Optimization of Energy Efficiency for OFDMA Femtocell Networks based on Effective Capacity

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Abstract—**This paper addresses how to improve the energy efficiency of OFDMA femtocell networks with sleep mode. Firstly, the energy consumption of the sleep mode is analyzed. Considering the requirements of improving the energy efficiency and ensuring the QoS of users, we extend the definition of effective capacity to formulate the tradeoff relationship between the energy efficiency and the waiting delay of users. Then two optimization schemes of sleep mode parameter are proposed: (1) Maximize the energy efficiency with effective capacity constraint; and (2) Maximize the effective capacity with energy efficiency constraint. And the performances are analyzed, including average energy efficiency, effective capacity and waiting time. Simulation results show that the effective capacity-based parameter optimization of sleep mode can achieve a good tradeoff between energy efficiency and QoS of users in OFDMA femtocell networks.**

Keywords- energy efficiency, femtocell networks, sleep mode, effective capacity

I. INTRODUCTION

With explosive increasing of communication traffic demand, the global information and communication technology (ICT) industry has consumed a fraction of the worldwide energy ranging between 2%-10% [1]. And the energy consumption of mobile networks is growing much faster than ICT on the whole. So, more and more researchers have focused on how to reduce the energy consumption and improve the energy efficiency of mobile networks.

The tradeoff relationship between energy efficiency and spectrum efficiency is discussed in cellular networks [2]. An effective approach based on cross-layer design and optimization was proposed to achieve energy saving in wireless communication systems [3]. It was found in [4] different deployment strategies have a significant impact on the energy consumption of cellular networks. A game-theoretic model is proposed to study the cross-layer problem of joint power and rate control with QoS support, and then derived a Nash equilibrium solution for the proposed non-cooperative game [5]. In addition, the impact of co-channel interference on energy efficiency of multi-cell cellular wireless networks was studied in [6] under a simple channel model.

Femtocell is consumer installed wireless data access point providing broadband coverage to indoor users, and potentially promises energy savings, since it reduces the required transmission power by shorten the propagation distance between nodes [7]. In order to cope with interference issues, orthogonal frequency division multiple access (OFDMA) femtocell is a more promising solution than code division multiple access (CDMA), mainly due to its robustness to multipath and channel variations in both frequency and time domains for the avoidance of interference [8]. However, the energy consumption of femtocell will become a pressing issue in the future. According to ABI Research, more than 36 million femtocells are expected to be sold worldwide by the end of year 2012. And the total energy consumption of all femtocells will be 3.784×109 kWh/annum (assuming 105.12 kWh/annum per femtocell) [9]. Thus, efficient methods are required to improve the energy efficiency of two-tier femtocell networks.

The power consumption of base station (BS) usually consists of two parts: static power consumption (or fixed site power), which is consumed already in an empty BS, and dynamic power consumption (or radiated power) depending on the load situation [10]. Wei W. et al. [11] analyzed the energy efficiency and area energy efficiency of two-tier networks with macro and pico cells. Similarly, H. Ying et al. [12] analyzed the relationships of power consumption, capacity and install rate of femtocells, and users' quality of service (QoS). Furthermore, some methods to optimize the energy efficiency of femtocell networks were also proposed, such as controlling *idle* or *sleep* mode behavior of femtocell by user activity detection [9], and grouping-based Low Duty Mode in IEEE 802.16m femtocell networks [13], and an energy efficient spectrum allocation strategy in marco-femto cellular networks to approach the minimal downlink energy consumption proposed in [14].

In the current standard of IEEE 802.16m [15], when the femto BS enters the operational state, it consists of normal mode and sleep mode, named as low duty operation (LDO) mode. In the normal mode, femto BS always becomes active on air interface by transmitting control messages (e.g. preambles) and data signal. The LDO scheme can effectively reduce the energy consumption of femto BS, but it may cause

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a long waiting delay for users to access the network if the related parameters are not configured reasonably. In this paper, the effective capacity theory is introduced to formulate the tradeoff relationship between the energy efficiency and the waiting delay of users. Then two optimization schemes of sleep mode parameters are proposed to achieve a good tradeoff between energy efficiency and the quality of service (QoS) in OFDMA femtocell networks: (1) Maximize the energy efficiency with effective capacity constraint; and (2) Maximize the effective capacity with energy efficiency constraint.

The reminder of this paper is organized as follows: Section II describes the system model and assumptions. In Section III the effective capacity-based parameter optimization of sleep mode is analyzed. Section IV gives the simulation results and performance analysis. And finally the concluding remarks are given in Section V.

II. SYSTEM MODEL AND ASSUMPTIONS

A. Energy consumption model

A femto BS can be turned off when it is not in operation, and this state is called a ''turn-off'' state and the femto BS in this state consumes E_1 of energy. Otherwise, when the femto BS is switched on, the radio part of it can be switched on or off. When the radio part is power off, the BS is called to be a ''radio-off'' state, and the total consumption of the BS is E_1+ E_2. Finally, when even the radio part is on, the BS is in a ''radio-on'' state and additional energy consumption due to the radio part is modeled as E_3. And the total power consumption of the BS is E_1+ E_2+ E_3.The term represents the utilization of radio resource allocated to BS ($0 \le \alpha \le 1$) and is given as

$$\alpha = \quad + (1 - \quad) \tag{1}$$

where denotes the portion of overhead, such as pilot signals, preambles, control signaling, feedback signaling, etc., and in this paper we assume = 0. 3. The term represents the utilization of data portion ($0 \le \gamma \le 1$). Contributing components to E_1, E_2, E_3 and their percentages to total energy consumption of a femto BS is given in Table I [16].

TABLE I. CONTRIBUTING COMPONENTS TO E_1, E_2, E_3 AND THEIR PERCENTAGES

Energy use	Contributing components	Percentage (%)
E_1	Power supply, cooling fans, central equipment, and cabling	38
E_2	Transceiver idling combining/duplexing	28
E_3	Power amplifier, transmit power , transceiver power	34

B. Sleep mode of femtocell networks

Femto BS may enter LDO mode if no MSs exist in its coverage, or if all MSs in the coverage are in sleep/idle mode [15]. In the LDO mode, femto BS changes alternately between available interval (AI) and unavailable interval (UAI) as shown in Fig. 1. During the UAI, femto BS becomes inactive on the air interface. During the AI, femto BS may become active on the air interface for synchronization and signalling purposes. To announce existence of femto BS to incoming users, it may transmit preambles during the AIs. The operation of LDO Mode is determined based on the pattern of Low Duty Cycle (LDC). The length of AI and UAI can be determined by the LDC pattern.

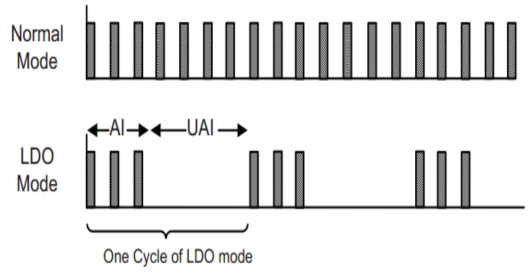

Figure 1. Normal and low duty mode operation for femtocell

The state transition of femto BS with sleep mode can be depicted in Fig. 2. The Normal mode, AI mode and UAI mode are presented as the three states S_1, S_2 and S_3, respectively. And the transition probability from the state S_i to the state S_j is denoted as P_{ij}.

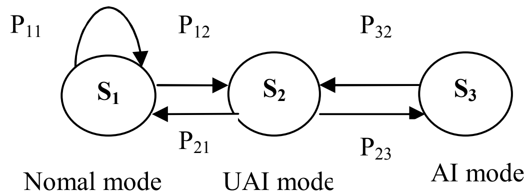

Figure 2. The state transition of femto BS with sleep mode

It is assumed that the service initiation procedure of users follows Poisson distribution with rate λ. Let t_a and t_b denote the duration time of UAI and AI, respectively. Then the probability that one femto BS is in "radio-on" state and "radio-off" state is calculated as

$$P_{11} = 1 - e^{-\lambda t_0} \tag{2}$$

$$P_{12} = -e^{-\lambda t_0} \tag{3}$$

$$P_{21} = 1 - e^{-\lambda t_a} \tag{4}$$

$$P_{23} = -e^{-\lambda t_a} \tag{5}$$

$$P_{32} = -e^{-\lambda t_b} \tag{6}$$

C. Network deployment

Considering the OFDMA femtocell networks with N femtocells, the available bandwidth W is divided into L orthogonal subchannels. And the signal to interference plus noise ratio (SINR) of femtocell user r scheduled on the n-th subchannel in femtocell i can be calculated as

$$\gamma_{i,n} = \frac{p_{i,n}\left|h_{ii,n}\right|^2}{\sum_{j\neq i} p_{j,n}\left|h_{ij,n}\right|^2 + \sigma^2} \tag{7}$$

where $h_{ij,n}$ denotes the channel frequency response on the n-th subchannel between femtocell user r and femtocell i and j, respectively. And $p_{i,n}$ denotes the transmission power of femtocell i on the n-th subchannel. σ^2 is the variance of Additive White Gaussian Noise (AWGN).

Then the achievable data rates for femtocell i is given by

$$R_i = W\sum_{n=1}^{L}\log_2(1+\gamma_{i,n}), 1 \le i \le N \tag{8}$$

III. EFFECTIVE CAPACITY-BASED PARAMETER OPTIMIZATION OF SLEEP MODE

A. Effective capacity theory

To facilitate the efficient support of QoS in next-generation wireless networks, it is essential to model wireless channel in terms of connection-level QoS metrics such as data rate, delay, and delay-violation probability. Effective capacity is introduced to analysis the resulted QoS providing of statistics time-delay [17]. And the definition of effective capacity is that: Let $\{S[k], k = 0,1,2,...,t\}$ denotes the service provided by the channel. Note that the channel service is different from the actual service received by the source; only depends on the instantaneous channel capacity. If the following limitation is existed, the effective capacity of stochastic decision process can be formulated as:

$$E_C(\theta) = \lim_{t\to\infty} -\frac{1}{\theta t}\log\left(E\left[e^{-\theta\sum_{k=1}^{t}S[k]}\right]\right), \theta > 0 \tag{9}$$

where θ is a constant quantity, named QoS Exponent. Obviously, if the stochastic sequence $\{S[k], k = 0,1,2,...\}$ is a non-related processing, the effective capacity can be formulated as:

$$E_C(\theta) = -\frac{1}{\theta}\log\left(E\left[e^{-\theta S[k]}\right]\right), \theta > 0 \tag{10}$$

B. Effective capacity-based sleep mode optimization

According to the energy consumption model in Section II, during the Normal mode, the femto BS is in "radio-on" state with data transmission, and the energy consumption is $N_1=E_1+E_2+E_3$; during the AI mode, the femto BS is in "radio-on" state without data transmission, and the energy consumption is $N_2=E_1+E_2+E_3$; during the UAI mode, the femto BS is in "radio-off" state, and the energy consumption is $N_3=E_1+E_2$. And the total energy consumption of femto BS in sleep mode can be formulated as

$$E_{total} = \frac{N_1(P_{11}+P_{21})t_0 + N_2(P_{12}+P_{32})t_a + N_3P_{23}t_b}{t_0+t_a+t_b} \tag{11}$$

Let $\overline{R}$ denote the average data rates during the time interval $T=t_0+t_a+t_b$. Then based on the definition in [11], the energy efficiency of femto BS with sleep mode is defined as

$$\delta = \overline{R} / E_{total} \tag{12}$$

Considering the requirements of improving the energy efficiency and ensuring the QoS of users, we extend the definition of effective capacity to formulate the tradeoff relationship between the energy efficiency and the waiting delay of users. And the extended definition of effective capacity is

$$E_C(t_a,\delta) = -\frac{1}{t_a}\log\left(e^{-t_a\delta}\right) \tag{13}$$

where t_a denotes the duration time of UAI. When the femto BS enters into the UAI, the users need to wait until the femto BS enters into the AI. So, t_a is the maximum waiting delay of the users. And δ still denotes the energy efficiency of one femto BS, and is defined by (12). According to the (13), we can see that the extended definition of effective capacity integrates the optimization objectives of energy efficiency and waiting delay of users.

Considering the distributed optimization manner, that is, each femtocell configures its parameters of sleep mode according to some objectives and constraints. For femtocell i in OFDMA femtocell networks, the parameter optimization problem of sleep mode can be modeled from two different aspects.

Problem A: **Maximize energy efficiency with effective capacity constraint (MEEwEC)**

$$\max_{t_a,t_b} \ \delta$$

$$s.t.\begin{cases} \delta = \overline{R} / E_{total} \\ E_C(t_a,\delta) = -\frac{1}{t_a}\log\left(e^{-t_a\delta}\right) \ge E_{th} \end{cases}$$

Problem B: **Maximize effective capacity with energy efficiency constraint (MECwEE)**

$$\max_{t_a,t_b} \ E_C(t_a,\delta)$$

$$s.t.\begin{cases} \delta = \overline{R} / E_{total} \ge \delta_{th} \\ E_C(t_a,\delta) = -\frac{1}{t_a}\log\left(e^{-t_a\delta}\right) \end{cases}$$

where E_{th} is the minimum effective capacity value for femtocell, and δ_{th} is the minimum energy efficiency value for femtocell.

Differential Evolution (DE) is a population-based stochastic evolutionary optimization algorithm to find a near-optimal solution for many fields where little knowledge is known or there are many conflicting constraints or objectives [18]. In this case, using DE can obtain the optimal parameter configuration for the sleep mode.

IV. Simulation and Performance Analysis

A. *Simulation assumptions and parameters*

We apply the system level simulation assumptions and parameters given in 3GPP specification [19]. The femtocell deployment method is modeled by Dual Strip Model. Fig. 3 depicts a block with two buildings. In our simulation, all users are uniformly dropped in the networks. The main system parameters are listed in Table II.

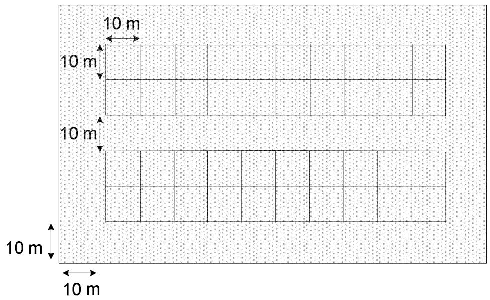

Figure 3. Dual Strip Model

TABLE II. System level simulation parameters

Parameters	Value
femtocell radius	30 meters
carrier frequency / bandwidth	2.0 GHz / 10 MHz
channel model	Typical Urban (TU)
transmission power of femtocell	20 dBm (0.1W)
maximum energy consumption of femtocell	12W
number of blocks per sector	1
number of floors per block	6
number of femtocells per apartment	1
maximum number of users per femtocell	4
traffic model	Full buffer
Thermal noise density (dBm/Hz)	174
Minimum energy efficiency threshold	0.3 Mbits/Joule
Minimum effective capacity threshold	1.0

B. *Simulation Results and Analysis*

In this section, we analyze the average energy efficiency, effective capacity and waiting time of two optimization scheme, including MEEwEC and MECwEE. As a comparison, the same simulation scenario is performed with all femtocells deployed with a fixed parameter configuration for sleep mode, t_a =100 ms and t_b=300 ms.

Based on the system assumptions, the average effective capacity per femtocell with different number of users is depicted in Fig. 4. It can be seen that, without sleep mode, the effective capacity of femtocell is very low, about 0.5; and for fixed sleep mode, the effective capacity is about 1.5 with 210 users in the networks; both of the MEEwEC and MECwEE can obtain a good performance of effective capacity, especially the MECwEE. The main reason is that, the effective capacity is depend on both the energy efficiency and waiting time of users. Though the waiting time is very short, the energy efficiency is also very bad without sleep mode.

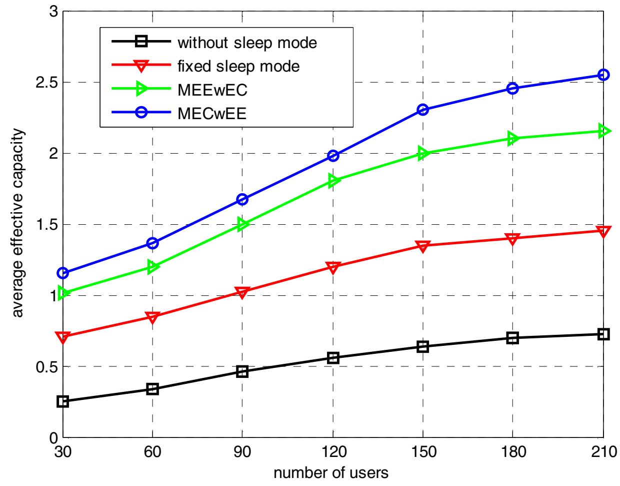

Figure 4. Average effective capacity per femtocell with different number of users.

Fig. 5 shows the average energy efficiency per femtocell with different number of users. As depicted in Fig. 5, the energy efficiency is very low without sleep mode, about 1.25 Mbits/Joule with 210 users in the networks. For the fixed sleep mode, the energy efficiency is about 1.5 Mbits/Joule with 210 users in the networks, and for the MEEwEC and MECwEE are about 2.3 Mbits/Joule and 1.9 Mbits/Joule, respectively. So, the sleep mode can effectively improve the energy efficiency of OFDMA femtocell networks, especially with proper parameter configuration.

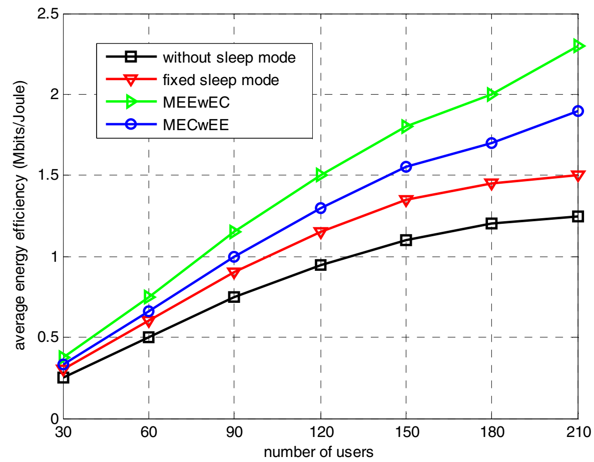

Figure 5. Average energy efficiency per femtocell with different number of users.

Fig. 6 shows the average waiting time per user with different number of users. As depicted in Fig. 6, the average waiting time of users is very low without sleep mode, about 2ms with 210 users in the networks. For the fixed sleep mode and the MEEwEC, the average waiting time of users is about 5ms, and for the MECwEE is about 3ms. So, the sleep mode may cause long waiting time of users if the parameter configuration is not reasonable.

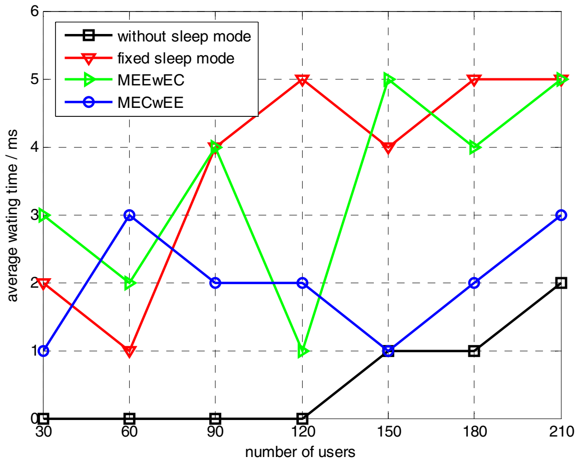

Figure 6. Average waiting time per user with different number of users.

V. CONCLUSIONS

This paper addresses how to improve the energy efficiency of OFDMA femtocell networks with sleep mode. Considering the requirements of improving the energy efficiency and ensuring the QoS of users, the definition of effective capacity is introduced to formulate the tradeoff relationship between the energy efficiency and the waiting delay of users. Then two optimization schemes of sleep mode parameter are proposed: (1) Maximize the energy efficiency with effective capacity constraint; (MEEwEC) and (2) Maximize the effective capacity with energy efficiency constraint (MECwEE). Simulation results show that both the MEEwEC and MECwEE can achieve a good tradeoff between energy efficiency and QoS of users in OFDMA femtocell networks. So, the results validate the effectiveness of the effective capacity-based parameter optimization of sleep mode.

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