ENERGY-EFFICIENT DOWNLINK TRANSMISSION WITH BASE STATION CLOSING IN SMALL CELL NETWORKS

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ABSTRACT

Shutdown of low traffic load base stations (BSs) is recognized as a promising approach to increase energy-efficiency (EE) and reduce total power consumption, especially for small cell networks (SCN). In this paper, we study BS closing strategies for downlink multi-antenna multi-carrier SCN supporting best effort traffics. We formulate the optimization problem of long-term BS closing, BS-user association and subcarrier allocation to maximize EE or minimize total power consumption under the constraints of average sum rate and rate proportion. We obtain an optimal solution for maximizing EE and a suboptimal solution for minimizing total power consumption. Simulation results show that the solutions provide substantial gain both in saving power consumption and increasing EE, and minimizing the total power consumption will not lead to the maximal EE.

1. INTRODUCTION

Energy-efficiency (EE) is becoming an important design goal for cellular networks except for spectrum efficiency (SE) [1]. Statistical results in mobile communications show that over 80% of the power is consumed by base stations (BSs) [2], and about 60% of the power consumed at each BS is taken up by processing circuits and air conditioning [3].

As a result, shutting down the BSs without active users is expected as an efficient way to reduce network power consumption [4, 5]. This is practically possible because the deployment of existing cellular networks, usually optimized for fully loaded traffics, leads to very inefficient usage of BSs during off-peak time. Moreover, the daily traffic variation due to user mobility and activities is predictable, which indicates that BS closing strategies can operate on a long-term time scale, e.g., in hours. Several BS closing schemes based on traffic load and channel conditions were studied, e.g., [6].

Small cell networks (SCNs) are gaining wide popularity to improve both SE and EE [7]. On one hand, dividing a large (Macro) cell into a number of small (Pico) cells bring the users closer to the BSs, which is one of the most effective ways to increase the network capacity. On the other hand, the idle BSs can be shut down to reduce power consumption.

To achieve high EE or low power consumption while ensuring the required performance of a particular system, the traffic feature should be considered. For best effort traffics, the requirement is to maximize the sum rate and to ensure the fairness in data rates among multiple users.

In this paper, we investigate BS closing strategies for multi-input-multi-output (MIMO)-orthogonal frequency duplex multiple access (OFDMA). We consider downlink SCN supporting best effort traffics. We formulate the problem of BSs closing, BS-user association and subcarrier allocation toward different optimization objective functions, maximize EE and minimize total power consumption, ensuring minimal average sum rate requirement and proportional rate fairness. The total power includes the circuit power and transmit power. We obtain an optimal solution for maximizing EE. Considering that the problem to minimize total power consumption is intractable for large scale networks, we resort to sparse optimization [8] to find a suboptimal solution.

2. SYSTEM AND POWER CONSUMPTION MODEL

2.1. System Model

Consider a downlink MIMO-OFDMA SCN, where B low power BSs each equipped with N_t antennas are deployed to serve M single-antenna users in the network without coordination. When a BS serves multiple users, L subcarriers are shared without overlapping. Denote $\mathbf{g}_{mb,j} = \sqrt{\alpha_{mb}}\mathbf{h}_{mb,j}$ as the channel vector between BS_b and user m at the jth subcarrier, where α_{mb} is the large scale fading gain including path loss and shadowing, $\mathbf{h}_{mb,j} \in \mathcal{C}^{N_t \times 1}$ is the small scale fading channel vector. Entries of different subcarriers channel vector are assumed independent and identically distributed (i.i.d.). We assume perfect instantaneous channel state information (CSI) is available at each active BS and the BS transmits to the user with maximal-ratio transmission (MRT) precoding.

Since a large portion of power is consumed by the circuits of active BSs, our main concern is how to save energy by closing unnecessary BSs. In SCN, the BSs transmit with low

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power, the idle BSs are closed, and user distribution is sparse [9]. This leads to negligible inter-cell interference and the scenario is noise limited. Then, if user m is served by BS$_b$, the average data rate can be expressed as

$$R_m = \Delta f \sum_{j=1}^{k_{mb}} \mathbb{E}\{\log_2(1+\frac{P\alpha_{mb}}{\sigma^2}\|\mathbf{h}_{mb,j}\|^2)\} \quad (1)$$
$$= k_{mb}\Delta f \mathbb{E}\{\log_2(1+\frac{P\alpha_{mb}}{\sigma^2}\|\mathbf{h}_{mb,1}\|^2)\} = k_{mb}\Delta f \bar{r}_{mb},$$

where Δf is the subcarrier spacing, k_{mb} is the number of subcarriers occupied by user m. We assume equal power allocation across all the subcarriers, P and σ^2 are respectively the transmit power and noise power at each subcarrier, $\bar{r}_{mb}$ denotes the average SE of user m.

2.2. Power Consumption Model

A typical power consumption model for low power BSs such as pico and femto cells is provided in [9]. The total power consumed by a BS consists of transmit power and circuit power. Denote η as the efficiency of the power amplifier. Then, the transmit power consumption of BS$_b$ is $P_{tr}^b = \frac{P}{\eta}\sum_{m\in\mathcal{S}_b} k_{mb}$. Besides a fixed circuit power consumption to maintain the operation of the BS, circuit power consumed for signal prossing depends on the number of subcarriers, i.e., $P_{sp}^b = p_{sp}\sum_{m\in\mathcal{S}_b} k_{mb}$, where p_{sp} is the signal processing power consumption of each subcarrier.

The total power consumption at BS$_b$ is modeled as,

$$P_{tot}^b = P_{tr}^b + P_{sp}^b + P_c^b, b = 1, \cdots B, \quad (2)$$

where P_c^b is the fixed circuit power consumption of the BS, and can be modeled by a piecewise function as

$$P_c^b = \begin{cases} P_{ca} & \text{if BS}_b \text{ is active,} \\ 0 & \text{if BS}_b \text{ is closed.} \end{cases}$$

3. BS CLOSING STRATEGIES

In this section, we study BS closing strategies for best effort traffics. We optimize the BS closing pattern, user access, and the subcarrier allocation of active BSs that maximize the EE and minimize the total power consumption under the constraint of a minimal average sum rate and rate fairness.

3.1. EE Maximization

Define BS-user association vectors $\mathbf{w}_m \in \{0,1\}^{B\times 1}$, whose bth entry w_{mb} is 1 if user m is connected to BS$_b$ and 0 otherwise. Then, the total power consumption in the SCN can be expressed as

$$P_{tot}(\{\mathbf{w}_i,\mathbf{k}_i\}_{i=1}^M)$$
$$= P_{ca}\sum_{b=1}^{B}\|\mathbf{e}_b^T\sum_{m=1}^{M}\mathbf{w}_m\|_0 + (\frac{P}{\eta}+p_{sp})\sum_{m=1}^{M}\mathbf{k}_m^T\mathbf{w}_m \quad (3)$$

where $\|\cdot\|_0$ denotes l_0-norm, $\mathbf{e}_b$ is a vector of zeros except that its bth entry is one, $\mathbf{k}_m \in \mathbb{R}^{B\times 1}$ whose bth entry is k_{mb}. Then, $\mathbf{e}_b^T\sum_{m=1}^M \mathbf{w}_m$ indicates the number of users connected to BS$_b$, and $\|\mathbf{e}_b^T\sum_{m=1}^M \mathbf{w}_m\|_0 = 1$ indicates that BS$_b$ is active while $\|\mathbf{e}_b^T\sum_{m=1}^M \mathbf{w}_m\|_0 = 0$ indicates it is idle and should be closed. Define the EE as

$$EE(\{\mathbf{w}_i,\mathbf{k}_i\}_{i=1}^M) = \frac{R_{sum}}{P_{tot}(\{\mathbf{w}_i,\mathbf{k}_i\}_{i=1}^M)}, \quad (4)$$

where $R_{sum} = \sum_{m=1}^M R_m$ is the sum rate.

To support best effort traffics for users, we formulate the optimization problem of BS closing, BS-user association and subcarrier allocation to maximize the EE under the constraints of minimal average sum rate and user rate fairness as follows

$$\max_{\{\mathbf{w}_i,\mathbf{k}_i\}_{i=1}^M} \quad EE(\{\mathbf{w}_i,\mathbf{k}_i\}_{i=1}^M) \quad (5a)$$
$$s.t. \quad R_{sum} \geq R_{min} \quad (5b)$$
$$R_m = \beta_m R_{sum} \quad 1\leq m\leq M \quad (5c)$$
$$\sum_{m=1}^M \mathbf{e}_b^T\mathbf{k}_m\cdot\mathbf{e}_b^T\mathbf{w}_m \leq L, 1\leq b\leq B \quad (5d)$$
$$\mathbf{1}^T\mathbf{w}_m = 1, \quad 1\leq m\leq M \quad (5e)$$
$$w_{mb} = 0 \,\text{or}\, 1, 1\leq m\leq M, 1\leq b\leq B \quad (5f)$$

where the fairness factor β_i is a positive real number and $\sum_{i=1}^M \beta_i = 1$, which ensures the fairness among the active users with a data rate proportion as in [10], (5d) ensures that each BS can at most allocate L subcarriers, i.e., $\sum_{m\in\mathcal{S}_b} k_{mb} \leq L$, $\mathbf{1}$ is a vector of one, and (5e) ensures each user to be connected to a single BS.

For given BS-user association vectors $\{\mathbf{w}_i\}_{i=1}^M$, constraint of (5c) leads to the following long-term subcarrier allocation for the active BSs: $k_{mb} = \lceil\frac{\beta_m R_{sum}}{\Delta f \bar{r}_{mb}}\rceil$. By ignoring the impact of ceil operation, the number of subcarriers is a linear function of the sum rate R_{sum}. Moreover, the first term of (3) is a constant, and the second term is a linear function of R_{sum}. Then, (4) can be rewritten as

$$EE = \frac{R_{sum}}{P_c^I + \kappa R_{sum}} = \frac{1}{\kappa} - \frac{P_c^I}{\kappa P_c^I + \kappa^2 R_{sum}}, \quad (6)$$

where $P_c^I = P_{ca}\sum_{b=1}^B \|\mathbf{e}_b^T\sum_{m=1}^M \mathbf{w}_m\|_0$ and $\kappa = (\frac{P}{\eta} + p_{sp})\sum_{m=1}^M\sum_{b=1}^B \frac{\beta_m}{\Delta f \bar{r}_{mb}} w_{mb}$ does not depend on R_{sum}. Therefore, EE is an increasing function of R_{sum}. It implies that in order to maximize the EE, the average sum rate (i.e., SE) should achieve the maximal value. This suggests that each active BS should employ available subcarriers as many as possible to serve the users connected to it.

We consider sparse user distribution and $B \gg M$. The solution of problem (5) is as follows: all the users should connect to their local BSs with strongest average receive signals, the idle BSs without users are closed, and at least one active BS allocates all the subcarriers to serve the user accessed to it, other active BSs allocate subcarriers according to (5c).

3.2. Total Power Minimization

The BS closing strategy maximizing the EE does not necessarily lead to the minimization of the total power consumption. In realistic systems, we need to reduce the total power consumption. When the equality in (5b) holds, the total power consumption will achieve the minimal. Further considering (5c), the two constraints of (5b) and (5c) lead to the following long-term subcarrier allocation for the active BSs: $k_{mb} = \lceil \frac{\beta_m R_{min}}{\Delta f \bar{r}_{mb}} \rceil$. Then, the optimization problem of BS closing and BS-user association to minimize the total power consumption under the constraints of minimal average sum rate and fairness can be formulated as

$$\begin{aligned} \min_{\{\mathbf{w}_i\}_{i=1}^M} \quad & P_{tot}(\{\mathbf{w}_i\}_{i=1}^M) \\ s.t. \quad & (5d), (5e), (5f). \end{aligned} \tag{7}$$

We introduce sparse concave relaxation to solve this problem. A standard approach to solve the sparse optimization problem is to relax the l_0-norm in objective function. The following relation for any given scalar $a > 0$ is given in [8], $\|a\|_0 = \lim_{\epsilon \to 0} \frac{\ln(1+a\epsilon^{-1})}{\ln(1+\epsilon^{-1})}$. We ignore the limit and relax the l_0-norm as follows

$$\|a\|_0 \approx \frac{\mu \ln(1 + a\theta^{-1})}{\ln(1 + \theta^{-1})}, \tag{8}$$

where $\theta > 0$ is a small constant, $\mu \in (0, 1]$ is a parameter to control the accuracy of the approximation.

By using (8), relaxing the binary integer constraints (5f) and normalizing the coefficient, problem (7) becomes

$$\begin{aligned} \min_{\{\mathbf{w}_i\}_{i=1}^M} \quad & f(\{\mathbf{w}_i\}_{i=1}^M) \triangleq \sum_{b=1}^{B} \ln(1 + \mathbf{e}_b^T \sum_{m=1}^{M} \mathbf{w}_m \theta^{-1}) \\ & \quad + \lambda \sum_{m=1}^{M} \mathbf{k}_m^T \mathbf{w}_m && (9a) \\ s.t. \quad & (5d), (5e), \\ & 0 \le w_{mb} \le 1, 1 \le m \le M, 1 \le b \le B, && (9b) \end{aligned}$$

where $\lambda = (\frac{P}{\eta} + p_{sp}) \ln(1 + \theta^{-1})/(\mu P_{ca})$.

The objective function is concave and differentiable. We can use the majorization-minimization (MM) algorithm [11] to find a sequence of vectors $\{\mathbf{w}_i^{(n)}\}_{i=1}^M$ such that $f(\{\mathbf{w}_i^{(n+1)}\}_{i=1}^M) \le f(\{\mathbf{w}_i^{(n)}\}_{i=1}^M)$. Denote

$$\begin{aligned} & g(\{\mathbf{w}_i\}_{i=1}^M, \{\mathbf{w}_i^{(n)}\}_{i=1}^M) = f(\{\mathbf{w}_i^{(n)}\}_{i=1}^M) \\ & + \sum_{i=1}^{M} (\mathbf{w}_i - \mathbf{w}_i^{(n)})^T \frac{\partial f(\{\mathbf{w}_i^{(n)}\}_{i=1}^M)}{\partial \mathbf{w}_i^{(n)}}, \end{aligned} \tag{10}$$

as the majorizing function used by the MM algorithm, where

$$\frac{\partial f(\{\mathbf{w}_i^{(n)}\}_{i=1}^M)}{\partial \mathbf{w}_i^{(n)}} = \sum_{b=1}^{B} \frac{\mathbf{e}_b}{\theta + \mathbf{e}_b^T \sum_{m=1}^{M} \mathbf{w}_m^{(n)}} + \lambda \mathbf{k}_i. \tag{11}$$

During the iteration, $\mathbf{w}^{(n+1)}$ can be obtained by solving the following problem

$$\begin{aligned} \min_{\mathbf{w}} \quad & g(\{\mathbf{w}_i\}_{i=1}^M, \{\mathbf{w}_i^{(n)}\}_{i=1}^M) && (12a) \\ s.t. \quad & \sum_{b=1}^{B} (\|\mathbf{e}_b^T \sum_{i=1}^{M} \mathbf{w}_i\|_0 - \|\mathbf{e}_b^T \sum_{i=1}^{M} \mathbf{w}_i^{(n)}\|_0)^2 \le 1, && (12b) \\ & (5d), (5e), (9b), \end{aligned}$$

where constraint (12b) ensures that in each iteration, at most one BS can change its operation mode.

To solve problem (12) without loss of optimality, we first solve the problem for a given BS whose mode has changed, which is a linear programming problem and can be solved efficiently. Next, we find which BS should change mode by exhaustive searching. We terminate the algorithm when $f(\{\mathbf{w}_i^{(n)}\}_{i=1}^M) - f(\{\mathbf{w}_i^{(n+1)}\}_{i=1}^M) < \varepsilon$, and obtain the suboptimal solution $\{\mathbf{w}_i^{\star}\}_{i=1}^M)$, where $\varepsilon > 0$ is a small value. It is not hard to prove the monotonicity and boundedness of $f(\{\mathbf{w}_i^{(n)}\}_{i=1}^M)$, then the algorithm is convergent.

Due to the relaxing of (5f), some entries of $\{\mathbf{w}_i^{\star}\}_{i=1}^M)$ are not integers. We map the entries onto binary integers in the following way. First, we connect user m to BS_b if $w_{mb} = 1$. Then, for the remaining users, say, user j, it is assigned to BS_i if w_{ji} is the largest entry less than 1 and BS_i still has subcarriers not yet allocated, $j \neq m$, $i \neq b$. If a user can not be assigned to any active BS, the nearest BS should be activated to serve the user.

The initialization of the MM algorithm is crucial to the performance. We find the initial value by searching as follows. For all values of $\mathbf{w}^{(0)}$ that ensure the number of active BSs less than B_0, compare all corresponding suboptimal solutions and select one with minimal total power consumption.

We refer to such an algorithm to find the solution of BS closing, BS-user association and subcarrier allocation toward total power minimization as suboptimal BS closing method.

4. SIMULATION RESULTS

In this section, we evaluate the power consumption and EE of the two BS closing methods.

The simulation setup is based on the parameters of a pico cell setup in [9]. The SCN includes 19 (three-tier) small cells. The radius of small cells is 50 m. $N_t = 2$, $L = 1024$, and $\Delta f = 15$ kHz. $\eta = 8.0\%$, $p_{sp} = 0.4$ mW, $P_{c,a}$ is either 2.2 W or 4 W [12]. Two propagation models are considered, and 10 m is the transition distance. In short-or long-range model, the large-scale fading model is $38.5 + 20 \log d$ (dB) [13] or $30.6 + 36.7 \log d$ (dB) [14]. The standard deviation of shadowing is 6 dB. When a BS is active, the transmit power is 21 dBm. To compare with the optimal solution of problem (7) obtained by exhaustive searching that is of high complexity, we set 5 users in the SCN. In the concave relaxation, $\theta = 0.1$ and $\mu = \theta \ln(1 + \theta^{-1}) = 0.24$, but the performance is not sensitive to these parameters. In the MM algorithm, $\varepsilon = 0.1$ and $B_0 = 2$. All the simulation results are obtained by averaging over 100 realizations of small scale fading channels and 100 random locations of the users.

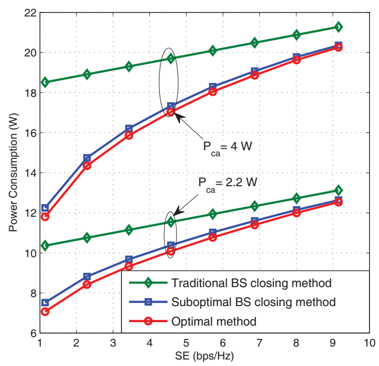

Fig. 1. Total power consumptions versus SE. SE^{EE} = 23 bps/Hz, P_{tot}^{EE} = 19 W for 2.2 W, and P_{tot}^{EE} = 28 W for 4 W.

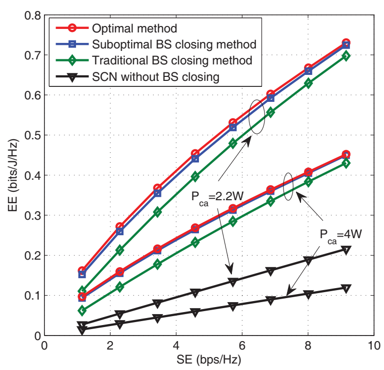

Fig. 2. EE versus SE. SE^{EE} = 23 bps/Hz, EE^{EE} = 1.2 bits/J/Hz for 2.2 W, and EE^{EE} = 0.8 bits/J/Hz for 4 W.

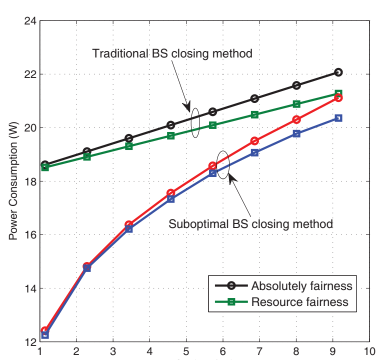

Fig. 3. Impact of fairness on total power consumption.

In Fig. 1, we compare the total power consumptions of the following strategies: 1) traditional BS closing method, where all the users connect to their local BSs, the idle BSs are closed, and each active BS allocates the subcarriers to ensure the required average data rate of each user, 2) suboptimal BS closing method, 3) optimal solution of problem (7), which is obtained by exhaustive searching, and 4) optimal solution of problem (5), whose performance is SE^{EE}, P_{tot}^{EE} and EE^{EE}. We can see that the optimization aiming at maximizing EE does not provide the minimal total power consumption. For the strategy that minimizes the total power consumption, the suboptimal method is very close to the optimal solution. Comparing the suboptimal method with the traditional method, the gain in saving power increases with the circuit power of the active BS, and decreases with the growing of the SE. This is because the gain comes from closing unnecessary BSs. When the SE is high, the suboptimal method has little gain because each BS does not have enough subcarriers to serve the users that are close to its adjacent BSs.

In Fig. 2, we compare the EE of the above-mentioned three strategies with that of the SCN without BS closing. A significant gain in EE is obtained by closing a large number of BSs that do not serve users. We can also see that in all of the scenarios, a high SE requirement leads to a high EE. Comparing the suboptimal method with the traditional BS closing method, the gain in saving power is more pronounced than the gain in EE for the low SE region. This is because the optimization to minimize the power consumption is subject to a given sum rate requirement but the optimization to maximize the EE is subject to a minimal sum rate requirement, such that the power consumption gain is more sensitive to SE.

In Fig. 3, we show the impact of fairness. We consider absolutely fairness ($\beta_i = 1/M$) and resource fairness (i.e., $\beta_i = \bar{r}_{ib_i} / \sum_{m=1}^{M} \bar{r}_{mb_m}$), which implies that cell center users obtain a higher rate while cell edge user obtains lower rate. We can see that different kinds of fairness have minor impact when SE is low, because the circuit power is dominant. When SE is high, absolutely fairness requires more power consumption than resource fairness, because the cell edge users with absolutely fairness needs more transmit power.

5. CONCLUSION

We have studied two methods for BS closing, user access and subcarrier allocation strategies to maximize EE and to minimize total power consumption. We found the optimal solution for the EE maximization problem, and proposed a suboptimal solution for the total power minimization problem. Simulation results show both strategies have significant gains in saving power and increasing EE over traditional BS closing scheme especially at low SE region. The proposed strategy toward power minimization consumes much less power than the strategy toward EE maximization. Fairness has minor impact when SE is low, while absolutely fairness consumes more power than resource fairness when SE is high.

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