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Distributed power optimization for spectrum-sharing femtocell networks: A fictitious game approach

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ABSTRACT

Power control techniques are becoming increasingly important for a two-tier network, where a central macrocell is underlaid with femtocells, since cross-tier and co-tier interference severely limits network performance. In this paper, we propose a distributed power control scheme for the uplink transmission of spectrum-sharing femtocell networks based on fictitious game. Each user announces a price that reflects its sensitivity to the current interference level, and adjusts its power to maximize its utility. Power and price are updated at terminals and base stations, respectively. The scheme is proved to converge to a unique optimal equilibrium. Furthermore, we propose a simple macrocell link protection scheme, where a macro user can protect itself by increasing its price. Most importantly, we investigate the power optimization scheme proposed in frequency-selective channels based on the Stackelberg game, in which each user prices its limited power allocated to subchannels. Numerical results show that the proposed schemes are effective in resource allocation for spectrum-sharing two-tier networks.

1. Introduction

Recent research has shown that nearly 90% of data services and 60% of voice services take place in indoor environments (Chandrasekhar et al., 2008). As one of the most promising technologies for indoor wireless communications, femtocells have attracted much attention. Femtocells are short-range, low-power and low-cost home base stations, which are deployed by end consumers and operate in licensed spectrum. Femtocells are connected to the operator's network via broadband connections such as digital subscriber line (DSL) or cable modem. Femtocells can provide better indoor user experience with lower transmit power, resulting in power saving of mobile devices. Femtocells can offload traffic from macrocells, consequently improving the network coverage and capacity (Kang et al., 2011).

Femtocells combined with orthogonal frequency-division multiple access (OFDMA) have been adopted by most next generation wireless networks, such as the 3GPP long-term evolution (LTE) (Ergen, 2009). It is necessary to study power optimization in multichannel femtocell networks, e.g., how users allocate their limited power across the available subchannels.

In practice, there are still some problems that need to be resolved for massive deployments of femtocells. A two-tier femtocell network is usually implemented with shared spectrum rather than split spectrum between tiers (Kang et al., 2011). However, cross-tier and co-tier interference may greatly impair network performance of spectrum-sharing femtocell networks (López-Pérez et al., 2009). This motivates the use of power optimization for interference management in two-tier femtocell networks. Prior research has investigated the power optimization scheme for cross-tier interference. In Kang et al. (2011, 2012), the authors presented a distributed power control algorithm for spectrum-sharing femtocell networks using Stackelberg game, which is very effective in distributed power allocation. In Chandrasekhar et al. (2009), the authors proposed a distributed utility-based Signal-to-Interference-plus-Noise Ratio (SINR) adaptation algorithm to alleviate cross-tier interference from co-channel femtocells to macrocells. Jo et al. (2009) proposed interference mitigation strategies that adjust the maximum transmit power of femto user equipments (FUEs) to suppress the cross-tier interference at macrocell base stations (MBSs). Yun and Shin (2011) proposed a distributed and self-organizing femtocell management architecture to mitigate cross-tier interference which consists of three control loops. But they did not consider the co-tier interference between femtocells. Mitigation of co-tier interference has also been investigated in previous work. In Sahin et al. (2009), the authors proposed an interference avoidance framework between macrocell and femtocell through frequency scheduling. Lee et al. (2011) devised a cooperative resource-allocation algorithm to improve intercell fairness in femtocell networks. However, only co-tier interference has been considered in these literatures. And it requires complete network information, including interference channel gains.

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A variety of game-theoretic approaches have been applied to interference management in different networks (Kim et al., 2010). In Wang et al. (2009), the authors investigated power control strategies to maximize the utility for spectrum-sharing cognitive radio networks (CRNs) using Stackelberg game. Huang et al. (2006) presented distributed power control algorithms for both signal-channel and multichannel ad hoc networks, in which power price and interference price are introduced to represent the dual variables corresponding to user's total power constraint and sensitivity to the current interference level, respectively. In this paper, we focus on femtocell networks instead of ad hoc networks.

In Kang et al. (2012) and Chandrasekhar et al. (2009), only the MBS can price uplink interference from FUEs. It is impractical to use centralized power control, since a central controller would require complete network information, including interference channel gains. Hence, we consider distributed power control in this paper.

In this paper, we propose a distributed power optimization scheme for the uplink transmission of spectrum-sharing femtocell networks based on fictitious game, where not only macrocells but also femtocells can price interference. Furthermore, in order to reduce signaling overhead, power and price are updated at terminals and base stations (BSs), respectively. Each user can estimate other users' total prices based on the sensing results from the energy detector. Moreover, if macro user equipment (MUE) cannot achieve its target SINR (Razaviyayn et al., 2010) with the maximum transmit power, the MBS increases its price. For multichannel networks, we need consider how the users allocate their power across to the available subchannels. We investigate the power optimization scheme for multichannel femtocell networks based on the Stackelberg game by introducing the power price, which represents the dual variable corresponding to user's total power constraint. Under the total power constraint, each user prices its power allocated to subchannels. Each user minimizes its loss due to the total power constraint. In the Stackelberg game, we also study two pricing schemes: uniform pricing and non-uniform pricing. In practice, the uniform pricing scheme can be implement in the same centralized way as that for the non-uniform pricing scheme, which requires large amounts of computation. However the optimization problem in the uniform pricing scheme has some nice properties that can be explored for the implement. Based on properties, we present an effective distributed power price bargaining algorithm, which only requires a small amount of computation.

The rest of this paper is organized as follows. We introduce the system model and formulate the multichannel power optimization problem in Section 2. In Section 3, we present the distributed power optimization algorithm for a single-channel network based on fictitious game (ADP algorithm) and propose the macrocell link protection scheme (ADP-P algorithm). Then we formulate the Stackelberg game to allocate power for multichannel networks subject to a power constraint and propose the ADP algorithm with macrocell link protection for multichannel femtocell networks (ADP-M algorithm) in Section 4. Numerical results are given in Section 5. Finally, we make the conclusion in Section 6.

2. System model and problem formulation

In this section, we first introduce the system model for the spectrum-sharing femtocell network. Then we formulate the multichannel power optimization problem.

2.1. System model

A two-tier femtocell network has been considered as shown in Fig. 1. For analytical tractability, we ignore co-channel interference from neighboring macrocell transmissions. Assuming that the system consists of a central MBS B_0 providing a macrocell coverage area with radius R_m. Within the macrocell coverage at a distance D_f from the MBS B_0, N co-channel femtocells $\{B_i\}$, $i=1\cdots N$, are located in a square grid—e.g. residential neighborhood—of area D_{grid}^2 Km^2 (Chandrasekhar et al., 2009). Each femtocell has a radio range of R_f meters. It is assumed that femtocells and macrocell use the same frequency bands, and there is one scheduled active user in each femtocell during each signaling slot. Each user is able to transmit over a set of $\mathcal{K}=\{1,\cdots,K\}$ orthogonal subchannels. Let $g_{i,j}^{(k)}$ denote the channel gain between transmitting mobile j and BS B_i at subchannel k. The channel gains are modeled following the channel model in Chandrasekhar et al. (2009).

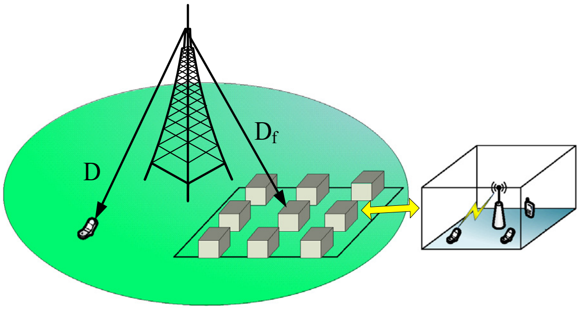

Fig. 1. Singal macrocell with underlaid femtocells.

2.2. Problem formulation

Let $i\in\{0,1,\cdots,N\}$ denotes the scheduled active user connected to its BS B_i. Transmit power on subchannel k of user i is $p_i^{(k)}$. The variance of additive white Gaussian noise (AWGN) on each subchannel is σ^2. The interference on subchannel k of user i is denoted by $I_i^{(k)}$, where

$$I_i^{(k)} = \sum_{j\neq i} p_j^{(k)} g_{i,j}^{(k)} + \sigma^2 \tag{1}$$

Consequently, the SINR $\gamma_i^{(k)}$ of user i at subchannel k can be expressed as

$$\gamma_i^{(k)} = \frac{p_i^{(k)} g_{i,i}^{(k)}}{\sum_{j\neq i} p_j^{(k)} g_{i,j}^{(k)} + \sigma^2} \tag{2}$$

The utility function $u_i^{(k)}$ on subchannel k of user i is an increasing and strictly concave function of SINR $\gamma_i^{(k)}$. For example, the utility function can be expressed as (Huang et al., 2006)

$$u_i^{(k)} = W\log(\gamma_i^{(k)}) \tag{3}$$

where W denotes the bandwidth of each subchannel. In this case, since a user's SINR is typically larger than 1, the utility function $u_i^{(k)}$ is approximately equal to the data rate of user i at subchannel k. The overall utility of user i is

$$u_i = \sum_{k=1}^{K} u_i^{(k)} \tag{4}$$

Then the overall utility of the network can be defined as

$$u = \sum_{i} u_i \tag{5}$$

The problem we consider is to determine power allocation of all users to maximize the utility summed over all users under the constraints $\sum_{k\in\mathcal{K}} p_i^{(k)} \le p_i^{\max}$ and $p_i^{(k)} \ge p_i^{\min}$.