Resource Allocation in Spectrum-Sharing OFDMA Femtocells With Heterogeneous Services

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***Abstract*—Femtocells are being considered a promising technique to improve the capacity and coverage for indoor wireless users. However, the cross-tier interference in the spectrum-sharing deployment of femtocells can degrade the system performance seriously. The resource allocation problem in both the uplink and the downlink for two-tier networks comprising spectrum-sharing femtocells and macrocells is investigated. A resource allocation scheme for cochannel femtocells is proposed, aiming to maximize the capacity for both delay-sensitive users and delay-tolerant users subject to the delay-sensitive users' quality-of-service constraint and an interference constraint imposed by the macrocell. The subchannel and power allocation problem is modeled as a mixed-integer programming problem, and then, it is transformed into a convex optimization problem by relaxing subchannel sharing; finally, it is solved by the dual decomposition method. Subsequently, an iterative subchannel and power allocation algorithm considering heterogeneous services and cross-tier interference is proposed for the problem using the subgradient update. A practical low-complexity distributed subchannel and power allocation algorithm is developed to reduce the computational cost. The complexity of the proposed algorithms is analyzed, and the effectiveness of the proposed algorithms is verified by simulations.**

***Index Terms*—Convex optimization, femtocell, heterogeneous services, OFDMA, resource allocation.**

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I. Introduction

RECENT studies have shown that more and more bandwidth-hungry services are in demand in indoor environments [1], where the coverage of macrocells is rather poor because of wall penetration losses. One of the potential solutions for improving indoor coverage is to deploy indoor femtocells [2]. 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 [1].

Due to spectrum scarcity and implementation difficulty, spectrum-sharing, rather than spectrum splitting, between femtocells and macrocells is preferable from the operator perspective [3]. However, cross-tier interference from femtocell to macrocell could be severe in spectrum-sharing based two-tier networks [4]. Due to the fundamental role of macrocells in providing blanket cellular coverage, macrocell user's QoS should not be affected by femtocell deployments. Therefore, resource allocation that considers the cross-tier interference has attracted much attention [5].

Power allocation has been widely used to maximize the user's capacity while alleviating cross-tier interference in two-tier networks. In [6], non-cooperative power allocation with signal-to-interference-plus-noise ratio (SINR) adaptation is used to alleviate the interference from femtocells to macrocells, while in [7] Stackelberg game based power control is formulated to maximize femtocells' capacity under a cross-tier interference constraint. In [8], open-loop and closed-loop power control based interference mitigation is proposed for two-tier networks. In [15], power control is utilized to ensure adequate SINR for the indoor cell edge femto user, and beamforming is used to maximize the SINR of macro users and femto users by mitigating cross-tier interference in a collaborative manner. In [11], a Lagrangian dual decomposition based power allocation scheme is proposed with cross-tier interference mitigation; on the other hand, channel allocation is applied to suppress the cross-tier interference. In [9], a hybrid frequency assignment scheme is proposed for femtocells deployed within coverage of a macrocell. Subchannel allocation in femtocells is formulated into a correlated equilibrium game-theoretic approach to minimize interference to the primary macro base station (MBS) in [14]. Moreover, joint power and subchannel allocation is also investigated in femtocells. In [10], a joint power and subchannel allocation algorithm is proposed to maximize the total capacity of densely deployed femtocells. In [12], a distributed resource allocation scheme based on a potential game and convex optimization is proposed to increase the total capacity of macrocells and femtocells. In [13], a collaborative resource allocation scheme is proposed in self-organizing networks for self-healing. However, in these works, joint subchannel and power allocation with QoS and cross-tier interference consideration has rarely been studied. In [3], a non-cooperative power and subchannel allocation for co-channel deployed femtocells is proposed, together with macrocell user transmission protection.

Femtocell networks should support heterogeneous QoS for delay-sensitive services such as online gaming and video phone calls, while maximizing the throughput of delay-tolerant services. In [16], resource allocation for mixed services under a total power constraint in OFDMA systems is investigated. A resource allocation scheme considering heterogeneous QoS is proposed using a cross-layer approach in [17]. However, to the best of our knowledge, resource allocation for heterogeneous QoS users in spectrum-sharing femtocells has not been studied in existing works.

On the other hand, interference mitigation in spectrum underlay systems is also a crucial issue considered in Cognitive Radio (CR) networks [7], [18]. Interference temperature limit is introduced in CR networks to constrain the interference from a Secondary network to a Primary network that has priority for utilizing the same spectrum [19]. Interference suppression based on resource allocation strategies has been studied in CR networks. In [20], a dual decomposition method based subchannel selection and power allocation, subject to interference temperature limit, is studied in CR networks. In [21], subchannel and power allocation based on discrete stochastic optimization is proposed for CR networks considering heterogeneous QoS users. Subchannel and power allocation to maximize the system capacity considering the interference temperature limit on each subchannel of active Primary users for multi-cell CR networks is investigated in [22], [23].

However, the interference temperature cannot be directly applied in femtocells [7], because of the absence of cognitive capabilities for femto users. To solve this problem, the interference temperature limit can be delivered to femtocells by backhaul from the MBS [7], [24].

In this paper, we focus on the subchannel and power allocation problem in OFDMA based two-tier femtocell networks, in which a central macrocell is overlaid with spectrum-sharing femtocells. Heterogeneous QoS requirements for femto users are considered, where delay-sensitive users have a QoS requirement and delay-tolerant users do not have one. After introducing the interference temperature limit, the resource allocation problem is formulated into a mixed integer non-convex programming problem. To transform this non-convex problem into a convex one, a time-sharing subchannel scheme is introduced. Next, we solve the joint subchannel and power allocation problem using the Lagrange dual decomposition approach, and devise a distributed joint power and subchannel allocation algorithm. Furthermore, a low-complexity approach is proposed to explore the tradeoff between performance and computational complexity. A significant reduction in computational burden is achieved by the proposed algorithm. The performance of our proposed algorithms is verified by simulations.

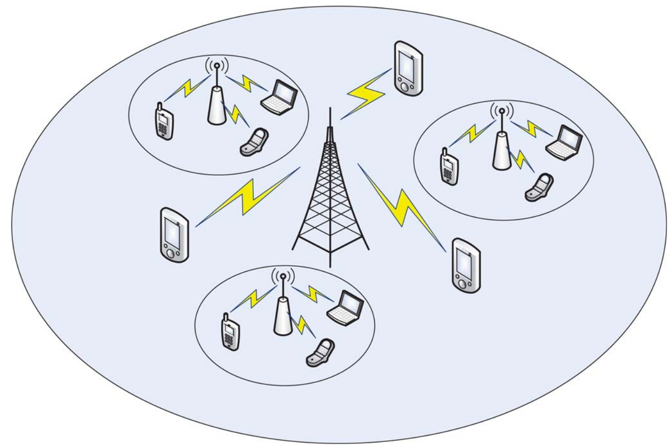

Fig. 1. Topology of the two-tier network.

The rest of this paper is organized as follows. Section II provides the system model and the problem formulation of resource allocation. In Section III, the subchannel and power allocation algorithm based on the dual decomposition method is proposed. A reduced-complexity algorithm is proposed together with a complexity analysis in Section IV. Performance of the proposed algorithms is evaluated by simulations in Section V. Finally, Section VI concludes the paper.

II. System Model and Problem Formulation

A. System Model

As shown in Fig. 1, we consider a two-tier OFDMA network where K co-channel FBSs are overlaid on a macrocell. We focus on resource allocation in the uplink of femtocells, and then extend it to the downlink case. Without loss of generality, we assume an equal power allocation and round-robin scheduling scheme for macro users, where macro users are uniformly distributed in the macrocell coverage area. Let M and F denote the numbers of active macro users camping on the macrocell and femto users camping on each femtocell, respectively.

All femtocells are assumed to be closed access and deployed in suburban residential houses. The OFDMA system has a bandwidth of B, which is divided into N subchannels. The channel fading of each subcarrier is assumed the same within a subchannel, but may vary cross different subchannels. Suppose channel fading is composed of large-scale fading (path loss) and small-scale fading (frequency-selective Rayleigh fading).

Let $g^{\mathrm{MF}}_{k,u,n}$ and $g^{\mathrm{F}}_{k,u,n}$ be the channel gains on subchannel n from user u in femtocell k to the MBS and FBS k, respectively, where $k \in \{1, 2, \ldots, K\}$, $u \in \{1, 2, \ldots, F\}$, $n \in \{1, 2, \ldots, N\}$; define $\mathcal{DS}_k$ and $\mathcal{DT}_k$ as the sets of delay-sensitive and delay-tolerant users camping on FBS k, respectively, where $|\mathcal{DS}_k| + |\mathcal{DT}_k| = F$, $\mathcal{DS}_k \cap \mathcal{DT}_k = \phi$, and delay-sensitive femto user u has a QoS requirement R_u to ensure the QoS; let $g^{\mathrm{FM}}_{k,w,n}$ as the channel gain on subchannel n from user $w(w \in \{1, 2, \ldots, M\})$ in the macrocell to FBS k; let $p^{\mathrm{F}}_{k,u,n}$ and $p^{\mathrm{M}}_{w,n}$ denote femto user u's transmit power on subchannel n in femtocell k and macro user w's power on subchannel n, and $\boldsymbol{P} = [p^{\mathrm{F}}_{k,u,n}]_{K\times F\times N}$ be the power allocation matrix of the K femtocells. Denote the subchannel indication matrix as $\boldsymbol{A} = [a_{k,u,n}]_{K\times F\times N}$, where $a_{k,u,n} = 1$ means subchannel n is assigned to femto user u in femtocell k, and $a_{k,u,n} = 0$ otherwise. Then, the received SINR at the kth FBS for femto user u occupying the nth subchannel is given by:

$$\gamma^{\mathrm{F}}_{k,u,n} = \frac{p^{\mathrm{F}}_{k,u,n} g^{\mathrm{F}}_{k,u,n}}{p^{\mathrm{M}}_{w,n} g^{\mathrm{FM}}_{k,w,n} + \sigma^2} \tag{1}$$

where $p^{\mathrm{M}}_{w,n} g^{\mathrm{FM}}_{k,w,n}$ is the interference caused by the macrocell, and σ^2 is the additive white Gaussian noise (AWGN) power, where the inter-macrocell interference is also considered as part of the AWGN because of the long inter-site distance.

Note that in (1), co-channel interference between femtocells is assumed as part of the thermal noise because of the severe wall penetration loss and low power of FBSs [2], [11], especially in sparsely deployed femtocells in suburban environments [7], where co-tier inter-femtocell interference is negligible as compared with cross-tier interference [2], [8].

Based on Shannon's capacity formula, the uplink capacity on subchannel n of femto user u in femtocell k is given by

$$C^{\mathrm{F}}_{k,u,n} = \log_2\left(1 + \gamma^{\mathrm{F}}_{k,u,n}\right). \tag{2}$$

B. Problem Formulation

When the channel state information is estimated by FBS for the uplink and fed back from femto users for downlink, the resource allocation is performed by an FBS for femto users under the following constraints:

- Total power constraint:

$$\sum_{n=1}^{N} a_{k,u,n} p^{\mathrm{F}}_{k,u,n} \le P_{\max}, \ \forall k, u \tag{3}$$

  where $P_{\max}$ denotes the maximal transmit power of each femto user.
- Heterogenous QoS guarantee: The QoS requirement R_u should be guaranteed for delay-sensitive femto user u to maintain its performance, which requires the following constraint:

$$\sum_{n=1}^{N} a_{k,u,n} C^{\mathrm{F}}_{k,u,n} \ge R_u, \ \forall u \in DS_k, \ \forall k \tag{4}$$

- Cross-tier interference constraint: We impose an interference temperature limit to constrain the cross-tier interference suffered by a MBS. Let I^{th}_n denote the maximum tolerable interference level on subchannel n for the macrocell, we have:

$$\sum_{k=1}^{K}\sum_{u=1}^{F} a_{k,u,n} p^{\mathrm{F}}_{k,u,n} g^{\mathrm{MF}}_{k,u,n} \le I^{th}_n, \ \forall n. \tag{5}$$

- User scheduling constraint: A subchannel is allocated to at most one femto user in each femtocell at a time. Thus, we have:

$$\sum_{u=1}^{F} a_{k,u,n} \le 1, \ \forall k, n. \tag{6}$$

Our target is to maximize the total capacity of delay-tolerant and delay-sensitive users in the K femtocells under the macrocell's interference constraint and delay-sensitive users' QoS constraints, thus, the corresponding problem for the uplink can be formulated as the following non-convex mixed integer programming problem:

$$\max_{a_{k,u,n},\, p^{\mathrm{F}}_{k,u,n}} \quad \sum_{k=1}^{K}\sum_{u=1}^{F}\sum_{n=1}^{N} a_{k,u,n} C^{\mathrm{F}}_{k,u,n} \tag{7}$$

$$\begin{aligned}
\text{s.t.} \quad & C1: \sum_{n=1}^{N} a_{k,u,n} p^{\mathrm{F}}_{k,u,n} \le P_{\max}, \ \forall k, u \\
& C2: p^{\mathrm{F}}_{k,u,n} \ge 0, \ \forall k, u, n \\
& C3: \sum_{n=1}^{N} a_{k,u,n} C^{\mathrm{F}}_{k,u,n} \ge R_u, \ \forall u \in DS_k, \ \forall k \\
& C4: \sum_{k=1}^{K}\sum_{u=1}^{F} a_{k,u,n} p^{\mathrm{F}}_{k,u,n} g^{\mathrm{MF}}_{k,u,n} \le I^{th}_n, \ \forall n \\
& C5: \sum_{u=1}^{F} a_{k,u,n} \le 1, \ \forall k, n \\
& C6: a_{k,u,n} \in \{0, 1\}, \ \forall k, u, n
\end{aligned} \tag{8}$$

where constraint C1 limits the transmit power of each femto user to be below $P_{\max}$ according to (3); C2 represents the non-negative power constraint of the transmit power on each subchannel; C3 sets the QoS requirement R_u to ensure the QoS of delay-sensitive femto user u in femtocell k in light of (4); C4 expresses the tolerable interference temperature level on each subchannel of a macrocell based on (5); C5 and C6 are imposed to guarantee that each subchannel can only be assigned to at most one user in each femtocell according to (6).

III. Subchannel and Power Allocation Algorithm

In this section, we first transform the non-convex mixed integer programming problem in (7), (8) into a convex optimization by relaxing the subchannel allocation indicators. Then, we solve the resulting subchannel and power allocation problem using the Lagrangian dual decomposition method [25], [26].

A. Transformation of Optimization Problem by Time-Sharing Relaxation

The optimization problem in (7) is a non-convex mixed integer programming problem because of the integer constraint for subchannel allocation in C6. The optimal solution of (7) under the constraints of (8) can be obtained by a Brute-force method, which has a high computational complexity. To make the problem tractable, we relax $a_{k,u,n}$ to be a continuous real variable in the range [0,1], where $a_{k,u,n}$ can be considered as a time-sharing factor for subchannel n. In this case, $a_{k,u,n}$ can be interpreted as the fraction of time that subchannel n is assigned to user k during one transmission frame. The time-sharing relaxation was first proposed in [27], resulting in a zero-duality gap that was proved in [28] and widely used to transform non-convex combinatorial optimization problems into convex optimization problems for multiuser subchannel allocation in multichannel OFDMA systems [3], [16]. For notational brevity, denote the actual power allocated to user u in femtocell k on subchannel n as $s_{k,u,n} = a_{k,u,n} p^{\mathrm{F}}_{k,u,n}$. Similarly, denote by $I_{k,u,n} = p^{\mathrm{M}}_{w,n} g^{\mathrm{FM}}_{k,w,n} + \sigma^2$ and $\tilde{C}^{\mathrm{F}}_{k,u,n} = \log_2(1 + (s_{k,u,n} g^{\mathrm{F}}_{k,u,n} / a_{k,u,n} I_{k,u,n}))$ the received interference power and capacity of user u on subchannel n in femtocell k, respectively. Now, the problem (7) subject to the constraints (8) can be converted into:

$$\max_{a_{k,u,n},\, p^{\mathrm{F}}_{k,u,n}} \quad \sum_{k=1}^{K} \sum_{u=1}^{F} \sum_{n=1}^{N} a_{k,u,n} \tilde{C}^{\mathrm{F}}_{k,u,n} \tag{9}$$

$$\begin{aligned} \text{s.t.} \quad & C1: \sum_{n=1}^{N} s_{k,u,n} \le P_{\max},\ \forall k, u \\ & C2: s_{k,u,n} \ge 0,\ \forall k, u, n \\ & C3: \sum_{n=1}^{N} a_{k,u,n} \tilde{C}^{\mathrm{F}}_{k,u,n} \ge R_u,\ \forall u \in DS_k,\ \forall k \\ & C4: \sum_{k=1}^{K} \sum_{u=1}^{F} s_{k,u,n} g^{\mathrm{MF}}_{k,u,n} \le I^{th}_n,\ \forall n \\ & C5: \sum_{u=1}^{F} a_{k,u,n} \le 1,\ \forall k, n \\ & C6: a_{k,u,n} \in [0, 1],\ \forall k, u, n. \end{aligned} \tag{10}$$

Since the Hessian matrix of every element "$a_{k,u,n} \tilde{C}^{\mathrm{F}}_{k,u,n}$" in (9) with respect to $s_{k,u,n}$ and $a_{k,u,n}$ is negative semi-definite, the objective function (9) is concave [25]. As the inequality constraints in (10) are convex, the feasible set of objective function is convex. Being a convex optimization problem, the transformed optimization problem in (9) has a unique optimal solution, that is, the local solution is the optimal solution, which can be obtained in polynomial time.

B. Dual Decomposition Method

In this subsection, the subchannel and power allocation optimization in (9) is solved by using the Lagrangian dual decomposition method. The Lagrangian function is given by

$$\begin{aligned} & L\left(\{a_{k,u,n}\}, \{s_{k,u,n}\}, \boldsymbol{\lambda}, \boldsymbol{\nu}, \boldsymbol{\mu}, \boldsymbol{\eta}\right) \\ &= \sum_{k=1}^{K} \sum_{u=1}^{F} \sum_{n=1}^{N} a_{k,u,n} \tilde{C}^{\mathrm{F}}_{k,u,n} \\ &\quad + \sum_{k=1}^{K} \sum_{u=1}^{F} \lambda_{k,u} \left(P_{\max} - \sum_{n=1}^{N} s_{k,u,n} \right) \\ &\quad + \sum_{n=1}^{N} \mu_n \left(I^{th}_n - \sum_{k=1}^{K} \sum_{u=1}^{F} s_{k,u,n} g^{\mathrm{MF}}_{k,u,n} \right) \\ &\quad + \sum_{k=1}^{K} \sum_{n=1}^{N} \eta_{k,n} \left(1 - \sum_{u=1}^{F} a_{k,u,n} \right) \\ &\quad + \sum_{k=1}^{K} \sum_{u \in DS_k} \nu_{k,u} \left(\sum_{n=1}^{N} a_{k,u,n} \tilde{C}^{\mathrm{F}}_{k,u,n} - R_u \right) \end{aligned} \tag{11}$$

where $\boldsymbol{\lambda}$, $\boldsymbol{\nu}$, $\boldsymbol{\mu}$ and $\boldsymbol{\eta}$ are the Lagrange multipliers (also called dual variables) vectors for the constraints $C1$, $C3$, $C4$ and $C5$ in (10), respectively. The boundary constraints $C2$ and $C6$ in (10) will be absorbed in the Karush-Kuhn-Tucker (KKT) conditions [25] to be shown later. Thus, the Lagrangian dual function is defined as:

$$g(\boldsymbol{\lambda}, \boldsymbol{\nu}, \boldsymbol{\mu}, \boldsymbol{\eta}) = \max_{\{a_{k,u,n}\}, \{s_{k,u,n}\}} L(\{a_{k,u,n}\}, \{s_{k,u,n}\}, \boldsymbol{\lambda}, \boldsymbol{\nu}, \boldsymbol{\mu}, \boldsymbol{\eta}) \tag{12}$$

The dual problem can be expressed as:

$$\min_{\boldsymbol{\lambda}, \boldsymbol{\nu}, \boldsymbol{\mu}, \boldsymbol{\eta}} \quad g(\boldsymbol{\lambda}, \boldsymbol{\nu}, \boldsymbol{\mu}, \boldsymbol{\eta}) \tag{13}$$

$$\text{s.t.} \quad \boldsymbol{\lambda}, \boldsymbol{\nu}, \boldsymbol{\mu}, \boldsymbol{\eta} \ge 0. \tag{14}$$

We decompose the Lagrangian dual function in (11) into a master problem and $K \times N$ subproblems. The dual problem can be solved iteratively with each FBS solving the corresponding local subproblem in each iteration using local information. Accordingly, the Lagrangian function in (11) is rewritten as

$$\begin{aligned} & L\left(\{a_{k,u,n}\}, \{s_{k,u,n}\}, \boldsymbol{\lambda}, \boldsymbol{\nu}, \boldsymbol{\mu}, \boldsymbol{\eta}\right) \\ &= \sum_{k=1}^{K} \sum_{n=1}^{N} L_{k,n}\left(\{a_{k,u,n}\}, \{s_{k,u,n}\}, \boldsymbol{\lambda}, \boldsymbol{\nu}, \boldsymbol{\mu}, \boldsymbol{\eta}\right) + \sum_{n=1}^{N} \mu_n I^{th}_n \\ &\quad - \sum_{k=1}^{K} \sum_{u \in \mathcal{DS}_k} \nu_{k,u} R_u + \sum_{k=1}^{K} \sum_{u=1}^{F} \lambda_{k,u} P_{\max} + \sum_{k=1}^{K} \sum_{n=1}^{N} \eta_{k,n} \end{aligned} \tag{15}$$

where

$$\begin{aligned} & L_{k,n}\left(\{a_{k,u,n}\}, \{s_{k,u,n}\}, \boldsymbol{\lambda}, \boldsymbol{\nu}, \boldsymbol{\mu}, \boldsymbol{\eta}\right) \\ &= \sum_{u=1}^{F} a_{k,u,n} \tilde{C}^{\mathrm{F}}_{k,u,n} - \sum_{u=1}^{F} \lambda_{k,u} s_{k,u,n} - \sum_{u=1}^{F} \eta_{k,n} a_{k,u,n} \\ &\quad + \sum_{u \in DS_k} \nu_{k,u} a_{k,u,n} \tilde{C}^{\mathrm{F}}_{k,u,n} - \sum_{u=1}^{F} \mu_n s_{k,u,n} g^{\mathrm{MF}}_{k,u,n}. \end{aligned} \tag{16}$$

According to the KKT conditions, the optimal solutions of the subproblems, denoted by $\{\hat{a}_{k,u,n}\}$ and $\{\hat{s}_{k,u,n}\}$, can be obtained as

$$\begin{aligned} \frac{\partial L_{k,n}(\ldots)}{\partial \hat{s}_{k,u,n}} &= \frac{1}{\ln 2} \left(\frac{(1 + \tilde{\nu}_{k,u}) a_{k,u,n} g^{\mathrm{F}}_{k,u,n}}{\hat{s}_{k,u,n} g^{\mathrm{F}}_{k,u,n} + a_{k,u,n} I_{k,u,n}} \right) - \lambda_{k,u} \\ &\quad - \mu_n g^{\mathrm{MF}}_{k,u,n} \begin{cases} = 0, \hat{s}_{k,u,n} > 0 \\ < 0, \hat{s}_{k,u,n} = 0 \end{cases} \forall k, n \end{aligned} \tag{17}$$

$$\frac{\partial L_{k,n}(\ldots)}{\partial \hat{a}_{k,u,n}} \begin{cases} < 0, \hat{a}_{k,u,n} = 0 \\ = 0, 0 < \hat{a}_{k,u,n} < 1 \ \ \forall k, n. \\ > 0, \hat{a}_{k,u,n} = 1 \end{cases} \tag{18}$$

Note that in (17), $\tilde{\nu}_{k,u} = \nu_{k,u},\ \forall u \in \mathcal{DS}_k$, and $\tilde{\nu}_{k,u} = 0$, $\forall u \in \mathcal{DT}_k$. By setting (17) equal to 0, we can get the optimal power allocated to femto user u in femtocell k at subchannel n as follows,

$$\hat{p}^{\mathrm{F}}_{k,u,n} = \frac{\hat{s}_{k,u,n}}{a_{k,u,n}} = \left(\frac{1}{\ln 2}\left(\frac{1+\nu_{k,u}}{\lambda_{k,u}+\mu_n g^{\mathrm{MF}}_{k,u,n}}\right) - \frac{I_{k,u,n}}{g^{\mathrm{F}}_{k,u,n}}\right)^+,\ \forall u \in \mathcal{DS}_k \tag{19}$$

$$\hat{p}^{\mathrm{F}}_{k,u,n} = \frac{\hat{s}_{k,u,n}}{a_{k,u,n}} = \left(\frac{1}{\ln 2}\left(\frac{1}{\lambda_{k,u}+\mu_n g^{\mathrm{MF}}_{k,u,n}}\right) - \frac{I_{k,u,n}}{g^{\mathrm{F}}_{k,u,n}}\right)^+,\ \forall u \in \mathcal{DT}_k \tag{20}$$

where $(x)^+ = \max(0, x)$.

The optimal power solutions in (18) and (19) follow as a multi-level water filling form. From (18) and (19), we can see that the water level of both delay-sensitive and delay-torrent users is influenced by $\mu_n g^{\mathrm{MF}}_{k,u,n}$. That is, more cross-tier interference channel gain $g^{\mathrm{MF}}_{k,u,n}$ results in lower water level and reduces the interference suffered by a MBS, also balances the cross-tier interference and users' performance for femtocells. Moreover, femto user u with higher $g^{\mathrm{F}}_{k,u,n}/I_{k,u,n}$ will be allocated more power on channel n. Users with different QoS requirement have different water levels, where the term $(1/\ln 2)\cdot((1+\nu_{k,u})/(\lambda_{k,u}+\mu_n g^{\mathrm{MF}}_{k,u,n}))$ ensures the QoS requirements in C3 for delay-sensitive users in femtocell k.

In (18), the partial derivative of the Lagrangian expressed as

$$\frac{\partial L_{k,n}(\ldots)}{\partial \hat{a}_{k,u,n}} = H_{k,u,n} - \eta_{k,n} \tag{21}$$

where

$$H_{k,u,n} = (1+\tilde{\nu}_{k,u})\log_2\left(1+\frac{\hat{p}^{\mathrm{F}}_{k,u,n} g^{\mathrm{F}}_{k,u,n}}{I_{k,u,n}}\right) - \lambda_{k,u}\hat{p}^{\mathrm{F}}_{k,u,n} - (1+\tilde{\nu}_{k,u})\frac{1}{\ln 2}\left(\frac{\hat{p}^{\mathrm{F}}_{k,u,n} g^{\mathrm{F}}_{k,u,n}}{\hat{p}^{\mathrm{F}}_{k,u,n} g^{\mathrm{F}}_{k,u,n} + I_{k,u,n}}\right) - \mu_n \hat{p}^{\mathrm{F}}_{k,u,n} g^{\mathrm{MF}}_{k,u,n}. \tag{22}$$

Note that in (22), $\tilde{\nu}_{k,u} = \nu_{k,u},\ \forall u \in \mathcal{DS}_k$ and $\tilde{\nu}_{k,u} = 0$, $\forall u \in \mathcal{DT}_k$. Subchannel n is assigned to user u with the largest $H_{k,u,n}$ in femtocell k, that is,

$$\hat{a}_{k,u^*,n} = 1|_{u^* = \max_u H_{k,u,n}},\ \forall k, n. \tag{23}$$

The optimal subchannel allocation solution in (23) using (22) suggests that subchannel allocation without timer-sharing can get better performance, because the intra-femtocell interference can be avoided without time-sharing. Delay-sensitive users have higher priority for the existing of $\tilde{\nu}_{k,u}$.

We use the subgradient method when (12) is not differentiable, and update the dual variables according to:

$$\lambda^{(i+1)}_{k,u} = \left[\lambda^{(i)}_{k,u} - \beta^{(i)}_1\left(P_{\max} - \sum_{n=1}^{N} s_{k,u,n}\right)\right]^+,\ \forall k, u \tag{24}$$

$$\nu^{(i+1)}_{k,u} = \left[\nu^{(i)}_{k,u} - \beta^{(i)}_2\left(\sum_{n=1}^{N}\tilde{C}^{\mathrm{F}}_{k,u,n} - R_u\right)\right]^+,\ \forall k, u \in \mathcal{DS}_k \tag{25}$$

$$\mu^{(i+1)}_n = \left[\mu^{(i)}_n - \beta^{(i)}_3\left(I^{th}_n - \sum_{k=1}^{K}\sum_{u=1}^{F} s_{k,u,n} g^{\mathrm{MF}}_{k,u,n}\right)\right]^+,\ \forall n \tag{26}$$

where $\beta^{(i)}_1$, $\beta^{(i)}_2$ and $\beta^{(i)}_3$ are the step sizes of iteration $i(i \in \{1, 2, \ldots, I_{\max}\})$, $I_{\max}$ is the maximum number of iterations, and the step sizes should satisfy the condition,

$$\sum_{i=1}^{\infty}\beta^{(i)}_l = \infty, \lim_{i\to\infty}\beta^{(i)}_l = 0,\ \forall l \in \{1, 2, 3\}. \tag{27}$$

Since the subchannel allocation solution is given by (23), it is not necessary to update the dual variable of $\boldsymbol{\eta}$ corresponding to $\boldsymbol{A}$. Moreover, only local information is needed for a FBS to update $\lambda^{(i+1)}_{k,u}$ and $\nu^{(i+1)}_{k,u}$. For the update of $\mu^{(i+1)}_n$ by a MBS, only received interference from co-channel femto users is needed. With the update of $\boldsymbol{\lambda}$, $\boldsymbol{\nu}$, $\boldsymbol{\mu}$ by (24), (25) and (26), not only the water-level in (19) and (20), but also the subchannel allocation indictor in (23) is adjusted dynamically. Especially, the update of $\nu^{(i+1)}_{k,u}$ in (25) forces femtocell k to allocate more resources to delay-sensitive users.

C. Semidistributed Iterative Resource Allocation Algorithm

Although the above (19)–(27) give a solution for the joint power and subchannel allocation problem, it still remains to design an algorithm to indicate the execution structure and the executing entity for the equations. Therefore, we propose Algorithm 1, which gives the procedures of the implementation.

Algorithm 1 Distributed Iterative Resource Allocation Algorithm

1: Initialize $I_{\max}$ and Lagrangian variables vectors $\boldsymbol{\lambda}, \boldsymbol{\nu}, \boldsymbol{\mu}$, set $i = 0$
2: Initialize $p_{k,u,n}$ with a uniform power distribution among all subchannels
3: Initialize $a_{k,u,n}$ with subchannel allocation method in [31], $\forall k, u, n$
4: **repeat**
5: **for** $k = 1$ to K **do**
6: **for** $n = 1$ to N **do**
7: **for** $u = 1$ to F **do**

a) Delay-sensitive users update $\hat{p}^{\mathrm{F}}_{k,u,n}$ according to (19);
b) Delay-tolerant users update $\hat{p}^{\mathrm{F}}_{k,u,n}$ according to (20);
c) Calculate $H_{k,u,n}$ according to (22);
d) FBS updates $\hat{a}_{k,u^*,n}$ according to (23);
e) FBS updates $\boldsymbol{\lambda}, \boldsymbol{\nu}$ according to (24) and (25).
end for
end for
end for
MBS updates $\boldsymbol{\mu}$ according to (26), and broadcasts those values to all FBSs via optical backhaul, $i = i + 1$.
until Convergence or $i = I_{\max}$

Note that in Algorithm 1, $g^{\mathrm{MF}}_{k,u,n}$ required in (19), (20), (22) and (26) for the uplink can be estimated at femto user u in femtocell k by measuring the downlink channel gain of subchannel n from the macrocell and utilizing the symmetry between uplink and downlink channels, or by using the site specific knowledge [29]. Furthermore, it can be assumed that there is direct wire connection between an FBS and the MBS for the FBS to coordinate with the central MBS [4], [7], according to a candidate scheme proposed for 3GPP HeNB mobility enhancement [24].

Algorithm 1 can be implemented by each FBS utilizing only local information and limited interaction with the MBS, therefore, Algorithm 1 is distributed and the practicability is guaranteed.

D. Downlink Case

Though the above proposed subchannel scheduling and power allocation scheme is for the uplink, the proposed Algorithm 1 derived for the uplink can also be applied in the downlink with some modifications. The structure of the downlink transmission is similar to the uplink counterpart, with only some differences lying in channel gains and power constraints [7]. The optimization problem formulation for the downlink in Section II and Section III can be easily obtained and replacing the uplink channel gains and power constraints with the corresponding downlink counterparts. Therefore, the major modifications include replacing the channel gains of the reverse link with those of the forward link, and replacing the total power constraint for a femto user in (8) and (10) with the power budget of an FBS. After applying the dual decomposition method in the downlink optimization problem, the corresponding solution in (19), (20), (22)–(26) should be replaced by the corresponding downlink channel gains and users' downlink received interference. Especially, (24) should be replaced by the following dual variable update:

$$\lambda_k^{(i+1)} = \left[\lambda_k^{(i)} - \beta_1^{(i)}\left(P_{\mathrm{k,max}} - \sum_{u=1}^{F}\sum_{n=1}^{N} s_{k,u,n}\right)\right]^+, \forall k \quad (28)$$

where $P_{\mathrm{k,max}}$ is the maximum transmit power of FBS k.

Specially, for the cross-tier interference limit constraint in the downlink, (5) can be replaced by

$$\sum_{k=1}^{K}\sum_{u=1}^{F} \tilde{a}_{k,u,n}\tilde{p}^{\mathrm{F}}_{k,u,n}\tilde{g}^{\mathrm{MF}}_{k,u,n} \le \tilde{I}_n^{th}, \forall n \quad (29)$$

where, $\tilde{a}_{k,u,n}$ and $\tilde{p}^{\mathrm{F}}_{k,u,n}$ are the subchannel and power allocation variables, respectively in the downlink, and $\tilde{g}^{\mathrm{MF}}_{k,u,n}$ is the interference channel gain from FBS k to the macro user who used subchannel n. $\tilde{I}_n^{th}$ is the cross-tier interference temperature limit in the downlink. Therefore, the update of the cross-tier interference's dual available in (26) can be given as

$$\tilde{\mu}_n^{(i+1)} = \left[\tilde{\mu}_n^{(i)} - \tilde{\beta}_3^{(i)}\left(\tilde{I}_n^{th} - \sum_{k=1}^{K}\sum_{u=1}^{F} \tilde{s}_{k,u,n}\tilde{g}^{\mathrm{MF}}_{k,u,n}\right)\right]^+, \forall n \quad (30)$$

where $\tilde{\mu}_n^{(i)}$ is the dual variable for the cross-tier interference constraint in iteration i, $\tilde{s}_{k,u,n}$ is the transformed subchannel allocation variable, and $\tilde{\beta}_3^{(i)}$ is the step size of iteration i.

Note that the cross-tier interference in the downlink is from FBSs to macro users. Therefore, when MBS updates the cross-tier interference constraint dual variable according to (30), the cross-tier interference $\sum_{k=1}^{K}\sum_{u=1}^{F}\tilde{s}_{k,u,n}\tilde{g}^{\mathrm{MF}}_{k,u,n}$ can be obtained from the feedback from macro users. Except for the above modifications, the power allocation and channel assignment for the downlink would be the same as for the uplink.

IV. Need For Practical Low-Complexity Algorithm

A. Practical Low-Complexity Algorithm

Algorithm 1 provides a near optimal solution to problem (7) under constraints in (8). However, the complexity of Algorithm 1 increases with K, F and N, and the practicality of Algorithm 1 will degrade. In this section, we propose a low-complexity Algorithm 2 to improve the practicality of Algorithm 1. The proposed low-complexity Algorithm 2, composed of a suboptimal subchannel assignment with heterogeneous QoS guarantee and a optimal power allocation scheme under cross-tier interference constraint, is proposed in Section III. Each resource is optimized while fixing the other, that is, given the power allocation for each subchannel, the suboptimal subchannel allocation ensures the QoS requirement of delay-sensitive users in C3 by forcing the scheduler in each FBS to allocate more subchannels to delay-sensitive users, then the scheduler tends to maximize the total capacity of all femto users by allocating the remaining subchannels. Afterwards, given the subchannel allocations, optimal power allocation together with dual variables update under cross-tier interference constraint is executed, where the optimal power allocation follows a multi-level water-filling principal [16]. Since the subchannel allocation is suboptimal in Algorithm 2, the system performance in terms of total user capacity will be lower compared with Algorithm 1. Consequently, Algorithm 2 achieves a tradeoff between performance and complexity.

Algorithm 2 A Practical Low-Complexity Algorithm

```
FBS set: $\mathcal{K} = \{1, 2, \dots K\}$; Femto user set per femtocell: $\mathcal{F} = \{1, 2, \dots F\}$.
Subchannel Assignment with QoS Guarantee
Allocate the same power to each subchannel, $a_{k,u,n} = 0$, $\forall k, u, n$;
Femto user $u$ in femtocell $k$ measures $g^{\mathrm{F}}_{k,u,n}$ and $I_{k,u,n}$, $\forall k, u, n$;
for each FBS do
  Subchannel set: $\mathcal{N} = \{1, 2, \dots, N\}$
  while $\mathcal{DS}_k \neq \phi$ do
    a) find $n^* = \arg\max_{n \in \mathcal{N}} (g^{\mathrm{F}}_{k,u,n} / I_{k,u,n})$;
    b) $a_{k,u,n^*} = 1, \mathcal{N} = \mathcal{N} - \{n^*\}$;
    if $\sum_{n=1}^{N} a_{k,u,n} C^{\mathrm{F}}_{k,u,n} \geq R_u$, $\forall u \in \mathcal{DS}_k$ then
      $\mathcal{DS}_k = \mathcal{DS}_k - \{u\}$;
    end if
  end while
  while $\mathcal{N} \neq \phi$ do
    a) find $(u^*, n^*) = \arg\max_{u \in \mathcal{F}, n \in \mathcal{N}} (g^{\mathrm{F}}_{k,u,n} / I_{k,u,n})$;
    b) $a_{k,u^*,n^*} = 1, \mathcal{N} = \mathcal{N} - \{n^*\}$;
  end while
end for
Optimal Power Allocation under Interference Constraint
Initialize $I_{\max}$ and Lagrangian variables vectors $\boldsymbol{\lambda}, \boldsymbol{\nu}, \boldsymbol{\mu}$, set $i = 0$
repeat
  for each FBS do
    for $n = 1$ to $N$ do
      a) Delay-sensitive users update $\hat{p}^{\mathrm{F}}_{k,u,n}$ according to (19);
      b) Delay-tolerant users update $\hat{p}^{\mathrm{F}}_{k,u,n}$ according to (20);
      c) FBS updates $\boldsymbol{\lambda}, \boldsymbol{\nu}$ according to (24) and (25).
    end for
  end for
  MBS updates $\boldsymbol{\mu}$ according to (26), and broadcasts those values to all FBSs via optical backhaul, $i = i + 1$.
until Convergence or $i = I_{\max}$
```

Similar to Algorithm 1, Algorithm 2 can be applied for the downlink, with the difference lying in that femtocells update the dual variables $\boldsymbol{\lambda}$ using (28) instead of (24) and replace the uplink channel gains by downlink counterpart.

B. Complexity Analysis

The asymptotic complexity of the proposed algorithms is analyzed in this subsection. In Algorithm 1, the calculation of (22) for every femto user on each subchannel in every femtocell entails KFN operations, and a worst-case complexity of searching (23) needs KFN operations in each iteration. Suppose the subgradient method used in Algorithm 1 needs Δ iterations to converge, the updates of $\boldsymbol{\lambda}$ and $\boldsymbol{\nu}$ need $O(KF)$ operations each [25], [28], and the computation of $\boldsymbol{\mu}$ calls $O(N)$ operations, therefore, Δ is a polynomial function of K^2F^2N. The total complexity of Algorithm 1 is thus $O(K^2F^2N^2\Delta)$. Compared with the exhaustive search for subchannel allocation, which has a worst-case complexity of $O(KF^N)$, the proposed Algorithm 1 has a much lower complexity. Moreover, Δ can be made small enough if the initial values of λ, ν and μ are well chosen, together with suitable values of iteration step sizes. In Algorithm 2, finding the best subchannels for every delay-sensitive user requires $O(N \log_2 N)$ operations, the QoS check of a delay-sensitive user needs N operations, while the subsequent subchannel allocation to maximize the total femto capacity calls $O((N - |DS_k|)F \log_2 F)$ operations. Therefore, the total asymptotic complexity of Algorithm 2 is

$$O\left((N \log_2 N + N)KF + (N - |DS_k|)\, F \log_2 F + \Delta\right)$$
$$= O(KFN \log_2 N + NF \log_2 F + \Delta). \quad (31)$$

As can be seen from the analysis above, both the proposed Algorithm 1 and Algorithm 2 have a much lower polynomial complexity than the exhaustive search based method. Moreover, Algorithm 2 has a even lower complexity than Algorithm 1.

V. Simulation Results and Discussion

Simulation results are given in this section to evaluate the performance of the proposed resource allocation algorithms. In the simulations, spectrum-sharing femtocells are uniformly distributed in the macrocell coverage area, and femto users are uniformly distributed in the coverage area of their serving femtocell; the carrier frequency is 2 GHz, $B = 10$ MHz, $N = 50$, $M = 50$, and $\sigma^2 = (B/N)N_0$, where $N_0 = -174$ dBm/Hz is the AWGN power spectral density. The coverage radius of the macrocell is 500 m, and that of a femtocell is 10 m. Each FBS/Macro user has a minimal distance of 40 m from the MBS. The minimal distance between FBSs is 40 m. Each macro user is uniformly distributed near one femtocell where the FBS and the macro user have a minimal distance of 15 m. A round-robin scheme is adopted for macro user scheduling in the simulation. We assume that the channel fading is composed of path loss, shadowing fading, and frequency-selective Rayleigh fading. The Rayleigh fading channel gains are modeled as i.i.d. unit-mean exponentially distributed random variables. The pathloss models for indoor femto users and outdoor macro users are based on [30]. The wall penetration loss between femtocells is 10 dB, the FBS-femto user or MBS-macro user's lognormal shadowing is 10 dB. The MBS-macro user's lognormal shadowing is 8 dB. The macro users' maximum transmit powers are uniformly set at 23 dBm, which means equal power allocation at the macro side. We assume that all the delay-sensitive users have the same QoS requirement. The "Existing Algorithm" included in simulations for comparison is the subchannel allocation scheme in [31] in conjunction with the optimal power allocation scheme proposed in this paper.

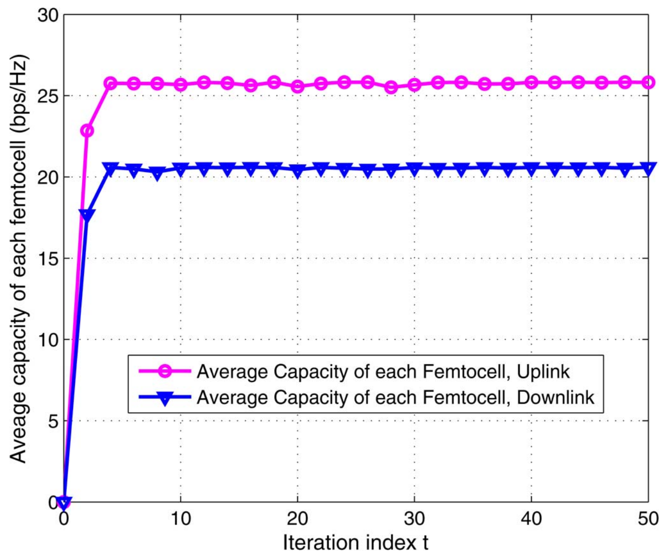

Fig. 2. The convergence in term of average capacity per femtocell over the number of iterations.

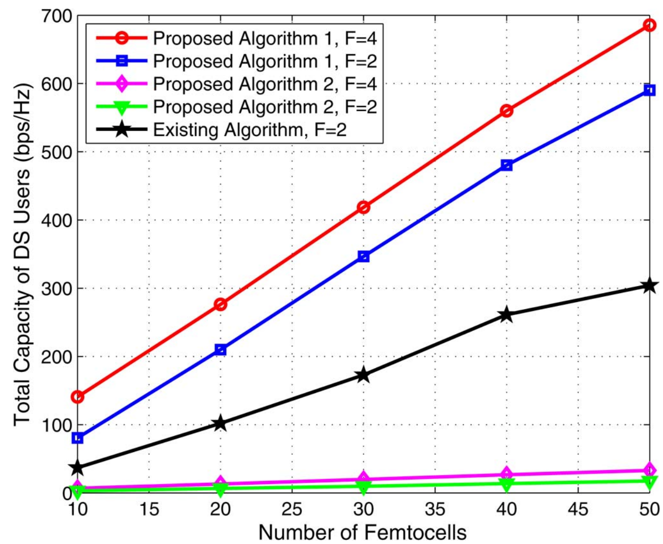

Fig. 4. Total uplink capacity of all delay-sensitive users of all femtocells versus K.

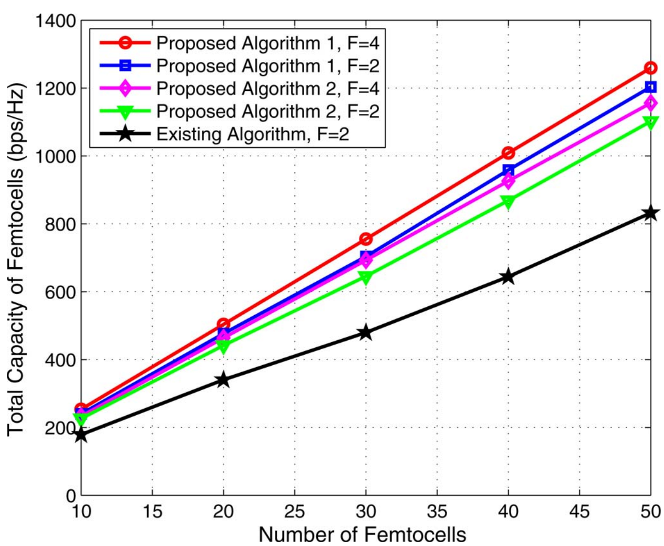

Fig. 3. Uplink total capacity of all femtocells versus the number of femtocells K.

Fig. 2 shows the convergence in terms of the average capacity of each femtocell for the proposed Algorithm 1 versus the number of iterations for both the uplink and downlink, where $F = 4$, $K = 10$, $Ru = 9$ bps/Hz (for any u), $P_{\max} = 23$ dBm (for any k), $P_{\mathrm{k,max}} = 20$ dBm and $I_n^{th} = 7.5 \times 10^{-14}$ w (-101.2 dBm) for all n. It can be observed that the proposed dual decomposition method based resource allocation algorithm (Algorithm 1) takes nearly 40 iterations to converge to stable solutions. This result, together with the previous analysis, ensures that the proposed Algorithm 1 is applicable in macrocell-femtocell two-tier networks.

Fig. 3 shows the total uplink capacity of K femtocells when the number of femtocells increases from 10 to 50, for Algorithm 1, Algorithm 2, and the "Existing Algorithm". The simulation parameters are set as $F = 2$ or 4, $Ru = 9$ bps/Hz, $P_{max} = 23$ dBm and $I_n^{th} = 7.5 \times 10^{-14}$ w (-101.2 dBm) for all n. We can see that Algorithm 1 outperforms Algorithm 2 in terms of the total capacity of femtocells by about 10% when the number of femtocells is larger than 20. This minor performance loss of the low-complexity Algorithm 2 compared with Algorithm 1 can be well justified by the much reduced computational complexity. Fig. 3 also shows that both Algorithm 1 and Algorithm 2 have better performance than the "Existing Algorithm". It also can be seen from the figure, the more number of femto users in femtocell is, the better of the performance is obtained. This is because that, as the number of the total subchannels in each femtocell is fixed as N, with the increase of the number of femto users F in each femtocell, each subchannel has more candidate femto users to select, which is known as multiuser diversity. Therefore, each femtocell's capacity increases, as a result, the total capacity of all K femtocells increases.

Fig. 4 shows the total uplink capacity of delay-sensitive users in K femtocells when the number of femtocells increases from 10 to 50, for Algorithm 1, Algorithm 2 and the "Existing Algorithm". The simulation settings of F, Ru, P_{max} and I_n^{th} are the same as in Fig. 3. Fig. 4 almost has the same trends as Fig. 3 but with higher capacity because of the multi-FBS gain. However, although the "Existing Algorithm" shows a lower total uplink delay-sensitive-user capacity than Algorithm 1, it provides a higher total uplink delay-sensitive-user capacity than Algorithm 2. This is because Algorithm 2 tends to maximize the total capacity of all femto users, regardless of the service type after the delay-sensitive users' QoS requirements have been guaranteed, while the "Existing Algorithm" allocates subchannels to guarantee fairness among users and then maximizes the total capacity using remaining subchannels, thus wasting some subchannels since delay-sensitive users don't need to use any data rate higher than R_u (for any u). For the same reason in Fig. 3, more femto users in each femtocell results in higher total capacity of delay-sensitive femto users.

Fig. 5 shows the total uplink capacity of K femtocells when the interference temperature limit increases from -120 dBm to -90 dBm, for $P_{max} = 20$ dBm or 23 dBm, $Ru = 9$ bps/Hz, $K = 10$, and $F = 4$. Algorithm 1 outperforms Algorithm 2

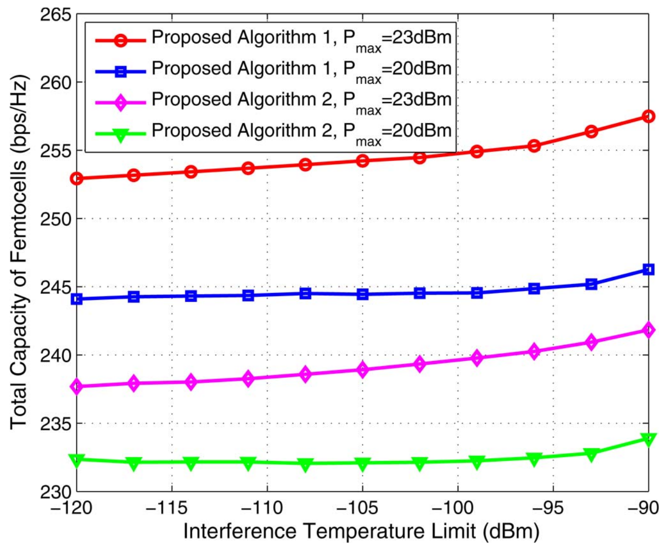

Fig. 5. Total uplink capacity of all femtocells versus the interference temperature limit.

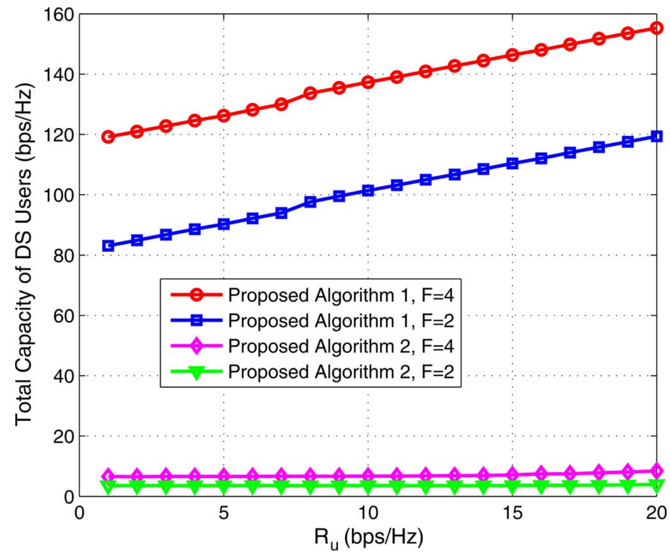

Fig. 7. Total uplink capacity of all delay-sensitive users in all femtocells versus R_u.

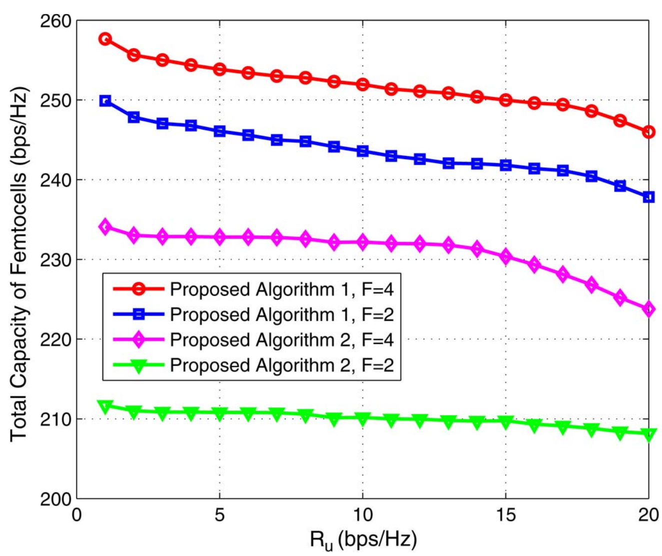

Fig. 6. Total uplink capacity of all femtocells versus R_u.

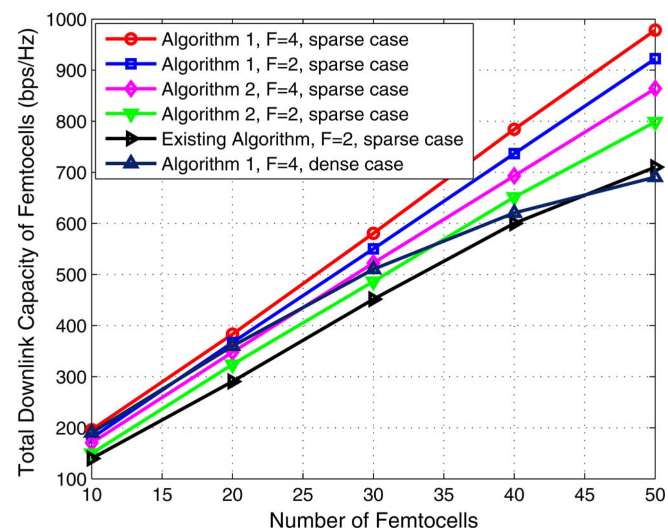

Fig. 8. Total downlink capacity of all femtocells versus the number of femtocells K.

by up to about a 7% increase in the total uplink femtocell capacity. As the interference temperature limit increases, the total uplink capacity of femtocells increases, because the tolerable interference caused by femtocells to the macrocell is effectively increased for an increased interference temperature limit. Moreover, a higher femto user transmit power budget results in a higher total uplink capacity.

Fig. 6 shows the total uplink capacity of K femtocells when the QoS request, which is assumed to be the same for all delay-sensitive femto users, increases from 1 bps/Hz to 20 bps/Hz, for $F = 2$ or 4, $P_{max} = 23$ dBm, $K = 10$, and $I_n^{th} = 7.5 \times 10^{-14}$ w (-101.2 dBm) for all n. The total uplink capacity of femtocells decreases as R_u increases for both Algorithm 1 and Algorithm 2, because larger R_u in $C3$ shrinks the feasible region of the optimization problem in (7), (8), leading to the decreased total capacity of all femtocells.

Fig. 7 shows the increase in the total uplink capacity of all delay-sensitive users in K femtocells versus R_u from 1 bps/Hz to 20 bps/Hz. The simulation parameter values are the same as in Fig. 6. For both Algorithm 1 and Algorithm 2, the total uplink capacity of delay-sensitive users increases as R_u increases, because more resources are allocated to delay-sensitive users as R_u increases, the latter because R_u is the QoS requirement that guarantees delay-sensitive femto user u maintains its performance in $C3$.

In all the parts above, we only consider the sparsely deployed case. Here, we discuss the densely deployed femtocells case, where co-tier interference should be added into the denominator of (1). Moreover, similar to (C4), a co-tier interference temperature limit $\hat{I}_n^{th}$ can be introduced, by relaxing the combinatorial subchannel allocation variable into a continuous one and replacing co-tier interference with $\hat{I}_n^{th}$, the correspondence non-convex subchannel and power allocation problem can be transformed into a convex problem. Fig. 8 and Fig. 9 show the total downlink capacity of K femtocells and delay-sensitive users as K increases from 10 to 50, respectively. We set

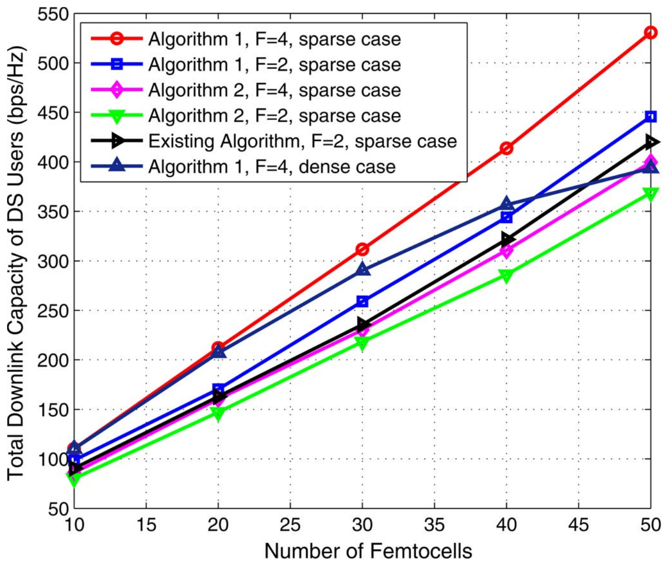

Fig. 9. Total downlink capacity of all delay-sensitive users versus the number of femtocells K.

$F = 2$ or 4, $Ru = 9$ bps/Hz, $P_{k,max} = 20$ dBm (for any k) and $\hat{I}_n^{th} = \tilde{I}_n^{th} = 7.5 \times 10^{-14}$ w (-101.2 dBm) for all n. For the densely deployed femtocells case, the pathloss models for indoor femto users and outdoor macro users in [30] are used. Owing to the symmetry between downlink and uplink, Fig. 8 and Fig. 9 show a similar performance to Fig. 3 and Fig. 4, respectively. Note that, both in Fig. 8 and Fig. 9, the total capacity of femtocells in dense deployment is smaller than that of the sparsely deployed case, this is because the co-channel interference between femtocells is considered.

VI. Conclusion

In this paper, we have investigated joint subchannel and power allocation for spectrum-sharing femtocells taking into account heterogeneous femto user QoS requirements, and we have introduced an interference temperature limit to protect the macrocell from co-channel femtocell transmissions. This resource allocation problem under heterogeneous QoS constraints and interference temperature limit was formulated into a non-convex mixed integer programming problem. By relaxing the combinatorial subchannel allocation constraint into a continuous variable, we transformed the non-convex subchannel and power allocation problem into a convex problem. A dual decomposition method together with a subgradient method was then proposed to solve this convex problem at each FBS, which only needs local information. Moreover, to reduce the computational complexity, we proposed a low-complexity resource allocation algorithm, which ensures the QoS requirements of delay-sensitive users and follows an optimal multi-level water-filling power allocation. We have also provided an analysis of complexity. Simulation results have shown that the proposed algorithms converge within only a few iterations, and the proposed low-complexity algorithm is able to provide satisfactory performance in both uplink and downlink. In the future works, the joint optimization of both the heterogeneous femto user and macro user will be considered.

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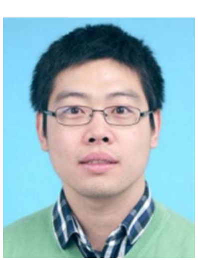

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