Radio Resource Allocation for Interference Management in OFDMA-Based Femtocell-Macrocell Deployment

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***Abstract*—In this paper, we consider a downlink resource allocation in an Orthogonal Frequency Division Multiple Access (OFDMA) based heterogonous cellular network. In order to use spectrum efficiently, we propose Non-Exclusive Spectrum Allocation scheme (NESA). The considered objective function of the NESA scheme is to maximize the sum rate of macrocell and femtocells subject to maximum transmit power and maximum acceptable interference from femtocells on Macrocell User Equipments (MUEs) constraints. To solve the proposed non-convex optimization problems, we divide the corresponding problems into two sub-optimal problems including sub-carriers allocation and power allocation. We then consider a lower bound on the objective function corresponding to the sub-problem of power allocation for femtocells and transform it into a convex problem. This problem is solved based on an iterative algorithm. Presented simulation results validate the accuracy of the developed scenario.**

***Index Terms*—Femtocell, macrocell, OFDMA, downlink, resource allocation.**

I. Introduction

Nowadays, due to the increasing demand of data traffic and data rate, the Macrocell Base Stations (MBSs) cannot guarantee the indoor coverage and Quality-of-Service (QoS) requirements. Accordingly, Femtocell Access Points (FAPs) are small cells, low power device which can absorb the indoor traffic and reduce the originating traffic from outdoor MBSs.

Compared with the orthogonal deployment, co-channel arrangement among femtocells and macrocells is more attractive method in these heterogeneous cellular network settings as it can offer a much higher spectral efficiency. However, in co-channel deployment, the co-tier and cross-tier interferences significantly affect the network performance [1].

There have been some recent works on interference management, resource allocation and performance analysis of Orthogonal Frequency Division Multiple Access (OFDMA) based heterogenous deployment networks. In [2], the authors propose the fair resource-sharing solution for uplink that maximizes the total minimum spectral efficiency of all femtocells subject to protection constraints for the prioritized macro users. In [3], the authors propose a semi-distributed interference management scheme based on joint clustering and resource allocation for femtocells. In [4], the interference from macrocell to femotcell is perceived. Then with considering the degree of received interference, an algorithm for orthogonal resource allocation to femtocells with low cross-tier interference is presented.

In this paper, we consider Non-Exclusive Spectrum Allocation (NESA) scheme in downlink OFDMA based two-tier deployment heterogeneous cellular networks. The objective function of the NESA scheme is to maximize the sum rate of macrocell and femtocells subject to maximum transmit power and maximum acceptable interference from femtocells on MUEs. To make non-convex optimization problem tractable, the Successive Convex Approximation for Low complExity (SCALE) algorithm is used. Thus, the power allocation problem is converted to a convex problem and dual decomposition method is adopted to allocate power to MUEs and FUEs.

The rest of this paper is organized as follows: Section II describes the system model and assumptions. Section III discusses the solution of optimization problem. Numerical results are presented in Section IV. Finally, Section V concludes the paper.

II. System Model and Problem Formulation

We consider OFDMA downlink of co-channel deployment femtocell network coexisting with macrocell network, depicted in Fig. 1. The set of Base Stations (BSs) is $f \in \mathcal{F} = \{0, 1, ..., F\}$ where $f = 0$ and $f \in \mathcal{F}_f = \{1, ..., F\}$ denote to MBS and FAPs, respectively. The set of users served by macrocell and femtocell f is denoted by $m_m \in \mathcal{M}_m = \{1, ..., M_m\}$ and $m_f \in \mathcal{M}_f = \{1, ..., M_f\}$, respectively. Moreover, we assume that the resource allocator is performed by a central processing unit and that all Channel State Information (CSI) is available at BSs.

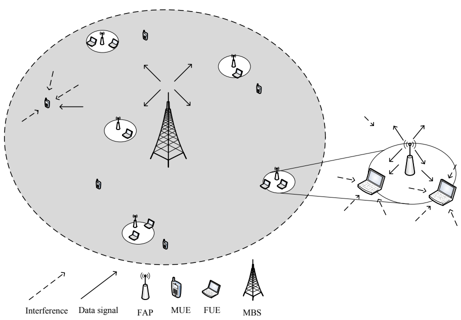

Fig. 1. Distribute of femtocell and UE in macrocell

Denote the sub-carrier assignment by a binary variable $\rho^n_{m,f}$. When sub-carrier n is assigned to user m in FAP f, $\rho^n_{m,f} = 1$ and otherwise $\rho^n_{m,f} = 0$. Let $\boldsymbol{\rho}^n = [\rho^n_{m,f}]^{M \times F}$. N_0 is the power spectral density of the white gaussian noise and B is the bandwidth of each sub-carrier. Let p^n_f and $\boldsymbol{p}^n = [p^n_0, p^n_1, ..., p^n_F]^T$ be the allocated power for sub-carrier n in femtocell f and the vector of transmit power at sub-carrier n, respectively.

All sub-carriers are divided into two sets called shared and non-shared. non-shared sub-carriers are only allocated to macrocell while shared sub-carriers can be simultaneously allocated to macrocell and femtocells. Let us denote $n^{sh} \in \psi^{sh}$ as a shared sub-carrier and $n^{nsh} \in \psi^{nsh}$ as a non-shared sub-carrier. The total set of sub-carriers is denoted by $\Omega = \psi^{sh} \cup \psi^{nsh}$.

The corresponding achievable data rate from BS $f \in \mathcal{F}$ to UE $m \in \mathcal{M}$ on sub-carrier $n \in \Omega$ can be obtained as follows:

$$r^n_{m,f} = \log_2\left(1 + \gamma^n_{m,f}\left(\boldsymbol{p}^n, \boldsymbol{\rho}^n\right)\right), \quad (1)$$

where $\gamma^n_{m,f}$ is the SINR from BS $f \in \mathcal{F}$ to UE $m \in \mathcal{M}$ on sub-carrier $n \in \Omega$. We define the SINR from BS f to UE m on sub-carrier n as follows:

$$\gamma^n_{m,f}\left(\boldsymbol{p}^n, \boldsymbol{\rho}^n\right) = \frac{\rho^n_{m,f} p^n_f h^n_{m_f,f}}{BN_0 + \sum\limits_{f' \neq f}^{F} \sum\limits_{m' \neq m}^{M} \rho^n_{m',f'} p^n_{f'} h^n_{m_f,f'}}, \quad (2)$$

where $h^n_{m_f,f'}$ is the channel power gain between UE m in BS f and BS f' at sub-carrier n.

The objective of resource allocation problem is to maximize the sum rate subject to the constraints on the maximum transmission power of each BS and imposed interference power on MUEs which are occupying the shared sub-carriers. We formulate the resource allocation problem in the following optimization framework:

$$\max_{\boldsymbol{P},\boldsymbol{\rho}} \quad \sum_{m=1}^{M} \sum_{n=1}^{N} \sum_{f=0}^{F} \rho^n_{m,f} r^n_{m,f}, \quad (3)$$

$$\text{s.t.} \quad \sum_{f_f=1}^{F} \sum_{m_f=1}^{M_f} \rho^n_{m,f} p^n_f h^n_{m_m,f} < I^n_{0,\max}, \quad \forall n \in \psi^{sh}, m_m \in \mathcal{M}_m, \quad (4)$$

$$\sum_{m=0}^{M} \sum_{n=1}^{N} \rho^n_{m,f} p^n_{m,f} < P_{f,\max}, \quad \forall f \in \mathcal{F} \quad (5)$$

$$\sum_{m=1}^{M} \rho^n_{m,f} \leq 1, \quad \forall n \in \psi^{sh}, f \in \mathcal{F} \quad (6)$$

$$\sum_{m=1}^{M} \rho^n_{m,0} \leq 1, \quad \forall n \in \Omega, \quad (7)$$

$$p^n_f \geq 0, \rho^n_{m,f} \in \{0, 1\}, \quad \forall m \in \mathcal{M}, f \in \mathcal{F}, n \in \Omega, \quad (8)$$

where $I^n_{0,\max}$ is the maximum tolerable interference threshold on macrocell at sub-carrier n and $P_{f,\max}$ is the maximum allowable transmt power of BS f. Constraint (4) denotes the imposed interference from FAPs on MUE $m_m \in \mathcal{M}_m$ at sub-carrier $n \in \psi^{sh}$ which should be smaller than $I^n_{0,\max}$. (5) is the transmission power constraint in which the allocated power for each BS should be smaller than $P_{f,\max}$. Likewise, constraints (6) and (7) make sure that sub-carrier n is only assigned to at most one UE m in each BS f.

III. Solution

Obviously, the above problem is combination of discrete and continuous variables with non-linear constraints, thus it is a non-convex and not tractable optimization problem. Hence, we propose a sub-optimal solution to reduce the computational complexity. We decouple the problem into two sub-optimal problems called the power allocation and the sub-carriers allocation and use the dual method for solving the proposed problems. As it is shown in [5], the duality gap for non-convex optimization problem always tends to zero as the number of sub-carriers goes to infinity.

A. sub-carriers allocation

We derive sub-carriers allocation in case that the power of each sub-carrier is given. The sub-carriers are allocated to the users which have the maximum rate on them as follows [6]:

$$m^* = \arg\max_{m} \left[r^n_{m,f}(\mathbf{p}^n)\right], \ \forall n \in \Omega, f \in \mathcal{F}, \quad (9)$$

$$\rho^n_{m^*,f} = 1, \qquad \rho^n_{m,f} = 0, \qquad \forall m \neq m^*. \quad (10)$$

B. power allocation

We decouple the power allocation problem into two sub-problems, power allocation for macrocell and femtocells.

1) Femtocell power allocation: The femtocell user power allocation is performed with considering constraint on the interference that FAPs generate on MUEs. In other words, transmission power in femtocell should be allocated such that the interference limitation on macrocell is fulfilled. The power allocation problem for femtocell users can be written as follows:

$$\max_{\boldsymbol{P}} \sum_{m\in\mathcal{M}_f}\sum_{n\in\psi^{sh}}\sum_{f\in\mathcal{F}_f} \rho^n_{m,f} r^n_{m,f}, \tag{11}$$

$$\text{s.t.} \sum_{f\in\mathcal{F}_f} p^n_f H^n_{m_m,f} \le I^n_{0,\max},\ \forall m_m \in \mathcal{M}_m, n\in\psi^{sh}, \tag{12}$$

$$\sum_{n\in\psi^{sh}} p^n_f \le P_{f,\max}, \quad \forall f\in\mathcal{F}_f, \tag{13}$$

$$\sum_{m\in\mathcal{M}_f} \rho^n_{m,f} \le 1, \quad \forall n\in\psi^{sh}, f\in\mathcal{F}_f. \tag{14}$$

As mentioned before, the above problem is non-convex. Hence, for solving this problem, at first, the tight lower bound of objective function which is parameterized by given power allocation $\tilde{\boldsymbol{P}}$, is used. To do this end, we first define the considered tight lower bound as follows [7]:

$$\underline{r}^n_{m,f}(e^{\boldsymbol{q}^n},\tilde{\boldsymbol{p}}^n) = \tilde{\alpha}^n_{m,f}\log_2\left(\gamma^n_{m,f}(e^{\boldsymbol{q}^n},\boldsymbol{\rho}^n)\right) + \tilde{\beta}^n_{m,f}, \tag{15}$$

$$\tilde{\alpha}^n_{m,f} = \frac{\gamma^n_{m,f}(\tilde{\boldsymbol{p}}^n,\boldsymbol{\rho}^n)}{1+\gamma^n_{m,f}(\tilde{\boldsymbol{p}}^n,\boldsymbol{\rho}^n)}, \tag{16}$$

$$\tilde{\beta}^n_{m,f} = r^n_{m,f}(\tilde{\boldsymbol{p}}^n,\boldsymbol{\rho}^n) - \tilde{\alpha}^n_{m,f}\log_2\left(\gamma^n_{m,f}(\tilde{\boldsymbol{p}}^n,\boldsymbol{\rho}^n)\right), \tag{17}$$

where $\boldsymbol{q}^n$ is the vector and $\boldsymbol{p}^n = e^{\boldsymbol{q}^n}$. Note that it is necessary $\tilde{\boldsymbol{P}}$ should belong to the set $\mathcal{P} = \{\boldsymbol{P}|\forall f,n\ p^n_f \in (0,P_{f,\max}]\}$, to guarantee that, $\gamma^n_{m,f} > 0, \forall n,m,f$.

As mentioned, for guaranteeing that $\gamma^n_{m,f} > 0$, we define a new set $\mathcal{P}_\epsilon = \{\boldsymbol{P}|\forall f,n,p^n_f \in [e^\epsilon, P_{f,\max}]\}$ and $\mathcal{Q}_\epsilon = \{\boldsymbol{Q}|\forall f,n,q^n_f \in [\epsilon,\ln(P_{f,\max})]\}$ where $\boldsymbol{P} = e^{\boldsymbol{Q}}$ and ϵ is a predefined very small negative number. Hence, (15) can be written as (18) and (19) where shown at the top of the next page:

$$Y(e^{\boldsymbol{Q}}) = \sum_{m\in\mathcal{M}_f}\sum_{n\in\psi^{sh}}\sum_{f\in\mathcal{F}_f}\log_2\left(1+\gamma^n_{m,f}(e^{\boldsymbol{q}^n},\boldsymbol{\rho}^n)\right), \tag{18}$$

Based on this lower band, (11) can be converted as follows:

$$\max_{\boldsymbol{Q}}\ \bar{Y}_{\tilde{\alpha},\tilde{\beta}}(e^{\boldsymbol{q}^n},\tilde{\boldsymbol{p}}^n), \tag{20}$$

$$\text{s.t.} \sum_{f\in\mathcal{F}_f} e^{q^n_f} H^n_{m_m,f} \le I^n_{0,\max}, \quad \forall n\in\psi^{sh}, m_m\in\mathcal{M}_m, \tag{21}$$

$$\sum_{n\in\psi^{sh}} e^{q^n_f} \le P_{f,\max}, \quad \forall f\in\mathcal{F}_f, \tag{22}$$

$$\boldsymbol{Q}\in\mathcal{Q}_\epsilon. \tag{23}$$

By relaxing the constraints, we obtain the Lagrangian dual function as follows:

$$\min_{\lambda,\nu\ge 0}\quad g(\lambda,\nu), \tag{24}$$

$$g(\lambda,\nu) = \max_{\boldsymbol{P}\succeq 0}\quad \bar{\Lambda}(\boldsymbol{P},\lambda,\nu), \tag{25}$$

$$\bar{\Lambda}(\boldsymbol{P},\lambda,\nu) \triangleq \bar{Y}_{\tilde{\alpha},\tilde{\beta}}(\boldsymbol{P}) + \sum_{f\in\mathcal{F}_f}\lambda_f\left(P_{f,\max} - \sum_{n\in\psi^{sh}} p^n_f\right) + \sum_{n\in\psi^{sh}}\sum_{m_m\in\mathcal{M}_m}\nu_{n,m_m}\left(I^n_{0,\max} - \sum_{f\in\mathcal{F}_f} p^n_f H^n_{m_m,f}\right), \tag{26}$$

Hence, the transmission power of sub-carrier n on BS f is derived as follows:

$$p^n_f = \left[\frac{\alpha^n_{m,f}}{\ln(2)\left(\lambda_f + \nu_{m_m,n}H^n_{m_m,f} + X^n_{m,f}\right)}\right]^+, \tag{27}$$

$$X^n_{m,f} = \sum_{\substack{j\in\mathcal{M}_f\\ j\neq m}}\sum_{\substack{i\in\mathcal{F}_f\\ i\neq f}} \frac{\alpha^n_{j,i}H^n_{j,f}}{\ln(2)\left(BN_0 + \sum\limits_{\substack{f'\in\mathcal{F}\\ f'\neq i}} p^n_{f'}H^n_{j,f'}\right)}. \tag{28}$$

We use the ellipsoid method or so-called the cutting-plane method for updating the dual variables [5].

2) Macrocell power allocation: In order to obtain the power for MUEs, we can ignore the interference constraint (4), because macrocell users have the highest priority than femtocell users.

By relaxing the constraints, we obtain the Lagrangian dual function of macrocell power allocation problem as follows:

$$\Lambda(\boldsymbol{P},\lambda_0) = \sum_{m\in\mathcal{M}_m}\sum_{n\in\Omega}\rho^n_{m,0}r^n_{m,0} + \lambda_0\left(P_{f,\max} - \sum_{n\in\Omega}p^n_0\right), \tag{29}$$

$$Y(e^{\boldsymbol{q}^n}) \geq \underbrace{\sum_{m\in\mathcal{M}_f}\sum_{n\in\psi^{sh}}\sum_{f\in\mathcal{F}_f}\left(\tilde{\alpha}^n_{m,f}\log_2\left(\gamma^n_{m,f}(e^{\boldsymbol{q}^n},\tilde{\boldsymbol{p}}^n,\boldsymbol{\rho}^n)\right)+\tilde{\beta}^n_{m,f}\right)}_{\bar{Y}_{\tilde{\alpha},\tilde{\beta}}(e^{\boldsymbol{q}^n},\tilde{\boldsymbol{p}}^n)} \tag{19}$$

where λ_0 is the lagrangian multiplier with respect to MBS. Note that the dual problem (29) is always convex regardless of the convexity of the primal problem. The allocated power on sub-carrier n can be yeilded as follows:

$$p^n_0=\left[\frac{1}{\ln(2)\lambda_0}-\frac{1}{\gamma^n_{m,0}(\boldsymbol{p}^n,\boldsymbol{\rho}^n)}\right]^+, \tag{30}$$

where $[\cdot]^+=\max(\cdot,0)$.

C. Algorithm

We propose an iterative algorithm for optimizing the power and sub-carrier allocation based on SCALE algorithm [7]. This algorithm is shown in Table I and Table II, where l_* is the loop iteration number, $L_{*,\max}$ is the maximum number of iteration and ϵ_* is the maximum tolerance which is used for convergence. The superscript l_* on variables indicates that the associated variables are given after l_*^{th} iteration. $\|\cdot\|$ represents the Euclidean norm of a vector.

TABLE I
ALGORITHM I

Overall resource allocation algorithm
Step1: Initialize the maximum number of iteration $L_{1,\max}$, the maximum tolerance ϵ_1, the power allocation variables $\boldsymbol{P}^0$ and Lagrangian variable $\boldsymbol{\lambda}$ and $\boldsymbol{\nu}$ from Theorem 3.
Step2: Set iteration index $l_1=0$.
Step3: For a given power allocation, obtain $\boldsymbol{\rho}^0$ from (9).
step4: Obtain $\tilde{\alpha},\tilde{\beta}$ from (16) and (17), respectively.
Step5: **repeat**
Step6: For a fixed $\boldsymbol{\rho}^{l_1}$, obtain power allocation matrix $\boldsymbol{Q}^{l_1+1}$ and $\boldsymbol{P}^{l_1+1}$ from Algorithm 2.
Step7: For a fixed $\boldsymbol{P}^{l_1+1}$ obtain sub-carrier allocation policies $\boldsymbol{\rho}^{l_1+1}$ from (9).
Step8: For a fixed resource allocation variable, update $\tilde{\alpha}$, $\tilde{\beta}$ according to (16) and (17), respectively.
Step9: **if** $\|\boldsymbol{P}^{l_1+1}-\boldsymbol{P}^{l_1}\|\leq\epsilon_2$.
Step10: Convergence=True.
Step11: **return** $\boldsymbol{P}=\boldsymbol{P}^{l_1+1}$ and $\boldsymbol{\rho}=\boldsymbol{\rho}^{l_1+1}$.
Step12: **else**
Step13: $l_1=l_1+1$.
Step14: $\boldsymbol{\rho}^{l_1}=\boldsymbol{\rho}^{l_1+1}$.
Step15: **end if**
Step16: **until** Covergence=True or $l_1=L_{1,\max}$

TABLE II
ALGORITHM II

Power allocation algorithm
Step1: Initialize maximum number of iteration $L_{2,\max}$, power allocation matrix $\boldsymbol{P}^{0,l_1}=\boldsymbol{P}^{l_1}$, Lagrangian variable $\boldsymbol{\lambda}^{0,l_1}=\lambda^{l_1}$ and $\boldsymbol{\nu}^{0,l_1}=\boldsymbol{\nu}^{l_1}$.
Step2: Set iteration index $l_2=0$ and ϵ_2.
Step3: For a fixed femtocell power allocation matrix $\boldsymbol{P}_f^{l_2,l_1}$ and $\lambda_0^{l_2,l_1}$ obtain macrocell power allocation vector $\boldsymbol{p}_0^{1_2+1,l_1}$ from (30).
Setp4: **repeat**
Step5: For a fixed femtocell power allocation matrix $\boldsymbol{P}_f^{l_2,l_1}$, macrocell power allocation vector $\boldsymbol{p}_0^{1_2+1,l_1}$, femtocell Lagrangian variable vector $\boldsymbol{\lambda}_f^{l_2,l_1}$ and $\boldsymbol{\nu}^{l_2,l_1}$ obtain $\boldsymbol{P}_f^{l_2+1,l_1}$ from (27).
Setp6: **if** $\|\boldsymbol{P}_f^{l_2+1,l_1}-\boldsymbol{P}_f^{l_2,l_1}\|<\epsilon_2$
Step7: Convergence=true.
Step8: **else**
Step9: $\boldsymbol{P}_f^{l_2,l_1}=\boldsymbol{P}_f^{l_2+1,l_1}$.
Step10: $l_2=l_2+1$.
Step11: **end if**
Step12: **until** Convergence=True or $l_2=L_{2,\max}$
Step13: For a fixed $\boldsymbol{P}^{l_2+1,l_1}$ update $\boldsymbol{\lambda}^{l_2+1,l_1}$ and $\boldsymbol{\nu}^{1_2+1,l_1}$ from Ellipsoid method.
Step14: **return** $\boldsymbol{P}^{l_1+1}=\boldsymbol{P}^{l_2+1,l_1}$, $\boldsymbol{\lambda}^{l_1+1}=\boldsymbol{\lambda}^{l_2+1,l_1}$ and $\boldsymbol{\nu}^{l_1+1}=\boldsymbol{\nu}^{l_2+1,l_1}$.

TABLE III
SIMULATION PARAMETERS

System parameter	Value
Macrocell radius (R_m)	500m
Femtocell radius (R_f)	20m
Pathloss exponent for macrocell and femtocell (ξ)	4
Number of MUE	20
Number of FAP	20
Number of sub-carrier	32
Noise power spectrum density (N_0)	-174dBm/Hz
Bandwidth (B)	180KHz
FUE number per femtocell (M_f)	1
Maximum transmit power of macrocell $(P_{0,\max})$	46dBm

IV. SIMULATION RESULTS

In this section, the simulation results for analysing the performance of the proposed system are provided. The channel power gain between BS and UE is represented as a combination of slow and fast fading components.

The path loss is $d_{m,f}^{-\xi}$, where $d_{m,f}$ is the distance from UE m to BS f and ξ is the path loss exponent. The multipath component is a random value generated according to the Rayleigh distribution and it is function of UE's environment which changes rapidly.

The network scenario in our simulation is shown in Fig. 1. We assume that there is one MBS in the considered area, which is located at the coordinate $(0, 0)$. For dense deployment, we consider FAPs and MUEs are randomly and uniformly deployed in the regions between radius 250 m and 500 m and angle between 0 and $\pi/2$ from MBS. Furthermore, we assume that the coverage area of FAP is 20 m and each FAP has one FUE, which is distributed randomly in femtocell coverage area. The initial macrocell and femtocells transmit power are $\boldsymbol{p}_0 = P_{f,\max}/(N^{sh} + N^{nsh})$ and $\boldsymbol{p}_f = P_{f,\max}/(N^{sh})$, respectively. Table III shows the considered parameters for the simulation set up.

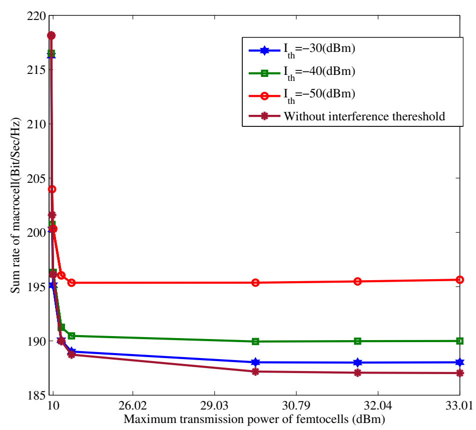

Fig. 2. Sum rate of macrocell versus transmission power of femtocells for different $I_{0,\max}^{n}$ in NESA scheme, $FAP = 20$, $N = 32$ and $M = 20$.

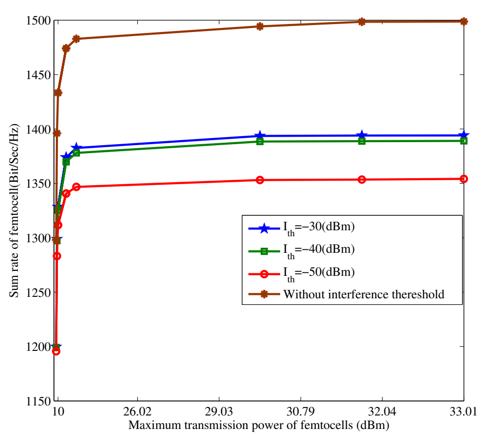

Fig. 3. Sum rate of femtocell versus transmission power of femtocells for different $I_{0,\max}^{n}$ in NESA scheme, $FAP = 20$, $N = 32$ and $M = 20$.

When there is a limitation on the received interference from FAPs to MUEs, the sum rate of MUSs can be increased, which it is illustrated in Fig. 2. However, this restriction can reduce the sum rate of FUEs which is represented in Fig. 3.

V. Conclusion

In this paper, we have proposed and developed an iterative algorithm for the joint allocation of sub-carriers and transmission power in a two-tier OFDMA downlink cellular network. The objective was to maximize of sum rate subject to maximum transition power of each BS and restriction the received interference from FAPs to MUEs. We have used SCALE Algorithm to convert power allocation problem in FUEs to convex one. The numerical simulations have confirmed that effectively reduces cross-channel interference and improve MUEs throughput however in cost of diminishing the sum rate of femtocells.

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