Distributed Resource Allocation in Two-Hierarchy Networks

Shuhui Liu, Yongyu Chang, Guangde Wang, and Dacheng Yang

In this paper, a new distributed resource allocation algorithm is proposed to alleviate the cross-tier interference for orthogonal frequency division multiplexing access macrocell and femtocell overlay. Specifically, the resource allocation problem is modeled as a non-cooperative game. Based on game theory, we propose an iterative algorithm between subchannel and power allocation called distributed resource allocation which requires no coordination among the two-hierarchy networks. Finally, a macrocell link quality protection process is proposed to guarantee the macrocell UE's quality of service to avoid severe cross-tier interference from femtocells. Simulation results show that the proposed algorithm can achieve remarkable performance gains as compared to the pure waterfilling algorithm.

Keywords: Distributed resource allocation, macrocell, femtocell, cross-tier interference.

Manuscript received July 15, 2011; revised Aug. 30, 2011; accepted Sept. 15, 2011.

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http://dx.doi.org/10.4218/etrij.12.0111.0451

I. Introduction

Femtocells have emerged as a solution to increase both the capacity and coverage while reducing both capital expenditures and operating expenses. Femtocells, which consist of miniature personal base stations and stationary or low-mobility end users deployed in an indoor environment, are located within an existing cellular network; a two-hierarchy network is deployed. Since femtocells operate in the licensed spectrum owned by wireless operators and share this spectrum with macrocell networks, how to allocate the resources (for example, subchannels and power) is a critical issue to mitigate the cross-layer interference and satisfy the user's quality of service (QoS).

The related works on femtocell resource allocation are mainly included in [1]-[6], which are about power allocation/control or/and subchannel resource allocation. Interference mitigation through power control for macrocell femtocell overlay is proposed in [1]. In [2], the authors derived a fundamental relation providing the largest feasible macrocell signal-to-interference-plus-noise-ratio (SINR), given any set of feasible femtocell SINRs. Then, they proposed a distributed power adaptation algorithm to satisfy their minimal SINR requirements. Unlike the underlay scheme in [2], the authors of [3] considered an overlay scheme in femtocell networks, and proposed an interference avoidance strategy, called the F-ALOHA algorithm, to alleviate cross-tier interference and co-channel interference at the same time. A dynamic resource partitioning scheme is proposed in [4] that mitigates destructive femtocell to macrocell interference using the downlink high interference indicator. The authors in [5] proposed a suboptimal centralized algorithm to solve the problem of resource allocation for a multiuser orthogonal frequency division multiplexing (OFDM)-based multicell cognitive radio system. The authors in [6] focus on the centralized radio resource management in the dense femto environment. Different from the multicell networks, there is no coordination between macrocells and femtocells in two-tier femtocell networks. In addition, femtocells are consumer-installed and the traffic requirements are user-determined without any operator influence. Consequently, distributed interference management strategies may be preferred.

In this paper, we propose a distributed resource allocation (DRA) algorithm that considers the subchannel and power allocation comprehensibly in an OFDMA macrocell and femtocell two-hierarchy networks. The target of the proposed algorithm is to minimize the overall transmitted power under each cell's (if there is no special explanation, the femtocell and macrocell are both called cell) maximum power constraint and satisfy the user's target data rate. Our work ties in with well-known resource allocation schemes in conventional cellular networks and prior work on utility optimization based on game theory, such as [7]-[10]. Also, there are two papers [11], [12] about resource allocation for femtocell/macrocell hierarchy networks based on game theory. However, there exist some differences compared with the above schemes. First, the problem formulation minimizes the overall transmission power bound by the target data rate and maximum power constraints in this paper. Second, this proposed scheme is iterative between subchannel allocation and power allocation which is guaranteed to converge to the optimal solution. Furthermore, a macrocell link quality protection scheme is proposed to guarantee the macrocell UE's QoS at the presence of severe cross-tier interference from femtocells. The influences of femtocell density and femto UE target data rate on macrocell performance are also investigated.

This paper is organized as follows. Section II provides the system model and problem formulation. The specific distributed resource allocation algorithm is given in section III. The simulation model and results are generalized in section IV. Finally, in section V, our conclusions are drawn.

II. System Model and Problem Formulation

We consider a downlink resource allocation in an OFDMA macro-femto two-tier system, which consists of a single central macrocell BS B_0 serving a region C with radius R_c. The macrocell is underlaid with N cochannel femtocells B_i. Each femto serves users located on the circumference of a disc with radius R_f. Also, K users are distributed in the region served by the macrocell B_0 and femtocells B_i. U_n denotes that the UE set belongs to the cell n. The total bandwidth B is divided into M subchannels. The vector $\mathbf{p}^n=(p_1^n,\ldots,p_M^n)$ denotes the transmission power of cells $n\,(0\le n\le N)$, with p_m^n denoting the transmission power at subchannel m. In addition, we denote by $\mathbf{P}=[\mathbf{p}^0,\mathbf{p}^1,\mathbf{p}^2,\ldots,\mathbf{p}^N]$ the network power vector, a concatenation of the transmission power vectors of the N+1 cells in the integrated region. We define the assignment matrix as $\mathbf{A}^n=[a_{mk}^n]_{M\times K}$, where a_{mk}^n is 1 if subchannel m is assigned to user k and 0, otherwise. Each subchannel in one cell is assigned to only one user.

The SINR of user k in subchannel m of cell n for the given network power vector $\mathbf{P}$ can be expressed by

$$\gamma_{mk}^n(\mathbf{P})=\frac{G_{mk}^n p_m^n}{\sum_{l=0,l\ne n}^{N} G_{mk}^l p_m^l+\sigma^2}, \tag{1}$$

where G_{mk}^n denotes the channel gain between user k and the cell n, and σ^2 is the noise power. Then, the achievable data rate of user k is given by

$$R_{mk}^n(\mathbf{P})=\frac{B}{M}\log_2\left(1+\frac{\gamma_{mk}^n(\mathbf{P})}{\Gamma}\right), \tag{2}$$

where $\Gamma=-\ln(5\text{BER})/1.5$ for the bit error rate (BER) requirement [13].

The total data rate of user k, R_k, depends on the power allocation in other cells as well as the subchannel assignment and the power allocation in the corresponding cell. Specifically, R_k is determined by $\mathbf{P}$ and $\mathbf{A}^n$ as follows:

$$R_k(\mathbf{P},\mathbf{A}^n)=\sum_{m=1}^{M} a_{mk}^n R_{mk}^n(\mathbf{P}). \tag{3}$$

Each user requires the satisfaction of the minimum data rate request R_k^{req}, and the total transmit power for each cell is bounded by the maximum transmit power $P_{\text{M}}^{\max}$ (for macrocell) and $P_{\text{F}}^{\max}$ (for femtocell). To mitigate the cross-tier interference and guarantee the QoS of users, we formulate the resource allocation problem in the two-tier networks as

$$\min_{\mathbf{A},\mathbf{P}} \sum_{n=0}^{N}\sum_{m=1}^{M} a_{mk}^n p_m^n,$$

$$\text{s.t.}\begin{cases} R_k \ge R_k^{\text{req}}, \forall k, \\ 0\le \sum_{m=1}^{M} p_m^n \le P_{\text{M}}^{\max} \text{ for } n=0, \\ 0\le \sum_{m=1}^{M} p_m^n \le P_{\text{F}}^{\max} \text{ for } 1\le n\le N. \end{cases} \tag{4}$$

As the problem in (4) is NP-hard [14], in the subsequent sections, we are going to solve this conflict problem in a distributed manner by adopting a theoretic game approach.

III. Distributed Resource Allocation

In this section, our focus is to solve (4) by non-cooperative game theory. First, we analyze the system's feasible region. Then, we will construct the non-cooperative resource allocation game and propose an iterative distributed algorithm between subchannel allocation and waterfilling power allocation. Finally, we introduce an effective mechanism called macrocell link quality protection process to primarily guarantee the data rate requirement of macrocell UE.

1. System's Feasible Region

Let us first consider the case when the target SINR per subchannel of the corresponding user is known. Then, every user should have SINR on its own allocated subchannels no less than the target SINR Γ_{mk}^{n}, that is, $\gamma_{mk}^{n} \geq \Gamma_{mk}^{n}$, $\forall m,n$. Rewriting these inequalities in matrix form, we have

$$(\mathbf{I}-\mathbf{\Gamma}_m\mathbf{G}_m)\mathbf{P}_m \geq v_m, \forall m, \quad (5)$$

where $\mathbf{I}$ is an $(N+1)\times(N+1)$ identity matrix, $v_m = [\upsilon_m^0, \upsilon_m^1, \ldots, \upsilon_m^N]'$ with $\upsilon_m^n = \sigma^2\Gamma_{mk}^n / G_{mk}^n$, $\mathbf{\Gamma}_m = diag\left\{\Gamma_{mk}^0, \ldots, \Gamma_{mk}^N\right\}$, $\mathbf{P}_m = \left[p_m^0, p_m^1, \ldots p_m^N\right]$, and

$$\mathbf{G}_m(n,l) = \begin{cases} \dfrac{G_{mk}^l}{G_{mk}^n} & (n \neq l), \\ 0 & (n = l). \end{cases}$$

Since $\mathbf{\Gamma}_m\mathbf{G}_m$ is non-negative, the spectral radius $\rho(\mathbf{\Gamma}_m\mathbf{G}_m)$ (defined as the maximum modulus eigenvalue $\max\left\{|\lambda| : \mathbf{\Gamma}_m\mathbf{G}_m - \lambda\mathbf{I}_{N+1} \text{ is singular}\right\}$) is an eigenvalue of $\mathbf{\Gamma}_m\mathbf{G}_m$. Applying Perron-Frobenius theory [12] to $\mathbf{\Gamma}_m\mathbf{G}_m$, there exists a positive power allocation if and only if $|\rho(\mathbf{\Gamma}_m\mathbf{G}_m)| < 1$, and then the optimal power solution is

$$\mathbf{P}_m = (\mathbf{I}-\mathbf{\Gamma}_m\mathbf{G}_m)^{-1} v_m. \quad (6)$$

The system's feasible region is defined as the supporting domain where there exist solutions and the constraints in (4) are satisfied. When a feasible region has been identified as such, the distributed iterative power control moves toward the optimal solution. Unfortunately, to find out whether the system (5) admits solution (6), we need to evaluate the eigenvalues of $\mathbf{\Gamma}_m\mathbf{G}_m$. However, using another properity of the weak Perron-Frobenius theorem [15] (denoted as Brauer-Solow's criterion), we can assert an upper limit to $\rho(\mathbf{\Gamma}_m\mathbf{G}_m)$, which is independent among cells.

$$\rho(\mathbf{\Gamma}_m\mathbf{G}_m) \leq \max_{0\leq n\leq N}\left(\frac{\Gamma_{mk}^n \sum_{l=0,l\neq n}^{N} G_{mk}^l}{G_{mk}^n}\right) < 1. \quad (7)$$

On each subcarrier, the target SINR must fulfill the condition $\Gamma_{mk}^n < T_{mk}^n$, where $T_{mk}^n = G_{mk}^n \Big/ \sum_{l=0,l\neq n}^{N} G_{mk}^l$ to guarantee the distributed iterative power control toward the optimal solution. In the next section, we will use this conclusion to ensure the convergence of the power allocation game.

2. Non-cooperative Resource Allocation Game

We model the radio resource allocation problem in OFDMA macrocell and femtocell two-hierarchy networks as a non-cooperative resource allocation game (NRAG), where the cells act as the rational and selfish players. Each player wants to minimize its transmitting power subjecting to the data rate constrains, regardless of other players in a distributed way. Formally, for all n $(n \in \mathcal{N})$, the game can be expressed as,

$$\begin{aligned} \text{NRAG:} \quad & \min_{\mathbf{p}^n \in \mathbb{P}^n, \mathbf{A}^n \in \mathbb{A}^n} u_n(\mathbf{p}^n, \mathbf{P}^{-n}, \mathbf{A}^n) \\ & = \min_{\mathbf{p}^n \in \mathbb{P}^n, \mathbf{A}^n \in \mathbb{A}^n} \sum_{m=1}^{M} a_{mk}^n p_m^n, \\ & \text{s.t. } R_k \geq R_k^{\text{req}} \ (\forall k \in U_n), \end{aligned} \quad (8)$$

where u_n is the utility function defined as the n-th cell's transmit power. $\mathbf{P}^{-n}$ denotes the reduced network power vector that remains after separating out $\mathbf{p}^n$, which indicates the interference power from other cells:

$$\mathbb{P}^n = \left\{\mathbf{p}^n \,\middle|\, 0 \leq \sum_{m=1}^{M} p_m^n \leq P_{\text{M}}^{\max}\right\} \ (\text{for } n=0),$$

$$\mathbb{P}^n = \left\{\mathbf{p}^n \,\middle|\, 0 \leq \sum_{m=1}^{M} p_m^n \leq P_{\text{F}}^{\max}\right\} \ (\text{for } 1 \leq n \leq N).$$

Also,

$$\mathbb{A}^n = \left\{\mathbf{A}^n \,\middle|\, a_{mk}^n = 0 \text{ or } 1 \text{ for all } m,k, \text{and} \sum_{k\in U_n} a_{mk}^n \leq 1, \forall m\right\},$$

where U_n represents the user set belonging to cell n. Each cell tries to determine the transmission power vector $\mathbf{p}^n$ and the subchannel assignment matrix $\mathbf{A}^n$ to minimize the utility under the target data rate constraints.

In the problem formulation in (8), each base station wants to minimize its transmit power by allocating the subchannel and power resources for users belonging to this cell, irrespective of other base stations in a distributed way. In the following, based on the analysis from [16], [17], power allocation is separated from subchannel allocation to reduce complexity.

We first consider the power allocation problem for a given subchannel assignment matrix $\mathbf{A}^{*n}$. Therefore, the resource allocation problem falls back into the power allocation problem and NRAG reduces to a non-cooperative power allocation game (NPAG) $G' = \left[\mathcal{N}, \left\{\mathbb{P}^n\right\}, \left\{u_n\right\}\right]$,

$$\text{NPAG:} \quad \min_{\mathbf{p}^n \in \mathbb{P}^n} u_n(\mathbf{p}^n, \mathbf{P}^{-n}, \mathbf{A}^{*n}) = \min_{\mathbf{p}^n \in \mathbb{P}^n} \sum_{m=1}^{M} a_{mk}^{*n} p_m^n, \quad \text{s.t. } R_k \geq R_k^{\text{req}} \ (\forall k \in U_n). \tag{9}$$

We formulate the SINR of user k in subchannel m of cell n for the given network power vector $\mathbf{P}$,

$$\gamma_{mk}^n(\mathbf{P}) = \frac{G_{mk}^n p_m^n}{\sum_{l=1,l\neq n}^{N} G_{mk}^l p_m^l + \sigma^2} = p_m^n \cdot I_{mk}^n, \tag{10}$$

with $I_{mk}^n = G_{mk}^n \Big/ \sum_{l=1,l\neq n}^{N} G_{mk}^l p_m^l + \sigma^2$.

The NPAG game of minimizing the sum power is equivalent to the following target SINR allocation problem:

$$\min_{\gamma_{mk}^n} \sum_{m=1}^{M} \sum_{k \in S_n} a_{mk}^n \gamma_{mk}^n \Big/ I_{mk}^n, \quad \text{s.t. } \sum_{m=1}^{M} a_{mk}^n \frac{B}{M} \log_2\left(1 + \frac{\gamma_{mk}^n}{\Gamma}\right) \geq R_k^{\text{req}}, \ (\forall k \in U_n). \tag{11}$$

Since the subchannel assignment matrix has been decided as $\mathbf{A}^{*n}$, the subchannel set that allocated to the user $k(k \in U_n)$ can be obtained and denoted as S_k. With the obtained conclusion in (7) to ensure the power allocation game converges toward the optimal power solution, the NPAG can be rewritten as

$$\min \sum_{m \in S_k} \gamma_{mk}^n \big/ I_{mk}^n, \ (\forall k \in U_n), \quad \text{s.t. } \sum_{m \in S_k} \frac{B}{M} \log_2\left(1 + \frac{\gamma_{mk}^n}{\Gamma}\right) \geq R_k^{\text{req}}, \quad 0 < \gamma_{mk}^n < T_{mk}^n. \tag{12}$$

The above is a convex optimization problem and can be solved with the KKT conditions [18].

The solution of this problem is as follows:

$$\gamma_{mk}^n = \min\left\{\left[\lambda I_{mk}^n - \Gamma\right]^+; T_{mk}^n\right\}, \tag{13}$$

where λ is a constant value that should be set so that the data rate condition $\sum_{m \in S_k} \frac{B}{M} \log_2\left(1 + \frac{\gamma_{mk}^n}{\Gamma}\right) = R_k^{\text{req}}$ is fulfilled. Once we get the target γ_{mk}^n , the power allocation vector $\mathbf{P}^n$ can be obtained through solving the linear function (13)

$$p_m^n = \gamma_{mk}^n \big/ I_{mk}^n . \tag{14}$$

Note that in (13), we use the conclusion in (7) to ensure that the power allocation game converges toward the optimal power solution. However, if the number of users is too many and the target data rate is too high, the final power allocation will not satisfy the maximum power constraint defined in (4). That is, in this situation, the optimal solution cannot be achieved. When the maximum power exceeds the constraint, we propose a heuristic scheme to reallocate the power scaled with SINR to get more system throughput gain. The higher the SINR on subchannel m, the less the power should be reduced. In this way, the limited power can be fully exploited to get improved throughput performance.

$$p_m^{*n} = p_m^n - \Delta \times \frac{1}{\gamma_{mk}^n} \Bigg/ \sum_m \frac{1}{\gamma_{mk}^n} \text{ for } p_m^n \neq 0, \tag{15}$$

where

$$\Delta = \begin{cases} P_{\mathrm{M}}^{\max} - \sum_{m=1}^{M} p_m^n & \text{for } n = 0, \\ P_{\mathrm{F}}^{\max} - \sum_{m=1}^{M} p_m^n & \text{for } 1 \leq n \leq N. \end{cases} \tag{16}$$

From the above NPAG, we can obtain the solution given the subchannel assignment matrix.

Next, we formulate the subchannel assignment problem from (9) for a given power vector $\mathbf{P}'$, which is given by

$$\min_{\mathbf{A}^n \in \mathbb{A}^n} \sum_{m=1}^{M} a_{mk}^n p_m^n, \quad \text{s.t. } R_k \geq R_k^{\text{req}}, (\forall k \in U_n). \tag{17}$$

Since the power vector is given, the interference achieved on each subcarrier m can be obtained. So, the above problem can be rewritten as

$$\min_{a_{mk}^n} \sum_{m=1}^{M} \sum_{k \in U_n} a_{mk}^n \gamma_{mk}^n \Big/ I_{mk}^n, \quad \text{s.t. } \sum_{m=1}^{M} a_{mk}^n \frac{B}{M} \log_2\left(1 + \frac{\gamma_{mk}^n}{\Gamma}\right) \geq R_k^{\text{req}}, (\forall k \in U_n). \tag{18}$$

As users cannot share the same subcarrier, allocating bits to a subcarrier essentially prevents other users from using that subcarrier. This dependency makes any greedy algorithm a non-optimal solution. This nonlinear optimization problem can be solved by employing integer programming [19]. In general, integer programming is a full-search approach that needs exponential computational time in the worse cases. Therefore, we usually propose suboptimal schemes to solve the subcarrier allocation problem for the OFDMA systems. In the following, subchannel allocation is performed with an adapted version of the iterative algorithm for power minimization under target data rate requirements. We assign each subchannel to the user that yields the maximum SINR under the constraint of satisfying the target data rate requirement and working below at the maximum power level. The probability of suffering severe cross-tier interference is evidently reduced because each user is to be allocated to the best subchannel. The process of this part can be given as:

For each NodeB n,

i) Initialization

For each user $k \in U_n$, set $\tilde{R}_k = 0$ as the estimated achievable data rate, $\mathfrak{M}^n = \{1, 2, ..., M\}$ denotes the available subcarriers set for cell n.

ii) Finding appropriate UE-channel-pair (k, m) that satisfies

$$(k, m) = \arg \max_{k \in U_n, m \in \mathfrak{M}^n} R_{mk}^n;$$

update $\tilde{R}_k$, $\mathfrak{M}^n$,

$$\tilde{R}_k = \tilde{R}_k + R_{mk}^n, \ \mathfrak{M}^n = \mathfrak{M}^n - \{m\};$$

if ($\tilde{R}_k > R_k^{\mathrm{req}}$)

$$U_n = U_n - \{k\};$$

if (U_n or $\mathfrak{M}^n$ is empty)

break;

else go to step 2.

We give an example to clarify the proposed subchannel algorithm in Fig. 1, where √ denotes the subchannel allocated to the corresponding UE and × means not. Under the given power vector, the data rate of each UE on each subchannel can be estimated, and we sort the UE-channel pair in descending order. Then according to this order, the UE-channel pair is checked sequentially to verity that this subchannel has never been allocated and this UE's data rate has not achieved the target data rate. When the above conditions are satisfied, the subchannel is allocated to this UE. Otherwise, the next UE-channel pair is checked. In the above scheme, the subchannel is allocated to the UE that yields the maximum data rate and the result is using fewer subchannels to satisfy the data rate request. Thus, the ICI will mitigate, and, in the NPAG process, the power needed will be lower.

From the above NPAG and subchannels allocation process, we can develop a new DRA algorithm in OFDMA macrocell and femtocell two-tier networks. The subchannel assignment and power allocation processes are iteratively implemented. The whole iteration process is shown as follows:

i) Each cell distributes the total power equally to each subchannel.

ii) Each user measures the SINR for all the subchannels for the given transmission power vectors of other base stations in the previous iteration.

iii) Each user feeds back the measured values to the base station associated with it.

iv) Each cell performs the above subchannels allocation process.

v) Each cell performs power allocation according to (13) and (14).

UE / RB	UE1	UE2	UE3	UE4	• • •
RB1	×	√	×	×	• • •
RB2	√	×	×	×	• • •
RB3	×	×	×	√	• • •
⋮	⋮	⋮	⋮	⋮	

Fig. 1. Example for subchannel process.

vi) If the power allocation in step v) cannot satisfy the maximum power constraint, reallocate the power according to (15) and (16).

vii) Iterate steps ii) to vi) until the resource allocation converges to equilibrium.

In the distributed resource allocation process above, we update the subchannel allocation and implement the waterfilling power allocation iteratively. At each iteration, each cell can minimize its utility with only local information (that is, SINR in each subchannel), so resource allocation can be performed in a distributed manner.

3. Macrocell Link Quality Protection

Due to the macrocell's primary role as an anytime-anywhere infrastructure, the macrocell user's communication should not be affected by femtocell users. Therefore, we should guarantee the macrocell link first and foremost. In this distributed resource allocation iterative process, if the two-tier system is very crowded and the co-channel interference is very large, a feasible domain will not exist, and the whole iterative process will not converge to a stable state. So, we introduce an effective mechanism called macrocell link quality protection (MLQP) process to primarily guarantee the macrocell UE data rate requirement.

The centralized MLQP is hard to implement because it will need the large exchange information between femtocells and macrocells. So, we propose a coordination process in a distributed way.

In the following part, a detailed description about the process of prohibiting some subchannels with severe interference from being used in certain femtocells to ensure the QoS of macrocell users is clarified. Following every M-th (assuming large M) update of the DRA iterative process elucidated in section III.2, the MLQP process is implemented once.

The set of the subchannels allocated to macrocell UE k that receives the most severe interference is denoted as I_k. Also, in each subchannel (without loss of generality, the subchannel is denoted as m), there exists the dominant interference set $F_k^m = \{B_l : G_{mk}^l p_m^l > y_k\}$, consisting of femtocells whose interference for UE k in subchannel m exceeds the interference threshold y_k whose initial value is set through system practical statistics. The system can estimate the maximum interference from femtocells that a UE k can tolerate to achieve the target SINR. Then, y_k can be obtained. In the following MLQP scheme, this threshold will be adjusted according to the interference situation. We put the severely interfered subchannel m into I_k and the dominant interference set pair (m, F_k^m) into the set II_k as the dominant interferer set. For every MLQP process, for each macrocell UE below the target data rate, we pick up the subchannel that receives the most severe interference and update the dominant interference set. The following steps are repeated until all of the macrocell UEs reach the target data rate.

i) UE k picks the subchannel m_k that owns the least gain-to-interference-plus-noise by formula $m_k = \arg\min_{m \in (S_k - \mathrm{I}_k)} I_{mk}^n$, if $S_k - \mathrm{I}_k$ is not empty, where S_k is the subchannel set allocated to the user k. The reason for $m \in (S_k - \mathrm{I}_k)$ is that if the m has not been selected in the former iteration, the new different subchannel should be restricted for the femtocells to reduce severe interference to the macrocell UEs. When $S_k - \mathrm{I}_k$ is empty, this means that all of the subchannels allocated to user k have been in the severe interference set. Therefore, the interference threshold y_k should be reduced by $step_{\_\mathrm{dB}}$ and $m_k = \arg\min_{m \in S_k} I_{mk}^n$. Then, the number of femtocells comprised in $F_k^{m_k}$ will get larger and the interference to the macrocell will be further mitigated.

ii) Put m_k into I_k.

iii) Picks the femtocells B_l as the interfering set for the macro UE k on subchannel m_k by $F_k^{m_k} \triangleq \{B_l : G_{m_k k}^l p_m^l > y_k\}$.

iv) Add subchannel m_k and dominant interference set pair $(m_k, F_k^{m_k})$ into II_k.

The above MLQP will be repeated until the data rate of marocell's UE k is greater than its target data rate. Thus, each macro UE, without satisfying data rate, can find a dominant interference set II_k and the macro NodeB will notify the femtocells according to the set II_k to prevent some femtocells from using certain subchannels. The signaling overhead is low since the implementation frequency of the MLQP process is low, and only the macro UEs without satisfying data rates need this coordination process.

IV. Simulation Models and Results

To show the improvements of the proposed DRA, we set up a system level simulation and make the pure power iterative waterfilling [20] algorithm as the reference algorithm. For this algorithm, all of the cells share all of the subchannels and the subchannels are evenly allocated to the users in one cell.

Table 1. System parameters.

Parameter	Variable	Simulation value
System bandwidth	B	10 MHz
Subchannel number	M	50
Maximum transmission powers	$P_\mathrm{M}^{\max}$, $P_\mathrm{F}^{\max}$	43, 23 dBm
Carrier frequency	f_c	2,000 MHz
Wall partition loss	W_dB	5 dB
Path loss exponents	$\alpha_c, \alpha_{fo}, \alpha_{fi}$	3.8, 3.8, 3
Cell radius	R_c, R_f	500, 35 m
Interference threshold step	$step_{\_\mathrm{dB}}$	5 dB

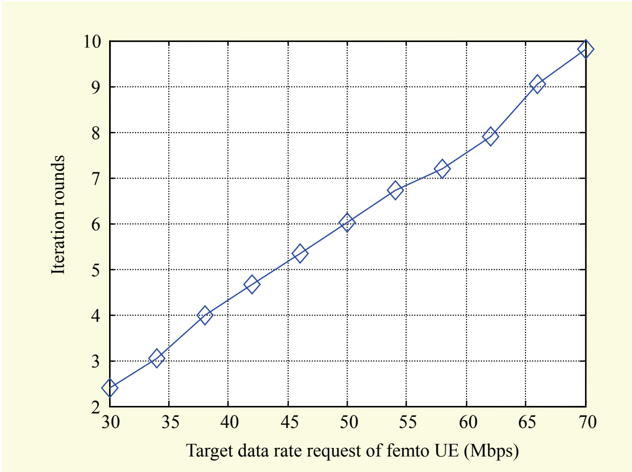

Fig. 2. Iteration rounds vs. target data rate of femto UE (number of femto NodeB = 20, number of macro UE = 10, target data rate of macro UE = 1 Mbps).

The simulation model uses the system deployment introduced in section II which comprises a single central macrocell BS and N femtocells. The indoor and outdoor path loss models for various scenarios expressed in [21] are introduced into this simulation and not repeated here due to limited space. In the simulation, without loss of generality, one UE is distributed in each femtocell and 10 active macro UEs in the macrocell. Also, the femtocells are not overlapped with each other. The main system parameters are presented in Table 1.

In Fig. 2, the iteration rounds needed to achieve the convergence is shown under the condition that the femtocell mumber is 20, active macro UE number is 10, and the macrocell UE data rate request is 1 Mbps. We can see that the number of iteration rounds is increasing when the data rate

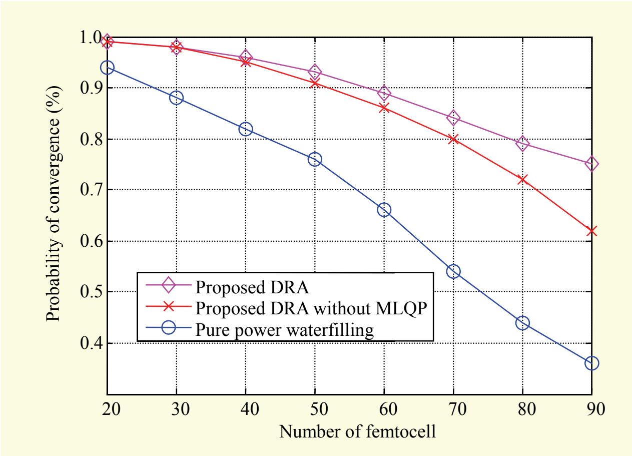

Fig. 3. Probability of convergence vs. number of femtocells (number of macro UE =10, target data rate of macro UE =1 Mbps, target data rate of femto UE =30 Mbps).

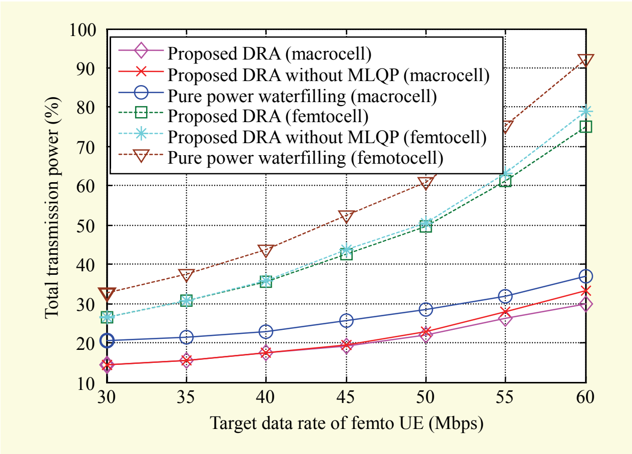

Fig. 4. Total transmission power vs. target data rate of femto UE (number of macro UE = 10, number of femtocell = 20, target data rate of macro UE = 1 Mbps).

request of femtocell UE becomes larger because the used subcarriers will get larger and the intercell interferences are larger (higher rate constraints). However, the convergence speed is in the accepted range.

Figure 3 depicts the convergence probability as the number of femtocell increasing. Besides pure power waterfilling, the proposed DRA without MLQP is also used as a reference algorithm. It shows that the proposed DRA can achieve much larger convergence probability compared with pure power waterfilling since it can coordinate the UEs to use the most appropriate subchannels and mitigate the severe cross-tier interference in two-hierarchy networks. Also, the proposed DRA can obtain larger convergence probability than the proposed DRA without MLQP. The reason is that, when the number of femtocells is larger, the system's feasible region may not exist. The MLQP process can reduce the target data

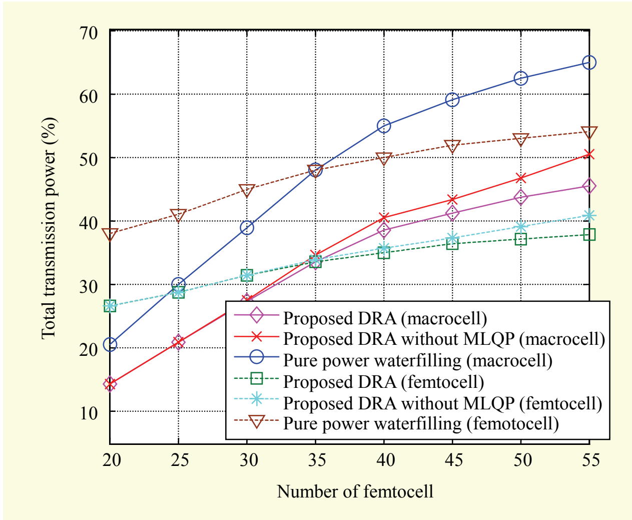

Fig. 5. Total transmission power vs. number of femtocell (number of macro UE = 10, target data rate of macro UE = 1 Mbps, femto UE data rate request = 30 Mbps).

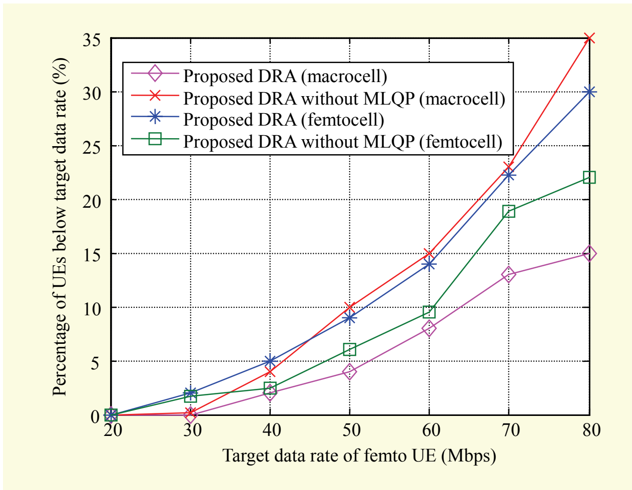

Fig. 6. Percentage of UEs below target data rate vs. target data rate of femto UE (number of macro UE = 10, number of femtocell = 20, target data rate of macro UE = 1 Mbps).

rate of femto UEs to enhance the probability that the system has solutions to reach convergence.

In Figs. 4 and 5, the total transmission power of femtocells and macrocells with regard to femto UE target data rate and the number of femtocells are plotted, respectively. Note that the total transmission power is normalized by the cell maximum power. Figures 4 and 5 show that the total transmission power increases with the data rate of femto UE and femtocell density, due to the increasing demand for subchannels and the interferences between the macrocell and the femtocell as well as among femtocells. From the two figures, we can conclude that the proposed DRA can save about 25% to 30% power compared with pure power waterfilling. This is because the pure power waterfilling algorithm makes some subchannels more crowded and wastes much power.

From Fig. 6, we can see the effectiveness of MLQP. The percentage of macrocell UEs below the target data rate is remarkably reduced compared with DRA without MLQP, especially when the number of femtocells is large at the cost of a little larger number of femtocell UEs below the target data rate.

V. Conclusion

We proposed a distributed resource allocation algorithm that considers the subchannel and power allocation comprehensibly in OFDMA macrocell and femtocell two-hierarchy networks. The new distributed resource allocation algorithm is based on the game theory and the MLQP is added to the DRA scheme when the system is crowded. The simulation results show that the new distributed algorithm can solve the resource allocation problem in two-hierarchy networks well with low complexity and achieve notable performance gain compared with the pure waterfilling algorithm.

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