Low Complex Energy-Efficient Resource Allocation in Femtocell Networks

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Abstract—Femtocells have attracted growing attention in academia, industry, and standardization forums in recent years. However, most of existing works on femtocell networks are focused on spectrum efficiency and interference mitigation, energy efficiency aspect is neglected. In this paper, we investigate the energy efficient resource allocation of downlink femtocell networks in sparsely and densely deployed scenario respectively. To decrease the complexity, joint subchannel allocation and power control are decomposed into two steps. Firstly, given subchannel allocation, a closed-form best response of transmit power is obtained. Secondly, a fair energy efficient subchannel allocation metric has been derived out. At last, we propose a distributed low-complex power control algorithm. Simulation results show that the proposed algorithm has a low complexity with slight loss of energy efficiency compared with Round-Robin Scheduling and a non-cooperative energy-efficient power optimization algorithm.

Index Terms—femtocell, energy efficiency, resource allocation, exponentially-weighted low-pass filter, game theory

I. INTRODUCTION

With the exponential growth of mobile data traffics, wireless communication networks play a more and more important role in the global emissions of carbon dioxide [1]-[2]. Obviously, the growing energy cost will cause a significant operational expense (OPEX) for mobile operators. On the other hand, the limited battery resources can not meet the massive data rate requirement either. Based on this background, the concept-green communication is proposed to develop environment friendly, and energy efficient technologies for future wireless communications. Therefore, pursuing high system energy efficiency is a trend for the design of next generation wireless communication.

In past decades, researchers have made much effort to enhance the system spectrum efficiency and mitigate the interference caused by neighbor-cells [3]-[6]. In [7], an opportunistic distributed power control algorithm for cellular network is proposed, and the simulation shows that the algorithm improves the system throughput greatly. To mitigate co-tier interference in femtocell networks, a decentralized model by joint considering modulation and coding schemes, subchannel and power allocation is proposed in [8], simulation results show that the user’s outages and system throughput are improved. In [9], authors introduce a dynamic joint subchannel allocation and power control scheme to minimize total transmit power and inter-cell interference, while meeting the given data rate requirement in femtocell networks.

Most of existing literatures always focus on system throughput and interference avoidance, the energy efficiency aspect is ignored in femtocell networks. Energy efficiency is measured in bit/joule, and is defined as the number of data bits delivered correctly for each energy-unit used in transmission [10]. In [11], authors propose a non-cooperative game to optimize system energy efficiency by distributed power control, but the complexity is high. A low complexity energy-efficient subchannel allocation scheme is proposed in [12], but the method does not consider interference caused by neighbors. Besides energy efficient resource management, there are other new techniques to save energy, e.g., new physical layer techniques, and heterogeneous networks, etc. [13]. Femtocell is an important component of heterogeneous networks, which is installed by end-users to enhance the indoor coverage. Since this type of deployment strategy brings transmitters closer to receivers, and reduces the penetration loss and path loss, the transmission energy can be saved [14]. Therefore, energy efficient resource allocation together with femtocell techniques can be very promising.

In this paper, we investigate the energy-efficient resource optimization for the downlink (DL) of femtocell networks. To decrease the complexity and time consumption when exhaustively searching the optimal power allocation as we studied in previous works [15], a closed-form best response of transmit power is obtained. For subchannel allocation, a fair time-averaged subchannel allocation metric based on exponentially-weighted low-pass filter has been derived out. At last, we introduce a suboptimal subchannel allocation and distributed low-complex power control algorithm. Simulation results show that the proposed low-complex algorithm has a slight loss of energy efficiency compared with Round-Robin Scheduling (RRS) and a non-cooperative energy-efficient power optimization (NEEPO) algorithm [11].

The rest of the paper is organized as follows. We first introduce the system model and problem formulation in

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Section II. We then investigate power control strategy in sparsely and densely deployed femtocell networks respectively, and a closed-form of transmit power is achieved in Section III. A fair time-averaged low-complex subchannel allocation metric has been proposed in Section IV. A distributed resource allocation algorithm is given in Section V. In Section VI, the performance of proposed algorithm is analyzed by simulations. Finally, we conclude the paper in Section VII.

II. System Description and Problem Formulation

A. System Description

Fig. 1 shows the considered scenario in this paper, which consists of B femtocells deployed in a rectangular area. Femtocell base stations (FBSs) considered here are in closed subscriber group (CSG) mode, i.e., mobile stations (MSs) that are not the members of the CSG, are not allowed to access the CSG FBSs.

Due to the fact that, femtocells are deployed over the existing macrocell networks and share the same frequency with macrocells totally or partially. For guaranteeing quality-of-service (QoS) of macrocell users, we will allocate the dedicated subchannels to femtocells to avoid the cross-tier interference. All of femtocells in this system operate over the same frequency band, indexed by $k \in K = \{1, 2, \ldots, K\}$, and channel state informations of MSs are perfectly known by the serving FBS. Assume each OFDMA frame consists of one OFDM symbol, and T denotes the OFDM time symbol.

Let $\psi : \{1, 2, 3, \ldots, B\}$ denote femtocells in the system. There are $M$ MSs distributed in $B$ FBSs, indexed by $m \in M = \{1, 2, \ldots, M\}$. Denote the index set of MSs in the $b$th FBS as $U_b$, $U_b \cap U_{b'} = \emptyset$, for $b \neq b'$, $\forall b, b' \in \psi$, and $U_1 \cup U_2 \cdots \cup U_B = M$. Let $C_{hm}[t]$ denote the index set of subchannels occupied by MS $m$ in the FBS $b$.

For the MS $m$ in the FBS $b$, the interference on subchannel $k$ caused by other FBSs at frame $t$ can be written as:

$$I^k_{hm}[t] = \sum_{i \in \psi, i \neq b} p^i_{t}[t] |g^k_{im}[t]|^2 + \sigma^2$$

where, $p^i_{t}[t]$ denotes the transmit power of FBS $i$ on subchannel $k$ at frame $t$. $g^k_{im}[t]$ denotes the channel gain between FBS $i$ and MS $m$ on subchannel $k$ at frame $t$. The variance of additive white gaussian noise (AWGN) at FBS $b$ is $\sigma^2$.

The signal to interference and noise ratio (SINR) of the link between FBS $b$ and MS $m$ on subchannel $k$ can be expressed as:

$$r^k_{hm}[t] = \frac{p^b_{t}[t] |g^k_{bb}[t]|^2}{I^k_{hm}[t]}$$

According to the Shannon’s capacity formula, the ideal achievable data rate of MS $m$ occupying subchannel $k$ in the FBS $b$ can be expressed as:

$$R^k_{hm}[t] = w \log_2 (1 + r^k_{hm}[t])$$

where, $w$ is the bandwidth of each subchannel, and $r^k_{hm}[t]$ is given by (2).

B. Problem Formulation

We focus on the energy-efficiency maximization of the whole system by efficient subchannel allocation and power control. In our previous works [15], we formulate the energy-efficiency to be the ratio of the instant data rate and instant transmit power plus circuit power per subchannel,

$$EE = \frac{R^k_{hm}[t]}{p^b_{t}[t]+ p_c}$$

where, $p_c$ represents the average energy consumption of device electronics, including mixers, filters, and digital-to-analog converters, and excludes that of the power amplifier. However, based on (1), (2), (3), we find (4) is difficult to get a closed-form solution on transmit power of each subchannel, which results in high complexity and time-consumed when exhaustively searching the optimal transmit power [16].

To deal with problem mentioned above, in this paper, we introduce exponentially-weighted low-pass filter [17] to get the average data rate of FBS $b$ at frame $t$, which can be expressed as [12],

$$T^b_{hm}[t] = (1 - \lambda) T^b_{hm}[t-1] + \lambda \sum_{m \in C_{hm}[t]} \sum_{k \in A_{hm}[t]} a^k_{hm}[t] R^k_{hm}[t].$$

$T^b_{hm}[t]$ is the estimated data rate value of FBS $b$ at frame $t$. Where $\lambda$ is a smoothing factor, and satisfies $0 < \lambda < 1$. The subchannel assignment indicator $a^k_{hm}[t]$ satisfies,

$$\sum_{k \in A_{hm}[t]} a^k_{hm}[t] \leq 1,$$

$$a^k_{hm}[t] \in A \in \{0, 1\}^{p \cdot M \cdot K}.$$
The constraints in (6) mean one subchannel can be occupied by only one user in each FBS. Where, $A$ is the subchannel allocation matrix, $a_{mn}^k = 1$, if FBS $b$ transmits to MS $m$ via subchannel $k$, otherwise is zero.

Similarly, the average power of FBS $b$ at frame $t$ can be written as,

$$P^b_b[t] = (1 - \lambda)P^b_b[t-1] + \lambda \sum_{k=1}^{K}a^k_m[t] + p_c.$$  

(7)

The energy efficiency of FBS $b$ is,

$$e^b_b[t] = \frac{(1 - \lambda)T^b_b[t-1] + \lambda \sum_{m \in U} \sum_{k \in C_m[t]}a^k_m[t]R^b_m[t]}{(1 - \lambda)P^b_b[t-1] + \lambda \sum_{k=1}^{K}p^k_t[t] + p_c}.$$  

(8)

The whole system energy-efficiency is,

$$E[t] = \frac{\sum_{b=1}^{B} e^b_b[t]}{B}.$$  

(9)

Our target is to maximize the total energy-efficiency of the whole system,

$$\max_{\sum_{k=1}^{K}p^k_t[t]} \frac{(1 - \lambda)T^b_b[t-1] + \lambda \sum_{m \in U} \sum_{k \in C_m[t]}a^k_m[t]R^b_m[t]}{(1 - \lambda)P^b_b[t-1] + \lambda \sum_{k=1}^{K}p^k_t[t] + p_c}.$$  

(10)

where, $p_{\text{max}}$ is the maximal transmit power in each subchannel. We notice that the solution of problem (10) is difficult, due to the following reasons. Firstly, from (8) and (9), the equation $E[t]$ is non-concave in $p^k_t$, it is a time-consuming process to search the globally optimal solution. Secondly, the joint power and subchannel allocation is known as NP-hard. To reduce the computation complexity, we decompose the problem (10) into two sub-problems, i.e., subchannel allocation and power control. Firstly, in the following section, we will investigate the power control in sparsely deployed and densely deployed femtocell networks respectively, when subchannel allocation is given. Secondly, considering fairness, a fair time-averaged energy efficient subchannel allocation metric is proposed.

III. LOW COMPLEXITY POWER CONTROL WITH GIVEN SUBCHANNEL ALLOCATION

A. Sparsely Deployed Femtocell Networks

In sparsely deployed scenario, e.g. in rural area, due to the path loss and penetration loss, the interference between FBSs can be ignored. And the problem (10) can be simplified,

$$\max_{\sum_{k=1}^{K}p^k_t[t]} \frac{(1 - \lambda)T_b[t-1] + \lambda \sum_{m \in U} \sum_{k \in C_m[t]}a^k_m[t]R^b_m[t]}{(1 - \lambda)P_b[t-1] + \lambda \sum_{k=1}^{K}p^k_t[t] + p_c},$$  

(10)

where, $p_{\text{max}}$ is the maximal transmit power in each subchannel. The whole system energy-efficiency is,

$$E[t] = \frac{\sum_{b=1}^{B} e^b_b[t]}{B}.$$  

(9)

Our target is to maximize the total energy-efficiency of the whole system,

$$\max_{\sum_{k=1}^{K}p^k_t[t]} \frac{(1 - \lambda)T_b[t-1] + \lambda \sum_{m \in U} \sum_{k \in C_m[t]}a^k_m[t]R^b_m[t]}{(1 - \lambda)P_b[t-1] + \lambda \sum_{k=1}^{K}p^k_t[t] + p_c},$$  

(10)

where, $p_{\text{max}}$ is the maximal transmit power in each subchannel. We notice that the solution of problem (10) is difficult, due to the following reasons. Firstly, from (8) and (9), the equation $E[t]$ is non-concave in $p^k_t$, it is a time-consuming process to search the globally optimal solution. Secondly, the joint power and subchannel allocation is known as NP-hard. To reduce the computation complexity, we decompose the problem (10) into two sub-problems, i.e., subchannel allocation and power control. Firstly, in the following section, we will investigate the power control in sparsely deployed and densely deployed femtocell networks respectively, when subchannel allocation is given. Secondly, considering fairness, a fair time-averaged energy efficient subchannel allocation metric is proposed.

B. Densely Deployed Femtocell Networks

In densely deployed femtocell scenario, e.g., in urban areas, the FBSs are deployed closely to each other, the
mutual interference between FBSs can not be ignored. On the other hand, for guaranteeing the quality of service (QoS), the aggregate interference caused by other FBSs is bounded, i.e. \( \sum_{i \in \mathcal{I}, j \in \mathcal{R}} p_i^k(t)g_{im}^k[t] \leq \delta_{im}^k \). where, \( \delta_{im}^k \) is the upper bound of interference suffered by MS \( m \) in FBS \( b \) on subchannel \( k \).

In this subsection, the problem (11) will be modeled as a non-cooperative game. The following are its game characteristics.

1) Non-cooperative game

According to the game theory, the non-cooperative time-averaged power allocation (NTPA) can be modeled as \( \mathcal{G} = [\{u_b\}, \{p_b[t]\}, \{f_b[t]\}], b \in \psi \). And \( \{u_b\} = [u_1, u_2, \cdots, u_B] \) denotes the set of players, which represents \( B \) FBSs. \( p_b[t] = [p_1[t], \cdots, p_B[t]] \) is a feasible strategies of players. \( f_b[t] \) is the collection of utility functions. The utility function \( f_b[t] \) can be written as,

\[
f_b[p_b[t], p_{-b}[t]] = e_b[t],
\]

(16)

where \( p_{-b}[t] = [p_1[t], \cdots, p_{b-1}[t], p_{b+1}[t], \cdots, p_B[t]] \) denotes the power vector of other players except \( u_b \).

Different from the traditional spectrum efficiency optimization, from (8), the denominator \( p_i^k[t] \) implies an implicit penalty to avoid player increasing its transmit power selfishly to pursue the maximization of throughput in non-cooperative game.

**Definition 1:** Given the \( p_{-b}[t] \), player \( u_b \)'s best response of power allocation is given by,

\[
p_b[t] = \arg \max_{p_b[t]} f_b[p_b[t], p_{-b}[t]].
\]

(17)

2) Existence and uniqueness of nash equilibrium point

In a non-cooperative game, players independently choose their most suitable strategies to get best responses. From (17), the best response of player \( u_b \) is determined by \( p_b[t] \) and \( p_{-b}[t] \).

**Definition 2:** A given power allocation strategy \( p^*[t] = [p_1^*[t], \cdots, p_B^*[t]] \) is a Nash equilibrium (NE) point in non-cooperative game, if for \( \forall b \in \psi \), the following inequality is satisfied [12],

\[
f_b[p_b^*[t], p_{-b}^*[t]] \geq f_b[p_b[t], p_{-b}^*[t]]
\]

(18)

In the NE point, no player can improve their utility by changing its transmit power unilaterally.

**Theorem 2:** A NE point exists in the game \( G \), if the following conditions are satisfied,

a) \( p_b[t] \) is non-empty, convex and compact subset in the Euclidean space \( \mathbb{R}^{K \times B} \);

b) \( f_b \) is continuous and quasi-concave in \( p_b[t] \).

c) Condition a) is easily satisfied, the proof of condition b) has been verified in sparse femtocell networks. Furthermore, similar to the sparsely deployed scenario, given interference power vector \( p_{-b}[t] \), a unique optimal power \( p_b[t] = (p_1^*[t], p_2^*[t], \cdots, p_B^*[t]) \) always exists, and \( p_b^*[t] \) is affected by strategies chosen by other players. Based on (19), the following equation is satisfied,

\[
p_i^*[t] = \frac{-w}{e_i[t] \log 2} - \frac{\sigma^2 + \sum_{m \in \mathcal{M}_i} a_{in}^m[t]g_{im}^k[t]}{\sum_{m \in \mathcal{M}_i} a_{in}^m[t]},
\]

(19)

From (1), \( i_{in}^k[t] \) is a function of \( p_{-b}[t] \), the best response \( p_i^*[t] \) is affected by strategies chosen by other players. Therefore, a change in strategy made by one player will affect all other players' best response, which results in a new iterative process to find the best strategy, until reach a stable state, i.e. NE point.

In [20], R. D. Yates has proved a non-cooperative game has unique NE point, if function \( F \) satisfies,

a) Positivity \( F(p(t)) > 0 \);

b) Monotonicity if \( p(t) > p(t) \), then \( F(p(t)) > F(p(t)) \);

c) Scalability \( \alpha F(p(t)) > F(\alpha p(t)) \).

Obviously, (19) does not satisfy monotonicity, and the proposed NTPA has multiple NE points. Based on the above analysis, there is no efficient algorithm to obtain the global optimal transmit power.

Fortunately, due to the fact that the aggregate interference caused by other FBSs is bounded, i.e.

\[
\sum_{i \in \mathcal{I}, j \in \mathcal{R}} p_i^k[t]g_{im}^k[t] \leq \delta_{im}^k
\]

There is no difficulty to get the low bound of transmit power, i.e.,

\[
p_i^*[t] = \frac{-w}{e_i[t] \log 2} - \frac{\sum_{m \in \mathcal{M}_i} a_{in}^m[t]g_{im}^k[t]}{\sum_{m \in \mathcal{M}_i} a_{in}^m[t]},
\]

(21)

where, \( \xi_{im}^k = \delta_{im}^k \).

**IV. FAIR TIME-AVERAGED SUBCHANNEL ALLOCATION**

In this section, the subchannel allocation scheme is studied based on the method in [12]. Miao proposes a low complexity of subchannel allocation scheme in single cell with multi-users, however, the scheme can not be used in multi-cell scenario because of inter-cell interference.

Based on the above analysis, we introduce a distributed subchannel allocation scheme in femtocell networks, there are no informations interchange between FBSs. The maximization of the total energy-efficiency of all MSs in FBS \( b \) can be formulated as,

\[
\max \sum_{m \in \mathcal{M}_b} e_{im}^m[t],
\]

(22)

the energy efficiency of MS \( m \) in FBS \( b \) is,

\[
e_{im}^m[t] = \frac{(1-\lambda)T_{im}^m[t][1] + \lambda \sum_{k \in \mathcal{K}_m} a_{in}^m[t]R_{im}^m[k]}{(1-\lambda)P_{im}^m[t][1] + \lambda \sum_{k \in \mathcal{K}_m} p_i^k[t][1] + p_e}.
\]

(23)
Considering fairness, i.e. to avoid $e_m[t] = 0$, we introduce geometric average of the energy efficiency of all MSs in the FBS $b$, named subchannel allocation with fairness. Then problem (22) can be written as,

$$\max \sum_{m \in U_b} \log(e_m[t]).$$

(24)

At time $t$, since the value $e_m[t-1]$ is fixed, the solution of (24) is equal to,

$$\max \sum_{m \in U_b} \{\log(e_m[t]) - \log(e_m[t-1])\}.$$  

(25)

Substituted (23) into (25), if smoothing factor $\lambda$ in (23) is close to zero, the optimal object (25) can be simplified as,

$$\max \sum_{m \in U_b} \{\log(e_m[t]) - \log(e_m[t-1])\} = \max A_m(m,k),$$

(26)

where, $A_m(m,k) = \frac{K_{r_m}(t)p^m_k(t)}{\sum_{m \in U_b} K_{r_m}(t)p^m_k(t)} - \frac{K_{r_m}(t)}{\sum_{m \in U_b} K_{r_m}(t)}$, $p^m_k(t)$ is given by (21), where, $\xi^m_k = 0$ in sparsely deployed scenario; in densely deployed femtocell networks, $\xi^m_k = \delta^m_k$. $K_{r_m}(t)p^m_k(t)$ is the optimal data rate with respect to $p^m_k(t)$. The details of the derivation can be found in [7].

Since $T_{in}[t-1]$ and $P_{in}[t-1]$ are fixed, $A_m(m,k)$ is determined by $p^m_k(t)$. In this paper, we assume the information about $T_{in}[t-1]$ and $P_{in}[t-1]$ can be collected by femtocell base station, based on the subchannel allocation metric $A_m(m,k)$, FBSs will allocate subchannels to each user.

The subchannel $k \in K$ is allocated to the user $m$ in the FBS $b$, if the following condition is satisfied, for $\forall m \neq n(m,m \in U_b)$,

$$\alpha^m_k[t] = \begin{cases} 1, & \text{if } A_m(m,k) \geq A_n(m',k) \\ 0, & \text{otherwise} \end{cases}$$

(27)

V. DISTRIBUTED RESOURCE ALLOCATION ALGORITHM

In this section, we introduce a distributed suboptimal subchannel allocation and power control algorithm with low complexity. From (21) and (26), subchannel allocation metric $A_m(m,k)$ is determined by $\xi^m_k$, we will discuss the impact of different $\xi^m_k$ in subchannel allocation and power control.

Based on the above analysis, we firstly allocate power equally to each subchannel before subchannel allocation. Secondly, we propose a suboptimal subchannel allocation algorithm based on (27). Thirdly, given subchannels allocation, we give a distributed low complexity power control algorithm. The detailed process can be found in Algorithm 1.

Algorithm 1 is effective in both sparsely scenario and densely scenario, the difference is just whether $\xi^m_k = 0$ or not. In the following process, the variable $b$ is fixed.

**Initial:** Allocate FBS $b$’s transmit power equally to each subchannel.

**Step 1:** FBS $b$ allocates subchannels to MSs according to (27).

**Step 2:** For transmit power on each subchannel, FBS $b$ updates its strategy by (21).

**Step 3:** Update (8) and (23) for all MSs, respectively. Return to step 1 for the next frame.

VI. SIMULATION AND RESULTS ANALYSIS

In this section, we present simulations for the proposed algorithm. Round-Robin Scheduling (RRS) and a non-cooperative energy-efficient power optimization (NEEPO) algorithm [11] are also simulated for comparing with the proposed algorithm.

We use Monte Carlo method in the simulation process, and develop a MATLAB-based simulator to model the experience environment. In the simulation, $B$ femtocells are distributed randomly in a rectangular area, the topology of the network is shown in Fig. 1. The channel-fading is modeled as i.i.d Rayleigh random variables with mean variance of 1. The channel gain includes path loss, and antenna gain, except channel-fading. Table I shows the simulation parameters, where, $\mu = 2 \times 10^{-4}$ [21].

**TABLE I. SIMULATION PARAMETERS**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Femtocell radius $r$</td>
<td>10m</td>
</tr>
<tr>
<td>Carrier frequency $f_c$</td>
<td>2GHz</td>
</tr>
<tr>
<td>System bandwidth</td>
<td>2MHz</td>
</tr>
<tr>
<td>Subchannel number $N$</td>
<td>10</td>
</tr>
<tr>
<td>Maximum transmit power of $b$ $P_{max}$</td>
<td>20dBm</td>
</tr>
<tr>
<td>Circuit power $p_c$</td>
<td>10dBm</td>
</tr>
<tr>
<td>The channel gain for femto-user $\mu$</td>
<td>$\mu$</td>
</tr>
</tbody>
</table>

Fig. 2 Sum-rate of femtocell when $\lambda = 0.05$

Without loss of generality, $\xi^m_k$ will be replaced by $\xi$. We investigate the sum-rate of femtocell with respect to the number of users per femtocell. In this scenario, femtocells are deployed in the rectangular area.

In Fig. 2, the sum-rate increases versus the number of users, due to the fact that more users distributed in the femtocell base station, more efficient subchannel allocation made. From other perspective, the case of $\xi = 0mW$ has the largest sum-rate compared to the other
two cases when $\xi = -110 \text{dBm}, -90 \text{dBm}$. In conjunction with formula (21), the case $\xi = 0 \text{mW}$ has the largest transmit power, which acquires highest sum-rate correspondingly.

In Fig. 3, we investigate the average energy-efficiency per subchannel w. r. t. the value of $\xi$ when $\lambda = 0.05$. From formula (21), the larger $\xi$ will cause transmit power lower, and decrease the transmission rate; the smaller $\xi$ results in higher transmit power, and decrease energy efficiency. From Fig. 3, we can find that the value of energy efficiency is maximized when $\xi = -90 \text{dBm}$.

![Fig. 3 Average energy-efficiency per subchannel when $\lambda = 0.05$](image)

Fig. 3 Average energy-efficiency per subchannel when $\lambda = 0.05$

We investigate the system energy efficiency versus different $\lambda$ values. Fig. 4 shows the average energy efficiency per subchannel based on the allocated subchannels versus the number of FBSs. The MS number is 6 in each FBS and $\xi = -90 \text{dBm}$ in the simulation. For decreasing the complexity, compared with NEEPO which maximized the instant energy efficiency, the proposed NTPA scheme has a discount of energy efficiency. From Fig. 4, we find the lower value of $\lambda$ the closer approaching to NEEPO. The energy efficiency loss of NTPA is less than 5% when $\lambda = 0.05$.

![Fig. 4 Energy-efficiency based on allocated subchannel](image)

Fig. 4 Energy-efficiency based on allocated subchannel

FBSs are deployed in the system, more serious interference is generated. Compared with RRS and NEEPO, the energy efficiency loss of the proposed resource allocation algorithm is about 8% when $\lambda = 0.05$ and $\xi = -90 \text{dBm}$.

![Fig. 5 Average Energy-efficiency per Subchannel When $\lambda = 0.05$](image)

Fig. 5 Average Energy-efficiency per Subchannel When $\lambda = 0.05$

VII. CONCLUSIONS

In this paper, we have investigated the energy efficient resource allocation in DL femtocell networks. For low complexity, the joint subchannel allocation and power control problem is decomposed into two sub-problems. Firstly, based on exponentially-weighted low-pass filter, we obtain a close-form optimal transmit power in sparsely deployed scenario. In densely deployed femtocell scenario, the power control problem is modeled as a non-cooperative game, and a low-complex best response of power allocation is driven out. Secondly, a fair time-averaged subchannel allocation metric is acquired. At last, we propose a suboptimal subchannel allocation and distributed low-complex power control algorithm. Simulation results show that the proposed algorithm has a low complexity at the price of slight loss of energy efficiency compared with RRS and NEEPO. In the future, QoS-aware energy-efficient resource allocation in femtocell networks will be investigated.

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