Physical Communication 7 (2013) 122–133

Contents lists available at SciVerse ScienceDirect

Physical Communication

journal homepage: www.elsevier.com/locate/phycom

Full length article

Price-based interference control for two-tier femtocell networks

Xinping Guan [a,b], Qiaoni Han [a], Kai Ma [a,*], Zhixin Liu [a]

[a] Institute of Electrical Engineering, Key Laboratory of Industrial Computer Control Engineering of Hebei Province, Yanshan University, Qinhuangdao 066004, China
[b] School of Electronic, Information and Electrical Engineering, Shanghai Jiaotong University, Shanghai 200240, China

ARTICLE INFO

Article history:
Received 31 December 2011
Received in revised form 17 June 2012
Accepted 16 November 2012
Available online 27 November 2012

Keywords:
Femtocell
Interference control
Price-based
Non-cooperative game
Nash equilibrium

ABSTRACT

This paper presents a novel price-based interference control scheme for two-tier femtocell networks, aiming to limit the interference from femtocell users to macrocell base station (MBS). Assuming that the MBS protects itself by pricing the interference power from the femtocell users, the femtocell users set their transmission powers by competitively selecting the interference power fractions under the constraint of the total tolerable interference. The problem of femtocell users' competitive interference occupation process is cast into a non-cooperative interference power purchase game, and the existence and uniqueness of the Nash equilibrium is proved. Then, a distributed interference power fraction iterative algorithm is developed to find the Nash equilibrium of the game, and the convergence analyses in both synchronous and asynchronous cases are presented. The distributed implementations are also shown. Simulation results show the convergence of the interference power fraction iterative algorithm and the effectiveness of the proposed interference control scheme.

1. Introduction

In recent years, femtocell, which is proposed as one of the most promising technologies for improving the indoor wireless service, has attracted considerable attention in both technology development and marketing. Femtocells are small base stations installed at home within an existing cellular network based on the basic IP backhaul, and mostly, they are randomly installed by end-users. To the overall network, femtocells provide higher spatial reuse with less interference to other users. The prominent features of femtocells are their low cost, low power and the usage of cellular standards and licensed spectrum, which are respectively distinguished from microcells and Wi-Fi [1].

Due to the spectrum scarcity and simple deployment, femtocells usually adopt co-channel operation. That is to say, femtocells are allocated the same carrier frequency as the macrocell [2]. However, for co-channel deployed two-tier femtocell network, cross-tier and inter-cell interference greatly restricts the system performance, especially in the uplink (UL) communication. This has been reported as an important problem in several works [2–4]. The interference management in two-tier femtocell network's UL communication is, mainly on adjusting the transmission powers of femtocell users [2–5], spectrum assignments [6,7], femtocells' adaptative access operation [8] and varying femtocell coverage area [9].

Here, we focus on the interference control in two-tier femtocell networks based on adjusting the transmission powers of femtocell users. In [2,3], the interference from femtocell users to macrocell base station (MBS) is controlled by restricting the maximum power of femtocell users. In [4], a distributed cellular link quality protection algorithm is proposed by reducing transmission powers of the femtocell users with the strongest interference. In [5], by applying the interference power constraint

* Corresponding author. Tel.: +86 335 8074881; fax: +86 335 8072979.
E-mail address: kma@ysu.edu.cn (K. Ma).

1874-4907/$ – see front matter Crown Copyright © 2012 Published by Elsevier B.V. All rights reserved.
doi:10.1016/j.phycom.2012.11.004

to the design of interference control for the UL transmission of femtocell networks, price-based resource allocation strategies are investigated, whereby the MBS controls the transmission power of femtocell users by pricing their resulted interference power levels at the MBS receiver subject to a maximum tolerable interference margin. However, the CTRL in [2] requires the implementations of complex control loops inside the femtocell, while the femtocell possesses low data processing capabilities. The power control scheme in [3] focuses on the protection of a macrocell's UL transmission without considering the convergence. The coordinated UL power-control architecture proposed in [4] is for both macrocell and femtocells, and requires macrocells to perform the proposed power control algorithm. Moreover, all the above interference control schemes are imposed at the femtocell user side, and the price-based resource allocation strategies in [5] impose the interference power constraint at the MBS side. However, the optimal interference price in Stackelberg game requires the MBS to measure and collect a large amount of information from each femtocell user even in the uniform-pricing case. This will incur great implementation complexity and feedback overhead for MBS and femtocells, even through the utility of MBS is optimized. Actually, to constraint the interference to macrocell users' UL transmission, we only have to ensure that the interference at the MBS is below a threshold which is either fixed or adaptative [2,3]. Therefore, unlike [5], we propose a novel price-based interference control scheme in this paper. This scheme can reduce the overhead for information exchanging. Assuming that the MBS protects itself by pricing the interference power from the femtocell users, the femtocell users set their transmission powers by competitively selecting the interference power fractions under the constraint of the total tolerable interference. The problem of femtocell users' competitive interference occupation process is formulated as a buyers' market competition and a price-based non-cooperative game is proposed to solve the problem. The main contributions of this paper are as follows:

(a) A non-cooperative interference power purchase game (IPPG) among femtocell users is formulated, aiming to effectively control the interference at the MBS. Then, the price for unit interference power fraction and the utility function for femtocell users are defined.
(b) The existence and uniqueness of Nash equilibrium are proved. To show the existence, we take the second order derivative of utility function, and then by proving the definite of system matrix, we show the uniqueness. In addition, we analyze the inefficiency of the Nash equilibrium.
(c) An interference power fraction iterative algorithm is developed to find the Nash equilibrium and the convergence analyses in both synchronous and asynchronous cases are presented. Moreover, the distributed implementations are shown.

The rest of the paper is organized as follows. In Section 2, a two-tier femtocell network model for uplink transmission is presented and the interference power purchase game is formulated. In Section 3, the proposed interference power purchase game is analyzed and solved in detail. Then, in Section 4, the simulation results are presented and discussed. Finally, in Section 5, the conclusions are drawn.

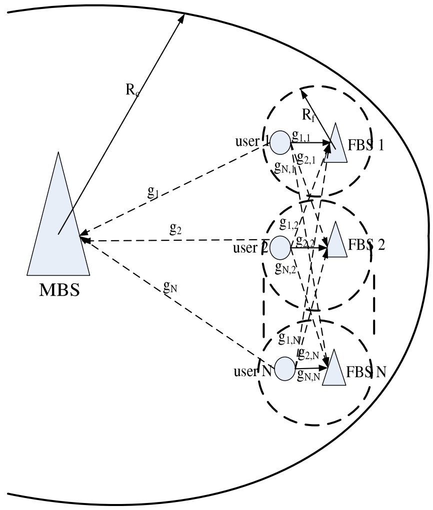

Fig. 1. UL transmission for two-tier femtocell networks.

2. System model and problem formulation

We consider a two-tier femtocell network consisting of one macrocell and N femtocells deployed randomly by home or office users. As shown in Fig. 1, the MBS serves in a region R_c. Each femtocell base station (FBS) provides service for several wireless devices, i.e., femtocell users, in a region R_f. For simplicity, the macrocell users are not shown. User i denotes the scheduled user transmitting to FBS i, where $i = 1, 2, \ldots, N$. Fig. 1 also describes the UL transmission of the two-tier femtocell network. The solid and dashed arrows from femtocell users to FBSs and MBS represent the uplink signals and interference, respectively. Additionally, it is assumed that all femtocells access the same frequency band as the macrocell. For analytical tractability, we also assume that, in each femtocell, there is at most one scheduled active user during each signaling time-slot at any given frequency band (e.g. one frequency subband in OFDMA-based femtocells). In this paper, we focus on UL transmission based on single frequency band.

All the terminals involved are assumed to be equipped with single antenna. The channel links between femtocell users and BSs (FBSs, MBS) are divided into outdoor, indoor, and outdoor-to-indoor links according to the radio environment. For simplicity, neither Rayleigh fading nor lognormal shadowing is modeled. The channel gain from a femtocell user to the MBS or a FBS is determined based on the IMT-2000 specifications described in [4] as follows:

$$g_{i,j} = \begin{cases} K_{fi} R_f^{-\alpha_{fi}}, & j = i \\ K_{fo} W^2 \min\left(D_{i,j}^{-\alpha_{fo}}, 1\right), & j \neq i, \end{cases} \tag{1}$$
$$g_i = K_{fo} W \min\left(D_i^{-\alpha_{fo}}, 1\right).$$

In (1), $g_{i,j}$ denotes the channel gain from user j to FBS i, and g_i denotes the channel gain from user i to MBS. R_f is the coverage radius of femtocell. $D_{i,j}$ is the distance between user j and FBS i. α_{fi} and α_{fo} denote the indoor and indoor to outdoor femtocell path loss exponents, respectively.