TRAFFIC-AWARE BASE STATION DOZE IN COOPERATIVE MULTICELL SYSTEMS

Shengqian Han, Chenyang Yang*, and Andreas F. Molisch†*

* School of Electronics and Information Engineering, Beihang University, Beijing, China
E-mail: sqhan@ee.buaa.edu.cn; cyyang@buaa.edu.cn
† Ming Hsieh Department of Electrical Engineering, University of Southern California, LA, USA
E-mail: molisch@usc.edu

ABSTRACT

In this paper a traffic-aware mechanism, named *cooperative base station (BS) doze*, is introduced and optimized, aimed at exploring the potential of a high spectrum efficiency (SE) technology, coordinated multi-point (CoMP) transmission, for improving energy efficiency (EE) of downlink cellular networks. The key idea is to allow BS idling by exploiting the delay tolerance of some users, and to increase the opportunity of the idling by using CoMP transmission. The cooperative BS doze strategy involves BS time-slot doze pattern, and multicell user scheduling and cooperative precoding, which are jointly optimized in a unified framework. Simulation results demonstrate the substantial EE gain of cooperative BS doze over Non-CoMP BS doze.

***Index Terms*—** Energy efficiency, base station doze, coordinated multi-point (CoMP).

1. INTRODUCTION

In the past years, energy efficiency (EE) has become an important design goal for cellular networks in addition to spectrum efficiency (SE) [1]. It has been widely recognized that SE can be effectively improved by coordinated multi-point (CoMP) transmission, [2]. However, since CoMP transmission requires considerably larger signal processing and backhauling energy consumptions than Non-CoMP [3], its high SE does not necessarily lead to a high EE.

Nonetheless, CoMP transmission has the potential for improving the EE. On one hand, the increased SE can shorten the transmission time to ensure the quality of service (QoS) requirements of users, which reduces the circuitry energy consumption. On the other hand, sharing data and channel state information (CSI) among coordinated BSs provides CoMP systems a large spatio-temporal resource pool, which can be allocated flexibly to save energy while accommodating various traffics in the network and various QoS requirements.

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To improve the EE without sacrificing QoS, exploiting the spatial and temporal fluctuation of the traffic is an essential principle [4]. One example of the traffic-aware mechanism is *BS doze*, which is also known as BS micro-sleep [5]. The basic idea behind BS doze to improve the EE is to provide *on demand* service. In particular, within the delay tolerance, the BS can aggregate data and transmit them with high rate during a part of the time slots, while remaining in idle mode during other time slots to save circuitry energy.

CoMP transmission and delay tolerant traffics have been separately considered to reduce energy consumption in the literature. The EE of CoMP transmission was evaluated in [3], which showed that the benefits of CoMP depend on the extra power consumption from the complicated signal processing and the increased backhaul traffic. CoMP assisted BS sleep was studied in [6] and [7]. CoMP assisted BS doze was investigated in [8], where the extra power consumption led by cooperative processing and backhauling was not considered. When accounting for delay tolerant traffics, transmission and idle time allocation was optimized respectively for sensor networks in [9] and for relay networks in [10].

In this paper, we summarize our recent investigations [11] of an energy-efficient transmission scheme, named *cooperative BS doze*, which employs BS idling to improve the EE, and employs CoMP to increase the opportunity of BS idling. The BS time-slot doze pattern, and multicell cooperative scheduling and precoding are jointly optimized in a unified framework, aimed at maximizing the network EE under per-user time-average rate constraints to meet the data rate and delay tolerance requirements of all users. We develop a hierarchical iterative algorithm to efficiently find a solution of the joint optimization problem. Simulation results using practical power consumption parameters show that cooperative BS doze can provide substantial EE gain over Non-CoMP BS doze.

2. SYSTEM AND POWER CONSUMPTION MODEL

2.1. System Model

Consider a universal frequency reuse downlink CoMP cluster consisting of L cooperative cells each including an

M-antenna BS. The radio resources are divided into a number of orthogonal time-frequency resource blocks (RBs), each including T time slots and with W Hz bandwidth. Within each RB, multi-user multi-input multi-output (MU-MIMO) precoding is employed to serve K single antenna users located in the L cells.

Consider that the users have different QoS requirements, which are characterized by packet delay and packet size. For the k-th user (denoted by MS_k), assume its packet delay as T_k time slots, within which it needs to successfully receive B_k bits of information. These two QoS requirements together can be represented by a *time-average data rate constraint* for MS_k during the T_k time slots. In contrast to an instantaneous data rate constraint, such a constraint allows BS doze. The values of T_k and B_k depend on the application type of MS_k.

We assume block and flat fading channel within each RB, and assume perfect sharing of data and channel information among the coordinated BSs. Denote $\mathbf{h}_{kb} \in \mathbb{C}^{M\times 1}$ as the composite channel from BS_b to MS_k, which is comprised of both large-scale and small-scale fading channels. Then the global channel of MS_k from all coordinated BSs can be expressed as $\mathbf{h}_k = [\mathbf{h}_{k1}^T, \ldots, \mathbf{h}_{kL}^T]^T$. We consider linear precoding, which provides good performance with low complexity. Denote $\mathbf{w}_{kt} = [\mathbf{w}_{kt,1}^T, \ldots, \mathbf{w}_{kt,L}^T]^T$ as the precoding vector for MS_k in the t-th time slot, where $\mathbf{w}_{kt,b} \in \mathbb{C}^{M\times 1}$ represents the precoder of MS_k at BS_b. Then the signal received at MS_k in the t-th time slot can be expressed as

$$y_{kt} = \underbrace{\mathbf{h}_k^H \mathbf{w}_{kt} x_{kt}}_{\text{desired signal}} + \underbrace{\mathbf{h}_k^H \sum_{j=1,j\neq k}^{K} \mathbf{w}_{jt} x_{jt}}_{\text{inter-user interference}} + z_{kt}, \quad (1)$$

where x_{kt} is the data symbol for MS_k in the t-th time slot with $\mathbb{E}\{|x_{kt}|^2\} = 1$, and z_{kt} is the additive white Gaussian noise (AWGN) with zero mean and variance σ^2.

When we treat the inter-user interference as white noise, the instantaneous achievable data rate of MS_k in the t-th time slot is $R_{kt} = \log_2(1 + \text{SINR}_{kt})$, where SINR_{kt} denotes the signal-to-interference plus noise ratio (SINR), defined as

$$\text{SINR}_{kt} = \frac{|\mathbf{h}_k^H \mathbf{w}_{kt}|^2}{\sum_{j\neq k} |\mathbf{h}_k^H \mathbf{w}_{jt}|^2 + \sigma^2}. \quad (2)$$

2.2. Power Consumption Model

A typical power consumption model for currently deployed BSs is presented in [1], which reflects the impact of power amplifier, radio frequency (RF) circuit, baseband processor, power supply and battery backup, and cooling. To capture the features of CoMP transmission, this model is extended similar to [3] as follows,

$$P_{\text{BS}}^{b,t} = aP_{\text{tx}}^{b,t} + P_{\text{sp}}^{b,t} + P_{\text{cc}}^{b,t} + P_{\text{bh}}^{b,t}, \quad (3)$$

where $P_{\text{BS}}^{b,t}$ is the total power consumption of BS_b in the t-th time slot, $P_{\text{tx}}^{b,t}$, $P_{\text{sp}}^{b,t}$, $P_{\text{cc}}^{b,t}$ and $P_{\text{bh}}^{b,t}$ denote the transmit power, the signal processing power, the circuitry power and the backhauling power in the t-th time slot, respectively, and the factor a reflects the impact of power amplifier, cooling, power supply and battery backup.

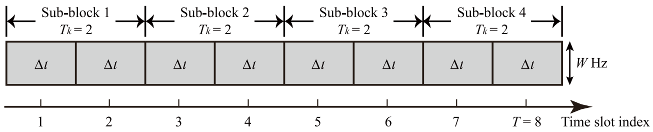

Fig. 1. Illustration of delay tolerance related parameters for MS_k with $T = 8$, $T_k = 2$, $G_k = 4$, and $\mathcal{S}_{k3} = \{5, 6\}$.

The transmit power of BS_b in the t-th time slot can be expressed as

$$P_{\text{tx}}^{b,t} = \sum_{k=1}^{K} \|\mathbf{w}_{kt,b}\|^2. \quad (4)$$

The signal processing power is modeled as

$$P_{\text{sp}}^{b,t} = p_{\text{sp,c}} L + p_{\text{sp,p}} L^2, \quad (5)$$

where $p_{\text{sp,c}} L$ and $p_{\text{sp,p}} L^2$ respectively denote the fraction of power consumption due to CoMP channel estimation and MU-MIMO precoding, both of which increase with the cluster size.

The backhauling power consumption comes from sharing channel and data among BSs. Considering the fact that the backhaul capacity required for channel sharing is negligible compared with data sharing under moderate Doppler speeds [12], we only take the power consumption for data sharing into account. Then the backhauling power consumption is modeled as

$$P_{\text{bh}}^{b,t} = \frac{\rho_D^{b,t}}{C_{\text{bh}}} p_{\text{bh}}, \quad (6)$$

where p_{bh} denotes the power consumption of the backhaul equipment under the maximum rate C_{bh}, and $\rho_D^{b,t}$ denotes the backhaul traffic in the t-th time slot due to data sharing for BS_b.

The circuitry power depends on the BS's operation modes, including the active mode when there is a signal to transmit and the idle mode when there is nothing to transmit [1]. The operation mode of a BS can be identified by examining its transmit power. Thus the circuitry power can be modeled as

$$P_{\text{cc}}^{b,t} = \delta_P \text{sign}(P_{\text{tx}}^{b,t}) + P_{\text{cc},i}, \quad (7)$$

where $\delta_P = P_{\text{cc},a} - P_{\text{cc},i}$, and $P_{\text{cc},i}$ and $P_{\text{cc},a}$ respectively denote the circuitry power in idle and active modes.

3. OPTIMIZATION OF COOPERATIVE BS DOZE

3.1. Problem Formulation

We define the EE as the ratio of total number of bits transmitted to all users to total energy consumed by all BSs in a

$$EE = \frac{B_{\text{total}}}{E_{\text{total}}} = \frac{W \cdot SE}{\frac{a}{T}\sum_{t=1}^{T}\sum_{k=1}^{K}\|\mathbf{w}_{kt}\|^2 + \left(p_{\text{sp,c}}L^2 + p_{\text{sp,p}}L^3\right) + \frac{1}{T}\sum_{t=1}^{T}\sum_{b=1}^{L}P_{\text{cc}}^{b,t} + \frac{Wp_{\text{bh}}}{C_{\text{bh}}}\sum_{b=1}^{L}\sum_{k\in\mathcal{U}_b}SE_k}. \tag{10}$$

RB. For notational simplicity, we assume that the time interval of a RB, T, is an integer multiple of T_k so that each RB can be divided into G_k sub-blocks for MS_k in time domain, where $G_k = \frac{T}{T_k}$, as illustrated in Fig. 1. Within each sub-block, B_k bits need to be delivered. Therefore, the total number of bits to be transmitted in a RB can be obtained as

$$B_{\text{total}} = \textstyle\sum_{k=1}^{K} G_k B_k. \tag{8}$$

This translates to the QoS constraint of MS_k in each sub-block

$$\textstyle\sum_{t\in\mathcal{S}_{kg}} W\Delta_t R_{kt} = B_k, \ \ g = 1,\ldots,G_k, \tag{9}$$

where $\mathcal{S}_{kg}$ denotes the index set of time slots in the g-th sub-block for MS_k, $|\mathcal{S}_{kg}| = T_k$, Δ_t is the duration of each time slot, R_{kt} is the data rate in the t-th time slot, and $|\mathcal{S}|$ denotes the cardinality of a set $\mathcal{S}$. Note that R_{kt} can vary for different time slots, because the number of the cooperative BSs who are active in the time slots may differ.

Further, according to the power consumption model in Section 2.2, we can obtain the network EE as (10) at the top of this page, where the per-RB SE of MS_k and the total per-RB SE of the system are respectively defined as

$$SE_k = \frac{G_k B_k}{WT\Delta_t}, \ \ SE = \sum_{k=1}^{K} SE_k = \frac{\sum_{k=1}^{K} G_k B_k}{WT\Delta_t}. \tag{11}$$

The optimization problem for cooperative BS doze aimed at maximizing EE while satisfying the QoS requirements can be formulated as follows,[1]

$$\max_{\mathbf{w}} EE \tag{12a}$$
$$s.\,t. \textstyle\sum_{t\in\mathcal{S}_{kg}} R_{kt} = \frac{B_k}{W\Delta_t}, \ \ g = 1,\ldots,G_k, \ \forall k \tag{12b}$$
$$\textstyle\sum_{k=1}^{K} \|\mathbf{w}_{kt,b}\|^2 \le P_0, \ \ \forall b, \ \forall t, \tag{12c}$$

where (12b) are the time-average rate constraints for multiple users that reflect their different delay tolerance and data rate demands, (12c) are the PBPC, and P_0 is the maximal transmit power per BS in each RB.

3.2. Cooperative BS Doze

Given the QoS requirements of MS_k, T_k and B_k, we can show that problem (12) can be equivalently written as

$$\min_{\mathbf{w},v,\beta} \sum_{t=1}^{T}\sum_{k=1}^{K}\|\mathbf{w}_{kt}\|^2 + \sum_{t=1}^{T}\sum_{b=1}^{L}\left(\delta_P q_{bt} + P_{\text{cc},i}\right) \tag{13a}$$
$$s.t. \sum_{t\in\mathcal{S}_{kg}} \beta_{kt}\epsilon_{kt} - \log_e \beta_{kt} \le \mu_k, \ g = 1,\ldots,G_k, \ \forall k \tag{13b}$$
$$\textstyle\sum_{k=1}^{K} \|\mathbf{w}_{kt,b}\|^2 \le q_{bt}P_0/N, \ \ \forall b, \ \forall t \tag{13c}$$
$$q_{bt} \in \{0,1\}, \ \ \forall b, \ \forall t, \tag{13d}$$

in the sense that the two problems have identical globally optimal solutions, where $\epsilon_{kt} = 1 - 2\Re\{v_{kt}^{*}\mathbf{h}_k^H\mathbf{w}_{kt}\} + (\sum_{j=1}^{K}|\mathbf{h}_k^H\mathbf{w}_{jt}|^2 + \sigma^2)|v_{kt}|^2$ and $\mu_k = T_k - \log_e 2 \cdot \frac{B_k}{\Delta_t W}$.

The basic idea to establish the equivalence is to introduce the binary variables q_{bt} to denote the BS time-slot doze pattern, together with exploiting the relationship between data rate and mean square errors (MSE). For space limitations, the details are given in [11], where the introduced auxiliary variables ϵ_{kt}, v_{kt} and β_{kt} are interpreted as the MSE, receive filter and the scalar weight for the MSE, respectively.

Problem (13) is a combinatorial optimization problem involving binary variables q and complex variables $\mathbf{w}$, v and β. To solve this problem, we propose a hierarchical iterative algorithm. In the outer iteration, a low-complexity greedy dozing algorithm is used to find the doze pattern q, and in the inner iteration, $\mathbf{w}$, v and β are alternatively optimized for given q.

We begin with the inner iteration. For a given value of q, the constraints (13b) are still not jointly convex for $\mathbf{w}$, v and β, which however are respectively convex for each of the variables. This allows us to find efficient suboptimal solutions. The inner iteration algorithm is summarized as follows.

1. Initialize by finding a feasible $\mathbf{w}$ satisfying all the constraints of problem (13).
2. Sequentially update $\mathbf{w}$, v, and β:
   - Given $\mathbf{w}$, update the receive filter v as
   $$v_{kt}^{\star}(\mathbf{w}) = \frac{\mathbf{h}_k^H\mathbf{w}_{kt}}{\sum_{j=1}^{K}|\mathbf{h}_k^H\mathbf{w}_{jt}|^2 + \sigma^2}, \ \forall k,t. \tag{14}$$
   - Given $\mathbf{w}$ and v, update the scalar weight β as
   $$\beta_{kt}^{\star}(\mathbf{w},v) = \epsilon_{kt}^{-1}, \ \forall k,t. \tag{15}$$
   - Given v and β, update $\mathbf{w}$ by solving problem (13), which becomes convex for $\mathbf{w}$.
3. Repeat step 2 until the required accuracy or the maximum number of iterations is reached. □

[1] In (12), the notation $\mathbf{w}$ is short for $\{\mathbf{w}_{kt}\}$, which denotes precoders $\mathbf{w}_{kt}$ for all k and t. The notations $q = \{q_{bt}\}$, $v = \{v_{kt}\}$, $\beta = \{\beta_{kt}\}$, and $\theta = \{\theta_{kg}\}$ in the following are defined similarly.

The proposed inner algorithm converges because the iterative procedure yields a non-increasing sequence of the objective function of problem (13) that is clearly bounded below.

Finding a feasible initial value of $\mathbf{w}$ for the inner algorithm is non-trivial because the maximal weighted sum MSE constraints (13b) and the PBPC contradict each other. To tackle this difficulty, we introduce auxiliary scalar variables θ_{kg} to relax the constraints in (13b), and find a feasible initial value from the following optimization problem:

$$\min_{\mathbf{w},v,\beta,\theta} \sum_{k=1}^{K}\sum_{g=1}^{G_k} \theta_{kg} \quad (16a)$$

$$s.\,t. \sum_{t\in\mathcal{S}_{kg}} \beta_{kt}\epsilon_{kt} - \log_e \beta_{kt} \leq \mu_k + \theta_{kg},\ \forall g,k \quad (16b)$$

$$(13c), \theta_{kg} \geq 0,\ \forall g,k.$$

It is not hard to see that if the optimal value of problem (16) is zero, then the corresponding $\mathbf{w}$ will be a feasible initial value of problem (13); otherwise, we say problem (13) is infeasible for the given doze pattern q. To solve problem (16), we note that it is respectively convex for $\{\mathbf{w},\theta\}$, v, and β. Hence we can also apply the same principle as the inner iterative algorithm, where finding an initial value is easy.

In the outer iteration, we propose a low-complexity greedy dozing algorithm. The basic principle is to successively turns the BSs into idle mode until the total transmit and circuitry power consumption will increase if one more BS is chosen. For space limitations, the details are given in [11].

4. SIMULATION RESULTS

Consider a CoMP cluster consisting of 3 cells. The cell radius is 250 m and the cell-edge signal-to-noise ratio (SNR) is 10 dB. The path loss model is $128.1 + 37.6\log_{10} d$, where d is the distance between the BS and the users in km. The shadowing follows lognormal distribution with a standard deviation of 8 dB, and the small-scale fading is flat Rayleigh fading. The BS is equipped with 2 antennas, with a maximum transmit power of 40 W [1]. $p_{\text{sp,c}}$ = 5.8 W and $p_{\text{sp,p}}$ = 1.74 W [3], and the circuitry power consumption in active mode is 252.46 W [1]. The circuitry power consumption in idle mode is set to 10 W as an optimistic estimate in [13] and 150 W as a conservative estimate in [1]. All the power consumption parameters are measured for an LTE system with 10 MHz bandwidth [1, 3, 13]. For a RB with W Hz bandwidth, $\frac{W}{10MHz}$ power consumption is considered. The backhauling power consumption is 50 W at the maximum rate of 100 Mbps [3], and the parameter a is set to 4.7 [1]. Moreover, we assume that the considered three cells require the same per-RB SE, i.e., $SE/3$, and each cell has two uniformly distributed users with different QoS requirements. Specifically, we set $SE_{2b-1} : SE_{2b} = 1 : 4$ and $T_{2b-1} : T_{2b} = 1 : 3$ for MS_{2b-1} and MS_{2b} in the b-th cell. To evaluate the EE gain of cooperative BS doze, we also apply the proposed BS doze strategy to Non-CoMP systems.

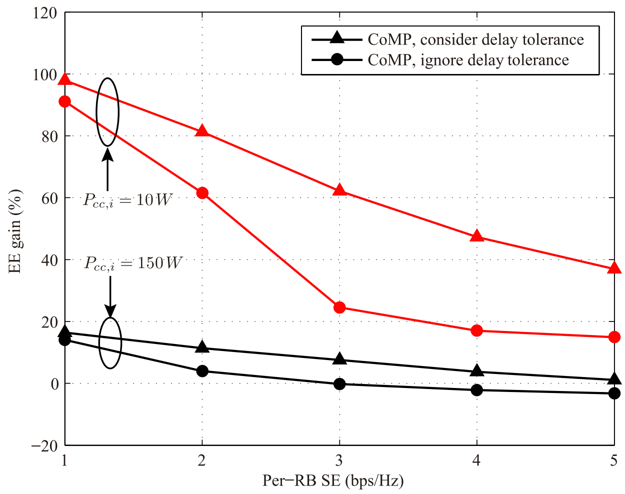

Fig. 2. EE gain of cooperative BS doze over Non-CoMP BS doze, $L = 3$, $T = 3$ and $T_k = \{1, 3\}$.

In Fig. 2 we show the EE gain of cooperative BS doze over Non-CoMP BS doze, defined as the ratio of the EE difference between CoMP and Non-CoMP to the EE of the Non-CoMP case. It is shown that if ignoring the delay tolerance (i.e., assuming $T_k = 1$ for all k), CoMP will be inferior to Non-CoMP for high SE and with large value of $P_{\text{cc},i}$, e.g., $P_{\text{cc},i} = 150$ W. Nevertheless, if considering the delay tolerance, CoMP will always provide higher EE than Non-CoMP for any required SE. If the idle circuitry power consumption can be significantly reduced (e.g., $P_{\text{cc},i} = 10$ W), which is challenging but not impossible [13], up to 35–100% EE gain can be achieved depending on the required SE.

5. CONCLUSIONS

In this paper, we studied a traffic-aware cooperative BS doze strategy to explore the potential of CoMP transmission for improving the EE of multicell systems. Cooperative BS doze exploits the benefit of CoMP to allocate the network spatial-temporal resources adaptively to accommodate various QoS requirements as well as the short-term traffic fluctuations in the network. A unified framework was developed to jointly optimize the BS-time slot doze pattern, user scheduling and cooperative precoding, and a hierarchical iterative algorithm was proposed to solve the optimization problem. Simulation results showed that despite of suffering from the increased signal processing and backhauling energy consumption, cooperative BS doze is able to effectively improve EE. Compared with Non-CoMP transmission, the cooperative BS doze strategy provides an EE gain up to 35-100% for the practical mixed traffic scenarios with delay-sensitive and delay-tolerant applications.

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