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4G Femtocells

Resource Allocation and Interference Management

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Haijun Zhang • Xiaoli Chu • Xiangming Wen

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Haijun Zhang
College of Information Science
and Technology
Beijing University of Chemical
Technology
Beijing, China, People's Republic

Xiaoli Chu
Department of Electronic
and Electrical Engineering
The University of Sheffield
Sheffield, UK

Xiangming Wen
Beijing University of Posts
and Telecommunications
Beijing, China, People's Republic

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Preface

Femtocells have been considered as a promising technology to provide better indoor coverage and spatial reuse gains in the last few years. Femtocells are low power, low cost and user deployed wireless access points that use local broadband connections as backhaul. Not only the users but also the operators benefit from femtocells. On the one hand, users enjoy high-quality links; on the other hand, operators decrease the operational expenditure (OPEX) and capital expenditure (CAPEX) due to the traffic offloading and user's self-deployment of femtocell base stations (FBSs). Orthogonal frequency division multiple access (OFDMA) based femtocells have been considered in major wireless communication standards, e.g., LTE/LTE-Advanced. Due to spectrum scarcity and implementation difficulty, spectrum-sharing, rather than spectrum splitting, between femtocells and macrocells is more preferable from the operator's perspective. However, co-channel deployed femtocells may lead to severe co-channel interference between femtocells in dense deployment, and cross-tier inference between macro-tier and femto-tier.

Due to the fading coefficients of different subchannels are likely to be independent for different users, which are known as multiuser diversity (MUD), maximum system spectral efficiency can be achieved by selecting the best user for each subchannel and adapting the associated transmit power. Therefore, resource allocation is one of the most important techniques for femtocells to maximize spectral efficiency and mitigate interference. Power control and subchannel allocation have been widely used to alleviate cross-tier and/or co-tier interference and satisfy diverse quality of service (QoS) for co-channel deployment of femtocells. However, there has not been any book specifically addressing femtocell network resource allocation with various objectives, constraints and optimizing variables taken into consideration.

In this book, we address the foregoing issues and provide an in-depth discussion on the latest resource allocation and interference management issues for femtocells. The discussion begins with introducing femtocells and their development in Chap. 1. After that, resource allocation in dense deployed femtocells is investigated in Chap. 2. Such techniques include user scheduling and power control to maximize capacity of femtocells. In Chap. 3, an interference-aware pricing-based resource allocation algorithm for co-channel femtocells is proposed to alleviate their interference to macrocells without degrading the femtocells' capacity. The subchannel and power allocation problem is modeled as a non-cooperative game. A suboptimal subchannel allocation algorithm and an optimal power allocation algorithm are proposed to implement the resource allocation game. In Chap. 4, resource allocation is investigated in both uplink and downlink for two-tier networks comprising spectrum-sharing femtocells and macrocells. A resource allocation scheme for co-channel femtocells is proposed, aiming to maximize the capacity for both delay-sensitive users and delay-tolerant users subject to delay-sensitive users' QoS constraints and the interference constraint imposed by the macrocell. The subchannel and power allocation problem is modeled as a mixed integer programming problem, then transformed into a convex optimization problem by relaxing subchannel sharing, and finally solved by the dual decomposition method. The complexity of the proposed algorithms is analyzed, and the effectiveness of the proposed algorithms is verified by simulations. In Chap. 5, we propose an energy-aware uplink power control scheme for two-tier femto-macro networks based on non-cooperative game. In Chap. 6, we propose a differentiated-pricing based power allocation algorithm for the uplink of spectrum-sharing femtocells, based on a non-cooperative game framework. Concluding remarks and future trends are provided in Chap. 7.

Beijing, China, People's Republic Haijun Zhang
Sheffield, UK Xiaoli Chu
Beijing, China, People's Republic Xiangming Wen

Contents

Chapter 1
Introduction to 4G Femtocells

Abstract Femtocells have been proposed for improving the performance of indoor users to provide better indoor coverage and spatial reuse gains in the 4G networks. On the one hand, users enjoy high-quality links; on the other hand, operators decrease the operational expenditure (OPEX) and capital expenditure (CAPEX) due to the traffic offloading and user's self-deployment of femtocell base stations (FBSs). As femtocells can meet users' demand and indoor coverage requirement well, they have been widely used in many wireless communication standards, such as WiMAX, and LTE/LTE-Advanced. However, there are still some challenges in the mass deployed femtocell environment. Interference management is considered as one of the major challenges in femto-macro two-tier networks. In this chapter, we survey different state-of-the-art approaches of resource allocation and interference management in orthogonal frequency division multiple access (OFDMA) femtocell networks. Moreover, some open challenges in interference and resource management are discussed.

1.1 4G Femtocell Networks

Fourth-generation (4G) mobile networks are expected to provide high capacity and wide coverage. However, since the 4G wireless systems, such as WiMAX and LTE/LTE-Advanced, are usually deployed in high frequency band, the penetration loss will be high. Moreover, above 50% of voice services and 70% of data traffics occur indoors nowadays [1]. The most promising solution to this problem is shortening the distance between the transmitter and the receiver.

Insufficient indoor coverage of macrocells has led to increasing interest in femtocells, which have been proposed for improving the quality of service (QoS) of indoor users [2]. Femtocells usually comprise small size, low-power, low-cost, and short-range home base stations. They work in the licensed frequency bands, and are connected to broadband Internet backhaul. As femtocells can meet

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customers' demands and indoor coverage requirements, femtocells combined with orthogonal frequency division multiple access (OFDMA) have been considered in many wireless communication standards, such as WiMAX and LTE/LTE-Advanced [3]. Two-tier OFDMA macrocell and femtocell networks are widely expected to improve coverage and capacity of indoor environments.

Dedicated-channel deployment of femtocells, where femtocells and macrocells are assigned with different (or orthogonal) frequency bands, may not be preferred by operators due to the scarcity of spectrum resources and complexities in implementation. While in co-channel deployment, where femtocells and macrocells share the same spectrum, cross-tier interference could be severe [2], especially when femtocell base stations (FBSs) are deployed close to a macrocell base station (MBS) [22]. Due to the fundamental role of macrocells in providing blanket cellular coverage, their capacities and coverage should not be affected by co-channel deployment of femtocells. As a result, resource allocation and interference management have become an important asset to enhance performance and have attracted much attention from the telecommunication industry.

1.2 Resource Allocation and Interference Management

In practice, there are still some technical challenges to be further addressed before extensive deployment of femtocells. A two-tier macrocell and femtocell network is usually implemented by sharing frequency rather than splitting frequency between tiers [4]. Hence, cross-tier interference (CTI) and inter-tier interference (ITI) are the key issues in two-tier macrocell and femtocell networks [1]. Maximization of the total data rate of femtocells with the consideration of cross-tier and inter-tier interference has become an interesting research area. Related works on femtocell networks in the literature are described in the following. Resource allocation algorithms aiming at the inter-cell interference management in femtocell networks are discussed and evaluated in [5]. A resource allocation scheme considering inter-femtocell fairness is proposed in [6]. In [7], a cross-tier interference mitigation algorithm based on power control is developed. The authors in [27] propose a distributed resource allocation algorithm based on Lagrangian dual method.

Power control has been widely used to mitigate inter-cell interference in co-channel deployment of femtocells. For alleviating uplink interference caused by co-channel femto users to macrocells, a distributed femtocell power control algorithm is developed based on non-cooperative game theory in [7], while in [4] femto users are priced for causing interference to macrocells in the power allocation based on a Stackelberg model. In [24], cross-tier interference is mitigated through both open-loop and closed-loop uplink power control. In [16], a distributed power control scheme is proposed based on a supermodular game.

A lot of work has also been done on subchannel allocation in co-channel deployment of femtocells. In [25], a hybrid frequency assignment scheme is proposed for femtocells deployed within coverage of a macrocell. In [17], distributed channel selection schemes are proposed for femtocells to avoid inter-cell interference, at the cost of reduced frequency reuse efficiency. In [18], a subchannel allocation algorithm based on a potential game model is proposed to mitigate both co-tier and cross-tier interference.

Recently, several studies considering both power and subchannel allocation in femtocells have been reported. In [26], a joint power and subchannel allocation algorithm is proposed to maximize the total capacity of densely deployed femtocells, but neither the interference caused by femtocells to macrocells nor the fairness between femto users has been considered. In the collaborative resource allocation scheme proposed in [29], cross-tier interference is approximated as additive white Gaussian noise (AWGN). In the Lagrangian dual decomposition based resource allocation scheme [27], constraints on cross-tier interference are used in power allocation, but subchannels are assigned randomly to femto users. In [28], a distributed downlink resource allocation scheme based on a potential game and convex optimization is proposed to increase the total capacity of macrocells and femtocells, but at the price of reduced femtocell capacity. In [21], the distributed power and subchannel allocation for co-channel deployed femtocells is modeled as a non-cooperative game, for which a Nash Equilibrium is obtained based on a time-sharing subchannel allocation, but the constraint on maximum femto-user transmit power is ignored in solving the non-cooperative game.

Game theory has been considered to mitigate interference in two-tier networks with co-channel deployed femtocells. In [4, 21], the minimization of co-tier and cross-tier interference though power control based on game theory is investigated. In [7], the authors introduce a distributed utility-based SINR adaptation algorithm in order to alleviate cross-tier interference caused by co-channel femtocells to the macrocell. In [19], a decentralized femtocell access strategy based on non-cooperative game is proposed to manage the interference between nearby femtocells and from femtocells to macrocells. The authors in [4] propose a distributed power control algorithm for spectrum-sharing femtocell network using Stackelberg game, which is very effective in distributed power allocation and macrocell protection while requiring minimal network overhead.

Recently, several studies considering pricing techniques together with power controls have been reported. In [21], the distributed cross-tier interference pricing in power allocation for co-channel deployed femtocells is modeled as a non-cooperative game, but the constraint on maximum femto-user transmit power is ignored in solving the non-cooperative game. For alleviating uplink interference caused by co-channel femto users to macrocells, a distributed femtocell power control algorithm is developed based on non-cooperative game theory in [7]; while in [4] femto users are priced for causing interference to macrocells in the power allocation based on a Stackelberg model.

1.3 Challenges and Issues

Interference mitigation based on resource allocation has been widely analyzed to maintain user's QoS, e.g., signal to interference and noise ratio (SINR) capacity, while alleviating cross-tier interference in two-tier networks. In [7], non-cooperative power allocation with SINR adaptation is used to alleviate the uplink interference suffered by macrocells; while in [4], Stackelberg game based power control is formulated to maximize femtocells' total capacity under cross-tier interference constraints. However, subchannel allocation is not considered. In [26], a joint subchannel and power allocation algorithm is proposed to maximize total capacity in dense femtocell deployments. While in [27], a Lagrangian dual decomposition based resource allocation scheme with constraints on cross-tier interference in power allocations is used. In [21], the distributed subchannel and power allocation for co-channel deployed femtocells is modeled as a non-cooperative game, for which a Nash Equilibrium is obtained based on a time-sharing subchannel allocation scheme. However, in these works, joint subchannel and power allocation with considerations of users' QoS and cross-tier interference is not studied. In [20], a distributed modulation and coding scheme in conjunction with subchannel and power allocation that supports different throughput constraints per users is proposed, but it does not consider two-tier networks. There have been very few works in the literature that make efforts to maximize the capacity of a two-tier network while jointly considering cross-tier interference, QoS requirements and the fairness among users in femtocell networks.

Moreover, femtocell networks should support the heterogeneous QoS requirements of delay sensitive services such as online gaming and video phone calls, while maximizing the throughput of delay tolerant services [32]. However, to the best of our knowledge, resource allocation for heterogeneous QoS users in femtocells has not been studied in previous works. Resource allocation strategies that have been widely studied in spectrum underlay Cognitive Radio (CR) networks [35,36] cannot be directly applied for Interference mitigation in two-tier macrocell and femtocell networks [4].

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Chapter 2
Ant Colony Algorithm (ACA) Based Downlink Resource Allocation in Femtocells

Abstract This chapter focuses on the resource allocation of femtocells in the Orthogonal Frequency Division Multiple Access (OFDMA) networks. A typical algorithm of swarm intelligence called Ant Colony Optimization (ACO) is adopted to resolve the optimization problem of maximizing the total capacity of femtocells considering the quality of service (QoS) requirement. An ACO based system model for the resource allocation, as well as three different schemes (ACOMAX, ACOPF and ACOCF) that are based on meta-heuristic methods is proposed. Due to the unique characteristics of ACO's heuristic searching mechanism, the proposed algorithms can guarantee a fast convergence speed. Simulation results show that ACOMAX can significantly increase the throughput of the system, and ACOCF as well as ACOPF can satisfy the requirements of throughput and guarantee fairness simultaneously.

2.1 Introduction

Femtocells have been proposed for improving the performance of indoor users [1]. Femtocells are usually comprised of small size, low-power, low-cost, and short-range home base stations. They work in the licensed frequency bands, and are connected to broadband Internet backhaul. As femtocells can meet customer's demands and indoor coverage requirements well, they have been widely introduced in many wireless communication standards, such as WiMAX, and LTE/LTE-Advanced [2]. Therefore, two-tier OFDMA networks comprising macrocells and femtocells are widely expected to improve the coverage and capacity of cellular networks.

In practice, there are still some technical challenges that need to be further addressed before widespread deployment of femtocells. A two-tier network is usually implemented by sharing frequency rather than splitting frequency between tiers [3]. Hence cross-tier interference (CTI) and intra-tier interference (ITI) are the key issues in two-tier networks [4], and maximization of the total data rate

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of femtocells with the consideration of CTI and ITI is a hot research area. The related works on femtocell networks in the literature are described in the following. Resource allocation algorithms aiming at the inter-cell interference management in femtocell networks are discussed and evaluated in [5]. A resource allocation scheme considering inter-femtocell fairness is proposed in [6], and in [7] a CTI mitigation algorithm based on power control is developed. The authors in [23] propose a distributed resource allocation algorithm based on Lagrangian dual method. However, with the consideration of CTI, quality of service (QoS) requirements and the fairness among users in femtocell networks, there is little work has been done related to maximize the capacity of the two-tier network.

Ant Colony Algorithm (ACA) is a typical swarm intelligence algorithm [9], which has been used for resource allocation in OFDM systems [10, 11]. The feature of robustness and parallel heuristic in ACA is fit for finding proper solution for resource allocation.But this approach has not been sufficiently explored in the two-tier network literature.

In this chapter, we consider a system model based on ACA in a two-tier network, where femtocells are deployed densely. Our goal is to maximize the total downlink rate of all femtocell users, while considering CTI, QoS requirement and fairness among users. We propose an ACA based algorithms to optimize the sub-channels allocation problem [13], and the performance of these algorithms is evaluated by simulation. Compared with the traditional round robin (RR) algorithm [12], the ACA based algorithm achieves better performance.

The rest of the chapter is organized as follows: Sect. 2.2 introduces the system model and problem formulation. In Sect. 2.3, the resource allocation algorithms based on ACA is presented. Simulation results and performance analysis are provided in Sect. 2.4. Finally, we conclude the chapter in Sect. 2.5.

2.2 System Model and Problem Formulation

2.2.1 System Model

In this chapter, we consider a two-tier OFDMA network as shown in Fig. 2.1, where femtocells are deployed densely [7]. A macrocell base station (MBS) locates in the center of a disc area with a radius of R_m. At a distance Df from the MBS and within the coverage region of the MBS, femtocell base stations (FBS) ($\{B_i\}(i = 1 \cdots K)$) are arranged in a square grid of area D^2_{grid} sq.km with $\sqrt{K}$ femtocells per dimension, at a distance D_f from MBS. The radius of each femtocell is R_f. Let D denote the distance between a transmitting mobile and the MBS. All femtocells are assumed to be closed access, and femtocells use the same frequency resource that the macrocell uses.

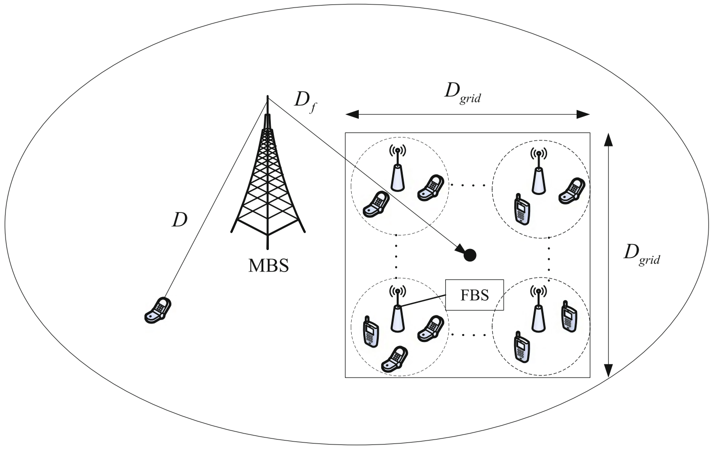

Fig. 2.1 The topology of a two-tier network

It is assumed that there are wired connections for the FBSs to communicate with the MBS. And there is one scheduled active user during each signaling slot in each femtocell. Let $k \in \{1, \ldots, K\}$ denote the scheduled active user connected to its FBS B_i. The system has a total bandwidth B and divides it into N sub-channels, each with a bandwidth of $B_0 = B/N$. The channel fading of each subcarrier is assumed the same within a sub-channel, but may vary cross different sub-channels.

We define $p_{k,n}^{(m)}$ as the transmission power of the MBS on sub-channel n to one of its users, $p_{k,n}^{(i)}$ and $p_{k,n}^{(i')}$ are the transmission powers of the serving FBS i to user k and the neighbor FBS i' to its scheduled user on sub-channel n respectively. Let $g_{k,n}^{i}$, $g_{k',n}^{(i')}$, and $g_{m,n}^{m}$ denote the channel gain from the serving FBS i, the interfering FBS i' and the MBS on sub-channel n to user k of femtocell i, respectively. We consider the channel model consisting of large scale fading and Rayleigh fading [14]. Therefore, the received signal to interference and noise ratio (SINR) for user k in femtocell i occupying the sub-channel n is given by:

$$\gamma_{k,n} = \frac{p_{k,n}^{i} \cdot g_{k,n}^{i}}{\sum\limits_{k'=1,k' \neq k}^{K} p_{k',n}^{i'} \cdot g_{k',n}^{(i')} + p_{k,n}^{(m)} \cdot g_{m,n}^{m} + N_0 \cdot B_0} \tag{2.1}$$

where $\sum\limits_{k'=1,k' \neq k}^{K} p_{k',n}^{i'} \cdot g_{k',n}^{(i')}$ is the interference caused by other co-channel femtocells, that is co-channel interference. $p_{k,n}^{(m)} \cdot g_{m,n}^{m}$ is the interference caused by the macrocell, and N_0 is the additive white Gaussian noise (AWGN) power spectral density.

In the following, we consider CTI only because CCI between different femtocells is much smaller than CTI caused by macrocell.

Based on Shannon's capacity formula, the capacity (i.e., maximum achievable data rate) of the user k occupying the sub-channel n in femtocell i is given by:

$$r_{k,n} = B_0 \cdot \log_2\left(1 + \alpha \cdot \gamma_{k,n}\right) \tag{2.2}$$

where α is a constant SINR gap of AWGN channel to meet the target bit error rate (BER), and is defined as $\alpha = -1.5/\ln(5BER)$.

2.2.2 *Problem Formulation*

Our target is to maximize the total data rate of all users of a femtocell (hereafter we omit the femtocell index i for simplicity), that is:

$$\begin{aligned}
& \max \sum_{k=1}^{K} \sum_{n=1}^{N} c_{k,n} r_{k,n} \\
s.t. \quad & \sum_{k=1}^{K} \sum_{n=1}^{N} c_{k,n} p_{k,n} \le p_{\max} \\
& p_{k,n} \ge 0,\ \forall k \in \{1,2,\ldots,K\}, \forall n \in \{1,2,\ldots,N\} \\
& BER_k \le BER_{request};\quad c_{k,n} \in \{0,1\},\ \forall\ k,\ n
\end{aligned} \tag{2.3}$$

where $c_{k,n}$ indicates whether sub-channel n is occupied by user k, and is denoted as follows:

$$c_{k,n} = \begin{cases} 1 & \text{if subchannel } n \text{ is occupied by user } k \\ 0 & \text{otherwise} \end{cases} \tag{2.4}$$

the total transmission power of an FBS is constrained by $p_{\max}$, and the power allocated on each sub-channel is nonnegative. The BER of each femtocell user k is upper bounded by the limit $BER_{request}$, which is set according to user's QoS requirement defines a sub-channel can only be used by one user at a time in each cell.

2.3 Resource Allocation Using ACA

In this section, ACA based resource allocation schemes are proposed in femtocells co-existing with a macrocell. We first present a scenario that apply ACA in the resource allocation process for system, and then propose algorithms based on ACA. The algorithms allocate the sub-channels to users under the consideration of cross-tier interference and fairness among users.