implemented in smart grid communications [18].

2. Literature review

In this section, we review some of the main works in the literature which studied the effect of equipping CRs with learning algorithms. In this context, some works apply the learning algorithms to learn the behavior of primary users (PU) and predict their presence/absence. In [4], CRs learn the subcarrier availability, again using a hidden Markov model (HMM). A CR ranks the subcarriers according to the likelihood that the subcarrier is unoccupied. Each CR then senses the subcarriers for transmission based on this ranking until the number of desired subcarriers is achieved; as a result, there is no need to sense all subcarriers before a decision is made. In [6], the HMM algorithm is applied to real data, and the authors also discuss the effect of the PU's duty cycle and of the Lempel–Ziv complexity of the PU's activity on the probability of finding an unoccupied channel.

The aforementioned works consider scenarios in which only one CR attempts to reuse the unoccupied spectrum. However, when there are multiple CRs in the system, collision among the CRs should be avoided. One way of avoiding collisions between the CRs is auctioning the available (unoccupied) channels among them.[5] In [19], the authors consider auction-based spectrum sharing, where a PU assigns the spectrum to CR bidders according to the bandwidth requirements from CRs without degrading its own performance. The paper adopts an OFDM framework and applies Vickrey–Clarke–Groves (VCG) auctions for bandwidth allocation. The OFDM subcarriers are assumed to be identical and the CRs have no preferences between them. The paper also presents a dynamic algorithm for the

[5] As mentioned in Section 1 there are other ways of avoiding this collision e.g., central channel allocation techniques.