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Semi-cooperative game theoretic framework for resource allocation in cognitive cellular networks



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ABSTRACT

Deployment of small cells beside macro cells has become the promising solution to meet the increasing service demand with limited bandwidth. However, the inter- and intra-tier interference limit the network capacity. Here, we present a semi-cooperative based resource allocation (SCRA) framework for cognitive small cells. The proposed framework allocates the underutilized spectrum of primary network for the downlink transmission of cognitive small cells such that the interference to primary users is below the threshold and the QoS (Quality of Service) of the associated user is satisfied. The game theoretic approach is adapted for distributed resource allocation where players (i.e. cognitive small cells) access primary channels in a non-cooperative manner. The utility of players is modeled as a negative weighted sum of the transmission power in the primary channels. We assume that the macro cell, after a specific interval of time, uses the primary users' cooperation to obtain the channel weights for the players. We show that there exists the Nash Equilibrium (NE) in the proposed game of resource allocation. Finally, the performance of proposed SCRA enabled two-tier networks is demonstrated through extensive simulations.

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1. Introduction

The exponential growth of mobile service demand has brought an evolution in the architecture of the cellular networks. The small cells (such as pico cells, micro cells, or femto cells) are being deployed across the network to regulate the increasing high data rate mobile services. However, the macro cells are retained for the ubiquitous connectivity and the low data rate services. The networks deployed using small cells and macro cells are generally referred as two-tier networks. In addition, universal frequency reuse is essential for deploying such networks to cope up with the service demand. This tends to increase the intra- and inter-tier interference in two-tiers networks which tends to limit the network capacity.

Recent studies have considered forming the cognitive radio (refer [1]) enabled cellular networks for better utilization of cellular spectrum. For example, a cognitive WiMAX architecture with femto cells is proposed in [2], where the authors developed an optimization framework for location-aware cooperative resource

management. Based on femto BSs (primaries) locations, the spectrum is accessed for multi-hop cognitive transmission of the macro users. In [3], a method for cognitive relay based inter cell interference (ICI) cancellation in cellular networks is presented for enhancement of the system capacity. On request from interference-limited users, the relay senses the unused channels by the BS to forward signal to the user. In [4] a cooperative game theoretic approach is presented for better utilization of cellular spectrum. Therein the authors assumed that each femto BS is equipped with cognitive radio capability for sensing the channels used by macro BS (MBS) or neighboring femto BSs so that the interference can be avoided. In recent years, the distributed control in two-tier cellular networks has acquired attention compared to the erstwhile centralized methods for its effectiveness in resource allocation, network overhead, network scalability, etc.

The game theoretical techniques became the prevalent topic of research for distributed resource allocation in wireless communications [5]. It allows the wireless transceivers to adapt the optimal transmission policy either through cooperation or through non-cooperation. In general, the cooperative games promise better resource utilization and better utilities for the involved wireless users or players. However, it has shortcoming over non-cooperative games in terms of the practical application in the real time as the huge amount of information exchange is required for

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the cooperation. Several studies have investigated the resource allocation by means of cooperative games such as [4,6–11]. The authors of [4,6–8] has considered the coalition games for distributed access in wireless networks. The authors of [4] proposed a cooperative game wherein the mobile users (players) form a coalition to access the network either through MBS or through femto BSs. An overlapping coalition game is presented in [8] for the resource sharing among the small cells through cross-tier (small cells to macro cell) and co-tier (among small cells) interference management. The small cells can be a part of more than one coalition. Here, the authors have proposed to optimize the sum-rate of each coalition under the maximum transmission power constraint while considering the transferable utility. In [9], the femto BSs are encouraged to provide services to nearby macro cell users, and the MBS releases a fractional spectrum to the femto BSs for avoiding cross-tier interference in return. This problem is modeled as a Stackelberg game where the MBS acts as a leader and the femto BSs as the followers. The utilities for the MBS and the femto BSs are defined as the average throughput and the distortion-rate function, respectively. The sub-carriers allocation to users using Nash bargaining solution is investigated in [10]. Therein, the FDM/TDM strategies are employed for the users to access the sub-carriers in flat as well as frequency selective fading scenario.

On the other hand, the resource sharing among the wireless transceivers/users through the application of non-cooperative games is gaining popularity due to the reduced network overhead [12–16]. A distributed utility based iterative SINR adaptation algorithm is introduced in [12] to mitigate the cross-tier interference at the macro cell from the co-channel femto cells. A non-cooperative game for the optimal frequency and power allocation to mobile users in the downlink multi-cell OFDMA systems is presented in [14]. The payoff function of a cell is assumed to be the difference between the weighted sum of data rates and the linear function of power consumption. An iterative algorithm is presented wherein each iteration employs the greedy approach for optimal frequency assignment to maximize the sum rate, whereas the power allocation obtained via best response function. In [16], a Bayesian game theoretic approach is presented for the power allocation to the mobile users with incomplete information of fading channel. Therein, authors have proved that there exists a unique Bayesian equilibrium under the assumption of each player maximizes the transmission rate. The authors of [17] consider the minimization of the transmission power in the Gaussian frequency-selective interference channels such that the rate constraint of each user is satisfied. Therein, the problem of distributed power assignment is formulated as a generalized Nash equilibrium game while considering the perfect information of channel gains. The knowledge of perfect information about the instantaneous channel gains helps the CBS to infer the strategies of other CBSs and accordingly devise the optimum strategy. Moreover, it will also help to maintain the interference constraint of primary users in a better fashion. However, the instantaneous information exchange may add huge overhead which may arise other network design issues. Therefore, in this paper, the knowledge of imperfect information about the channel gains is considered to develop the game model for resource sharing among CBSs.

In the existing literature, the major focus is paid on the resource allocation to femto cells while preventing the interference to macro cell users. However, most of them do not consider the interference management among small cells which limits their application in the deployment of multi-tier cellular networks. A distributed cooperative allocation for small cells is presented in [8,18]. The [18] presents a method for joint power and multi-carrier allocation to small cells. Therein the max sum rate and proportional fair utility functions are considered. The mobile users are

schedule based on the scheduling weights which are determined using the obtained utilities. However, authors of [8,18] have not considered the temporal channel variation. Nevertheless, above discussed investigations have considered the reuse of the macro cell spectrum for small cells by the means of cooperation or non-cooperation. Therefore, such studies, in general, provide the upper bounds on the network performance.

On the other hand, offloading the traffic of few small cells' from cellular spectrum to the underutilized spectrum, borrowed from another (primary) networks, can be a potential solution for many issues in today's cellular networks such as cellular user's QoS support, inter- and intra-tier interference, cell capacity. This scenario, in a true sense, can be a heterogeneous network. For example in [19,20], a method for opportunistic access of TV spectrum for the cellular network is proposed. The authors of [20] consider that the cognitive cellular BS will use its transmission power to cooperate with the TV system in order to compensate for its interference. The authors of [21] have considered enabling the bandwidth aggregation by sharing spectrum owned by other cellular operators, or opportunistically utilizing unused spectrum bands licensed to other services such as digital TV, public safety. However, exploration of such opportunities for multi-tier scenario does not exist in the literature.

In this paper, we consider the opportunistic spectrum access for the downlink transmission of cognitive base stations (CBSs) of small cells in underlay manner to improve the network capacity while keeping the interference to the primary users (PUs) below the threshold. A game theoretic approach is presented for the distributed sharing of opportunistic spectrum among the CBSs. The proposed approach assumes the cooperation among the PUs and the CBSs to estimate the channel gains after the long time interval. Based on the channel gains, the primary channel access weights are allocated to the CBSs. This helps to priorities the channels access patterns for the CBSs and maintain the interference to PUs below the threshold. The channel weighting algorithm restricts the CBSs from accessing a particular channel, which are potentially able to violate the interference outage constraint of the PUs active in that channel. Each CBS prioritize the channels access in ascending order of the interference received at its reserver. This allows a CBS to be cognizant of strategies of other CBSs and choose the transmission strategy accordingly. Each CBS select its joint strategy, i.e. channels and power level, by playing the proposed game independently in every transmit time interval (TTI) based on its instantaneous channel conditions without any further cooperation. While playing the game, each player (CBS) tries to select its strategy such that the expected throughput is above threshold. The utility function of the players is modeled as the negative weighted sum of the transmission powers in the primary channels.

The rest of the paper is organized as follows. Section 2 describes the system model. The formulation of the game is discussed in Section 3. The analysis for the existence of the Nash Equilibrium is presented in Section 4. Next, we discuss the proposed SCRA framework for the cognitive two-tier cellular networks in Section 5. The simulation methodology and numerical results demonstrating the relative merits of the SCRA enabled two-tier cellular network is discussed in Section 6. Finally, Section 7 concludes the paper.

2. System model

The typical illustration of the proposed framework is depicted in Fig. 1, wherein PU, MBS, CBS, CUE, MUE represent primary user, macro BS, cognitive small BS, UE associated with CBS, UE associated with MBS, respectively. The CBSs (e.g. 1, 3, 5, and 6) that are considerably far from the reach of PUs can access the primary spectrum in order to avoid the harmful interference to PUs. These CBSs select their strategy (i.e. transmission power and

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