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Resource allocation for OFDMA-based multicast cognitive radio networks using a Stackelberg pricing game

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ABSTRACT

The resource allocation problem for orthogonal frequency-division multiple-access (OFDMA)-based multicast cognitive radio networks is investigated under the spectral activities of primary users (PUs). The interactions between PUs and secondary users (SUs) are modelled using a Stackelberg game where the PUs are the leaders while the SUs are the followers. Using an efficient pricing framework, the PUs who are the licensed spectrum owners compete to lease their subcarriers to the SUs. The competition among PUs is modelled using a non-cooperative game in which they greedily adjust the pricing coefficients to harvest maximum profits while maintaining tolerable interference. Based on the pricing coefficients, the SUs autonomously form coalitions and collectively adjust their received power so as to access more subcarriers at affordable costs. Two disjoint algorithms are proposed to facilitate successful transactions between PUs and SUs so that Stackelberg equilibrium can be achieved where both the PUs and SUs can obtain maximum payoffs. Simulation results demonstrate that the proposed scheme outperforms the conventional unicast and multicast schemes in cognitive radio networks while achieving a near-optimal performance comparable to the exhaustive search scheme.

1. Introduction

Spectrum scarcity is one of the major bottlenecks of high-quality and delay-sensitive wireless services. Nonetheless, it is revealed in a report by the Federal Communications Commission (FCC) [1] that spectrum access is in fact a more significant problem than spectrum scarcity, mainly due to the rigid spectrum management policies which restrict potential wireless users to acquire spectrum. Intuitively, spectrum utilization can be improved considerably by making it possible for an unlicensed user to access a spectrum band licensed to a primary network (PRN) based on certain criteria. This has led to the invention of cognitive radio (CR) which is viewed as a viable future communication technology for improving spectral efficiency. According to [2], the software-defined radio based CR system is an intelligent wireless communication system that is capable of detecting available channels in a wide spectrum and adjusting the transmission or reception parameters accordingly to allow coexistence of licensed or primary users (PUs) and unlicensed or secondary users (SUs).

The adoption of CR technology in multicast systems is initiated by the apparent lack of spectrum due to growing demand of multicast services [2]. This promising technology can potentially alleviate spectrum scarcity in multicast systems by allowing multicast SUs to opportunistically access the spectrum licensed to PUs. Since PUs have access priority, SUs are required to exert minimal effect on PUs. The protection of PUs is necessary because no PRN will be willing to share its spectrum with a multicast CR network (MCRN) if the secondary users' activities on the licensed band are detrimental to the PUs. Therefore, the main task of the MCRN is to ensure that SUs can maximize the spectrum utilization under the constraints of multiple PUs' interference temperatures [3]. In order to efficiently utilize the valuable spectrum, the orthogonal frequency-division multiple-access (OFDMA) technique is adopted in MCRNs and an efficient radio resource management (RRM) scheme for subcarrier and power allocation (SPA) is employed [4–10].

Over the past decade, substantial efforts have been devoted to designing efficient RRM schemes for OFDMA-based CRNs, particularly for unicast communications [4]. Recently, due to the explosive growth of mobile applications which fuel the demand for wireless multicast services especially wireless streaming and internet-protocol television (IPTV), RRM for MCRNs has garnered immense research interest. In [5], the authors modelled the multicasting problem in MCRNs where they considered PUs' maximal interference and solved the problem using a subgradient update algorithm. Resource allocation for OFDMA-based MCRNs which consid-

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ers scalable video transmission using H.264 has been studied in [6]. In this work, integer programming is adopted for subcarrier allocation to different SUs with consideration of interference tolerance of PUs. Besides, RRM of MCRNs is formulated in [7] by taking the maximization of the expected sum rate of cognitive multicast groups as the design objective and an efficient joint SPA technique is proposed. Subsequently, the work in [8] optimizes real-time video multicast in CRNs where fined grained scalability is used to encode each video into a base layer and an enhancement layer to accommodate heterogeneous channels. This work has been extended to a mesh MCRN [9] where an assistance strategy for relaying is proposed to reduce the effect of channel heterogeneity. In [10], the optimization problem of MCRNs is solved using a Lagrangian dual decomposition approach by developing an asymptotically optimal joint SPA algorithm.

Undeniably, many design and implementation issues exist in the realization of an MCRN, particularly the issue on how to achieve "peaceful" coexistence between PUs and multicast SUs on different subcarriers. The unregulated and self-organized nature of MCRNs makes the RRM problem very challenging. One feasible approach to model the interaction between PUs and SUs is to use a pricing mechanism. Apparently, pricing for CRNs has been embraced in the work carried out in [11] as an effective tool for creating policies for resource sharing between PUs and SUs. In [12], the authors proposed a spectrum leasing framework under which the PUs are rewarded for allowing SUs to operate in their licensed bands. Notably, the work in [13] formalized the profit maximization problem which can be solved using stochastic dynamic programming. Successively, the authors explored the price dynamics in a competitive market consisting of multiple service providers [14] while a recent work [15] considered the competition among multiple PUs in an attempt to sell spectrum. In contrast, the study in [16] focused on the competition among multiple SUs to acquire licensed bands and this work was extended in [17] to study spectrum trading across multiple PUs and multiple SUs. In addition, the work in [18] studied the investment and pricing decisions of a network operator under spectrum supply uncertainty. In [19], a spectrum allocation scheme is modelled using the hybrid game model based on reputation instead of pricing, which deals with multiple PUs and SUs coexisting and sharing the spectrum. The work in [20] manages to address a Stackelberg game model with pricing in which individual users attempt to hierarchically access to the wireless spectrum while maximizing their energy efficiency. Besides, the authors in [21] study the database-assisted dynamic access network where spectrum brokers compete to provide service for SUs with different quality of service (QoS) demands and budget. The interaction among the BSs and SUs is characterized as a two-stage Stackelberg game which is able to yield optimal profits for BSs and SUs. Likewise, the work in [22] investigates spectrum procurement and pricing which utilizes the differentiated pricing among the heterogeneous SUs to improve the profit of the CR networks. The spectrum procurement and pricing is modelled as a five-stage Stackelberg game to analyze the optimal decisions for CR networks by using backward induction.

Unlike the aforementioned schemes which model the SUs as selfish users, however, in the current work, the SUs are regarded as altruistic wireless users who tend to cooperate with each other to maximize spectral efficiency. In this paper, resource allocation in MCRNs is formulated as a clustering problem to alleviate the effect of channel heterogeneity, but clustering optimization is complicated by the introduction of interference temperature which is used by PUs to control spectrum usage of SUs. The interaction between PUs and SUs can be captured using a Stackelberg game [23,24] where the PUs (leaders) who are the spectrum owners attempt to lease their spectrum to the SUs (followers). Spectrum leasing between PUs and SUs is regulated by a non-cooperative pricing framework under which the PUs greedily adjust their pricing coefficients to garner maximum profit while keeping the interference below a threshold. Under this pricing architecture, the cooperation among SUs is modelled using a coalitional game where the SUs wisely form coalitions and collectively adjust their power to acquire more subcarriers from PUs at minimal costs. To achieve Stackelberg equilibrium (SE) [23], two disjoint algorithms are proposed to enable successful transactions between PUs and SUs so that the proposed games can reach their respective equilibria at which all PUs and SUs are satisfied with their payoffs.

The rest of this article is organized as follows. In Section 2, we outline the system model of a hybrid system comprising a PRN and MCRN. In this section, the interference temperature model for MCRN is also described. Section 3 formulates the cognitive Stackelberg game with pricing (CSGP) which consists of a non-cooperative price adjustment game (NPAG) and a multicast coalitional game with pricing (MCGP) for PRN and MCRN, respectively. An algorithm that guides the CSGP to achieve its SE is proposed in Section 4 and its complexity is analyzed. Simulation results and performance analysis are presented in Section 5. We end the article with some concluding remarks in Section 6.

2. System model and problem formulation

Consider a hybrid network comprising a PRN and a MCRN as illustrated in Fig. 1, both are single-cell OFDMA-based networks that co-exist within the same geographical area. In the PRN, there are M licensed PUs with each PU $m \in \mathcal{M} = \{1, \ldots, M\}$ receiving distinct unicast traffic on the licensed spectrum in the downlink from a primary BS (PBS). At the same time, the MCRN consists of a secondary BS (SBS) accommodating K SUs where only the downlink multicast transmission is considered. As shown in Fig. 1, the channel gains of different links are defined as follows.

- $|h_{k,\,n}|^2$ denotes the channel gain of the communication link from the SBS to the kth SU on the nth subcarrier,
- $|g^P_{k,n}|^2$ denotes the channel gain of the interference link from the PBS to the kth SU on the nth subcarrier,
- $|g^S_{m,n}|^2$ denotes the channel gain of the interference link from the SBS to the mth PU on the nth subcarrier.

For brevity, $|g^P_{k,n}|^2$ and $|g^S_{m,n}|^2$ are be generally known as "interference gains" which will be used throughout this paper.

In this hybrid network, the PUs are licensed to operate on a specific frequency band which is partitioned into N orthogonal subcarriers with each subcarrier exclusively assigned to one PU at a time. Thus, all PUs can simultaneously receive data from the PBS without any internal interference caused within the PRN. At the same time, the SUs are permitted to access the licensed spectrum if the interference created externally by SUs is tolerable to the PRN. If spectrum access by SUs is detrimental to data transmission of the PUs, the latter will automatically discontinue spectrum sharing with the MCRN. As a result, the transmit power of the SBS must be carefully controlled so as to exert minimal interference effect on the PUs while ensuring satisfactory QoS at the receivers of SUs. In this context, it is also assumed that the PUs and SUs do not have any prior knowledge of each other's spectrum utilization.

2.1. System model for OFDMA-based multicast cognitive radio networks

In the MCRN, the SBS transmits G downlink traffic flows to one distinct multicast group of SUs. Let $\mathcal{K}_g$ denote the user set of the gth multicast group corresponding to the gth traffic flow. For simplicity, it is assumed that each user only belongs to one multicast group, so that $\mathcal{K}_g \cap \mathcal{K}_h = \emptyset$, $g \neq h$, $g, h \in \mathcal{G}$ where $\mathcal{G} = \{1, 2, \ldots, G\}$ is the multicast group set. However, the proposed method is still