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Distributed hierarchical game-based algorithm for downlink power allocation in OFDMA femtocell networks

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ABSTRACT

Femtocell is a promising technique for mobile operators to improve coverage and to provide high-data rate services in a cost-efficient manner. In this study, we investigate the problem of downlink power allocation in an orthogonal frequency division multiple access femtocell network. Femto-access points and macro-base stations in the network maximize their capacity and compete with each other through power allocation. This competition is captured in the framework of a Stackelberg game, and the Stackelberg equilibrium is introduced as the problem solution. We divide the strategy of MBSs into two substrategies (channel selection strategy and power strategy) to improve the performance of MBSs. The two substrategies interact with each other in the process of achieving Stackelberg equilibrium. The hierarchical iterative algorithm is proposed for MBSs and FAPs to achieve the maximum capacity game equilibrium in a distributed manner. A dynamic step size mechanism and a method that copes with variational player number are proposed to decrease the algorithm cost. Numerical results show that the performance of the proposed algorithm is better than the performances of other algorithms.

1. Introduction

As a result of the widespread use of wireless devices and the rapid diversification of wireless services, data traffic in wireless communication networks is explosively increasing. More than 50% of voice services and 70% of data traffic have occurred indoors in recent years [1]. Thus, insufficient indoor coverage and the demand for high data rates are some of the problems in existing cellular systems. Femtocell emerges as one of the most promising technologies for improving indoor wireless service. Femto-access points (FAPs) are low-cost, low-power, and short-range base stations installed by home users to improve indoor voice and data reception [2,3].

A variety of technical challenges in mass deployment of femtocells have been addressed in recent years. Given that femtocells share the same licensed frequency spectrum with macrocells, co-channel interference affects the overall performance of femtocell networks, and the capacity of macro-base stations (MBSs) and FAPs is considered one of the major challenges in femtocell networks [4].

Schemes based on game theory for power allocation in wireless networks have been widely investigated in recent years [5–7]. Most works have dealt with the Nash equilibrium (NE) of the resulting power control game [8–10], and a few works have modeled the problem as a Stackelberg game. In [9,10], the multiple-user multiple-channel power allocation problem was considered, and the NE of the resulting game in orthogonal frequency division multiple access (OFDMA) femtocell networks was addressed. However, in the algorithms, subchannels were allocated first, followed by power, and the change in the power strategy did not affect the subchannel strategy, thereby leading to non-optimal

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results. In [11], a Nash game was applied to copy with the downlink interference management in a femtocell network assuming that the MBS's power was constant, and without changing the MBSs strategy. Femtocell networks are two-tier, and the hierarchical Stackelberg equilibrium (SE) performs better than the one-tier NE. Accordingly, most works [12–16] have been conducted using the Stackelberg game in the power control problem, including pricing data and power. In [15], MBS behaved as a leader and controlled the cross-tier by setting the prices for interference to each FAP, while FAP behaved as a follower that responded to the price strategy by optimizing the power allocation strategy; the authors proposed an efficient heuristic price-searching mechanism in the game. In [16], a Stackelberg-game-based power control was formulated to maximize the capacity under cross-tier interference constraints without considering subchannel allocation. Pricing mechanisms are useful in developing decentralized optimal power allocation for wireless networks without interference. However, methods do not result in globally optimal power allocations for cellular networks with interference [17]. In [18], the authors proposed a concept in which SE was considered a solution to the power control in wireless networks, and they showed that SE was superior to NE. However, only one-leader one-follower game with two subchannels was analyzed. In [19,20], the authors considered the interference management for femtocell networks, and the analytical solution was obtained for the Stackelberg game with only one subchannel. The work of Ngo et al. [21] developed an efficient iterative algorithm that assigned subchannels to receivers, allocated power to transmitters, and alternatively searched for the optimal joint allocation solution. In [22], the author proposed an efficient algorithm for a multiple-leader multiple-follower Stackelberg game and proved that SE was better than NE in downlink power allocation in OFDMA femtocell networks. Nevertheless, the leaders needed to have perfect knowledge of all channel gains and know the channel selection strategy of all the corresponding followers. Thus, considerable information exchange caused the algorithm to become high cost and undistributed.

In this study, we address the issue of transmit downlink power control with multiple channels and users by each station in interference channels with a total power constraint base on OFDMA. We aim to devise a distributed low-cost and high-throughput joint subchannel and power allocation algorithm for hierarchical networks. We apply the distributed downlink power allocation method. The station allocates its power to multiple subchannels without the knowledge of channel gains and the channel selection strategy of others to improve the capacity in OFDMA femtocell networks. We assume that every station has an objective to maximize its individual capacity. Thus, the hierarchical downlink power control problem can be formulated as a Stackelberg game in which MBSs are the leaders and FAPs are the followers. The player in the Stackelberg game competes with other players to maximize its utility. The solution of such a game is SE. We propose a hybrid strategy that combines channel selection and power strategies for leaders to achieve the maximum capacity SE. The leaders can abandon some low-quality subchannels to achieve more capacity from other subchannels. In other words, the leaders maximize capacity based on the balance between bandwidth and low interference. If the leaders once create some "holes" in spectrum, then the followers exploit them for more capacity. Our algorithm efficiently improves the capacity of both MBSs and FAPs with low-cost mechanisms under high-interference conditions.

The main contributions of this study are as follows:

1. We propose a distributed algorithm for a multiple-leader multiple-follower Stackelberg game. The solution (SE) efficiently improves the capacity of a femtocell network.
2. We divide the multiple-subchannel power allocation strategy into two substrategies, namely, the channel selection strategy and the power strategy. The two substrategies interact with each other in the game to achieve SE rather than fix one and then search the other one.
3. A subchannel quality-estimating method is proposed. MBSs estimate a subchannel based on the method and then generate the channel selection strategy.
4. A mechanism for dynamic step size is proposed to accelerate the algorithm convergence. The iterative time and the algorithm cost are decreased.
5. Our proposed algorithm can cope with a variational player number at a minimal cost.

The rest of this paper is organized as follows. In Section 2, the system model for downlink transmission is presented and the Stackelberg game model is formulated. In Section 3, the problem formulation and solution for sub-games are presented. In Section 4, the detailed algorithm for Stackelberg equilibrium is presented and analyzed. Then, Section 5 shows the simulation results and analysis of them. Finally, conclusions are given in Section 6.

2. System model

2.1. Hierarchical OFDMA network model

An OFDMA system is composed of macrotier and femtotier. As shown in Fig. 1, the transmitters of each tier are made up of MBSs and FAPs. Let $\mathbf{M}=\{1,\dots,M\}$ denote the set of MBSs and $\mathbf{N}=\{1,\dots,N\}$ denote the set of FAPs. Spectrum is divided into $\mathbf{L}$ subchannels indexed by l, with $l\in\mathbf{L}=\{1,\dots,L\}$. The set of orthogonal subchannels is shared by and universally reused in both tiers. Each subchannel has a unit bandwidth.

g_{ij}^{lk} is denoted as the link gain for the channel l of transmitter i to the channel k of receiver j. We assume that a channel state is stationary in one time slot. Given the orthogonality of subchannels, gain $g_{ij}^{lk}=0$ for $k\neq l$. The link gains are normalizing such that $g_{ii}^{kk}=1$ for all $i\in\mathbf{M}\bigcup\mathbf{N}$ and $k\in\mathbf{L}$. Noise is additive, white and Gaussian, with power n_j^k in the subchannel k of receiver j. The power of transmitter i in subchannel k is denoted as p_i^k. The interference from other transmitters observed by the receiver j in subchannel k is given by $\nu_j^k=\sum_{i\neq j}g_{ij}^k p_i^k+n_j^k$.

We assume that the receivers can distinguish the useful signal from the interference and know the power value. The signal to interference plus noise power ratio is observed by the receiver j in channel k is given by