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On the Energy Efficiency of Base Station Sleeping with Multicell Cooperative Transmission

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***Abstract*—Switching underutilized base stations (BSs) to sleep mode is recognized as a promising approach to reduce energy consumption of cellular networks, but it may increase the transmit power of remaining active BSs to guarantee service coverage. Coordinated multi-point (CoMP) can effectively reduce transmit power of BSs through BS cooperation but requiring extra power consumption due to extra signal processing and backhaul traffic. In this paper, we investigate the energy efficiency of BS sleeping combined with CoMP. A joint power and subcarrier allocation algorithm is proposed to minimize the overall network power consumption with minimum data rate constraints, which can be implemented distributedly across multiple clusters. Simulation results show that BS sleeping combined with CoMP can improve network energy efficiency for high data rate users compared with Non-CoMP systems without BS sleeping.**

I. Introduction

Improving energy efficiency (EE) has become an important design goal for future mobile cellular networks [1]. Statistical results of power consumption in mobile telecommunications show that over 80% of the power is consumed by base stations (BSs) [1], and about 60% of the total energy consumption per active BS is taken up by processing circuits and air conditioner [2]. Therefore, switching underutilized BSs to sleep mode is expected as an efficient way to reduce network energy consumption. This is possible because the network, usually optimized for peak traffic load, leads to very inefficient usage of BSs during off-peak time. Several BS sleeping schemes based on traffic load, user requirements and channel conditions have been studied, see e.g., [3, 4] and references therein.

When one BS is switched off, its service coverage should be guaranteed by remaining active BSs, which may lead to the growth of either outage probability for users in the coverage of sleeping BSs or transmit power of active BSs due to the increase of propagation distance. Coordinated multi-point (CoMP) schemes are able to solve this problem through multicell cooperation [4, 5]. In [4], a single-user CoMP scheme, macro diversity, is employed to provide reliable service to users in the coverage of sleeping BSs. Recently, the energy efficiency of coherent multiuser CoMP is investigated via simulations in [5]. The results show that CoMP can reduce the overall energy consumption of BSs when the extra power consumption due to complex CoMP processing and increased backhaul traffic is low.

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In this paper, we investigate the EE of BS sleeping combined with CoMP in cellular networks, where some underutilized BSs are switched off and corresponding users are jointly served by adjacent active BSs. A joint power and subcarrier allocation algorithm is proposed to minimize the network power consumption while meeting users' data rate targets. The algorithm can also be applied for Non-CoMP systems and for systems without BS sleeping. By comparing the performance of four possible combined scenarios according to whether BS sleeping or CoMP is employed, we show that combining BS sleeping with CoMP achieves better trade-off between EE and spectrum efficiency because it can provide high EE for high data rate users.

II. System and Power Consumption Model

A. System Model

Consider an area covered by a cellular network during its off-peak time, e.g., residential areas in daytime, office districts at night, and most places after midnight. We model the network by dividing it into multiple equal-shaped clusters without overlap, as shown in Fig. 1. Each cluster includes one sleeping BS and L active BSs, which serve all users within the cluster. The considered model results in uniformly selected sleeping BSs across the whole network, which is reasonable since traffic intensity of all cells is similar in the considered scenario. Moreover, this model employs the static clustering strategy to avoid the conflict of selecting serving BSs for users in the coverage of different sleeping BSs.

Assume that each cell has K users, then L active BSs need to jointly serve all $K(L+1)$ users within each cluster. Consider that orthogonal frequency-division multiple access (OFDMA) in conjunction with spatial-division multiple access (SDMA) is employed as the multiple access scheme, i.e., a group of users in the same frequency resource are served by SDMA, and different groups are served by OFDMA. Specifically, suppose that users in the cth cluster are divided into F_c non-overlapped groups, denoted by $\mathcal{S}_1^c, \ldots, \mathcal{S}_{F_c}^c$ [1]. For the group $\mathcal{S}_f^c$, let J_f^c and

[1]Such a user grouping can be achieved by using some existing spatial user schedulers together with opportunistic round robin scheduler (ORS) [6]. It is shown in [6] that ORS outperforms proportional fair scheduler for heterogeneous users.

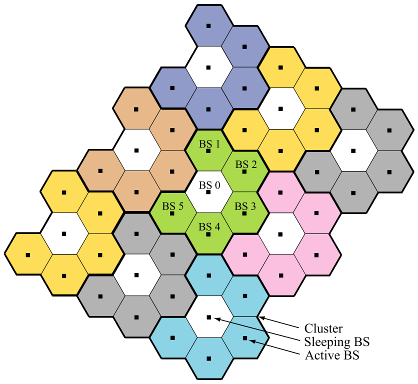

Fig. 1. An example of considered network model. Each cluster consists of 6 cells, where BS_0 is switched off and BS_1-BS_5 serve all users in the cluster.

M_f^c respectively denote its size and the number of allocated subcarriers to it. Then we have $\sum_{f=1}^{F_c} J_f^c = K(L+1)$ and $\sum_{f=1}^{F_c} M_f^c = B/\Delta_B$ with B and Δ_B representing the whole system bandwidth and subcarrier spacing, respectively.

Assume that each BS has N_t antennas and each user has one antenna. In the cth cluster, the channel from BS_b (the bth BS) to $MS_{j,f,c}$ (the jth user in the fth group) at an arbitrary subcarrier is denoted as $\mathbf{h}_{jb,f,c} \in \mathbb{C}^{1\times N_t}$. Elements in $\mathbf{h}_{jb,f,c}$ are independent and identically distributed (i.i.d.) random variables with zero mean and variance $\alpha_{jb,f,c}$, which is the large-scale channel gain from BS_b to $MS_{j,f,c}$. Then the global channel of $MS_{j,f,c}$ from all cooperative BSs is $\mathbf{h}_{j,f,c} = [\mathbf{h}_{j1,f,c}, \ldots, \mathbf{h}_{jL,f,c}]$.

With perfect channel and data sharing amongst active BSs, coherent CoMP transmission can be conducted within each cluster. We employ the zero-forcing beamforming (ZFBF) for downlink SDMA, which is of low complexity and is widely applied [7]. The ZFBF matrix can be expressed as

$$\mathbf{G}_{f,c} = \mathbf{H}_{f,c}^H(\mathbf{H}_{f,c}\mathbf{H}_{f,c}^H)^{-1}\mathbf{P}_{f,c}^{\frac{1}{2}} \triangleq \mathbf{H}_{f,c}^{\dagger}\mathbf{P}_{f,c}^{\frac{1}{2}}, \qquad (1)$$

where $\mathbf{H}_{f,c} = [\mathbf{h}_{1,f,c}^H, \ldots, \mathbf{h}_{J_f^c,f,c}^H]^H$, $\mathbf{P}_{f,c} = \frac{1}{M_f^c}\text{diag}\{\mathbf{p}_{f,c}\}$ is a diagonal matrix with $\mathbf{p}_{f,c}/M_f^c$ along the diagonal, $\mathbf{p}_{f,c} = [p_{1,f,c}, \ldots, p_{J_f^c,f,c}]$, and $p_{j,f,c}$ is the allocated power to $MS_{j,f,c}$ that is equally distributed over M_f^c subcarriers.

Consider a universal frequency reuse in the network, then the received signal of $MS_{j,f,c}$ can be expressed as

$$y_{j,f,c} = \sqrt{\frac{p_{j,f,c}}{M_f^c}} s_{j,f,c} + \sum\nolimits_{n\in\mathcal{I}_{j,f,c}^{\bar{c}}}^{\bar{c}\neq c} I_{jn,f,c} + z, \qquad (2)$$

where $s_{j,f,c}$ is the transmitted signal, $\mathcal{I}_{j,f,c}^{\bar{c}}$ denotes the set of interfering BSs in the $\bar{c}$th cluster to $MS_{j,f,c}$, $I_{jn,f,c}$ is the interference from BS_n, and z is the additive white Gaussian noise (AWGN) with noise power spectral density of σ^2.

We assume that inter-cluster interference is AWGN[2]. Then we can use power density to model the interference, and the achievable data rate of $MS_{j,f,c}$ over M_f^c subcarriers can be derived as

$$R_{j,f,c} = B_{f,c}\log\left(1 + \frac{p_{j,f,c}}{B_{f,c}(\sigma^2 + \sum_{n,\bar{c}}\rho_{n,\bar{c}}N_t\alpha_{jn,f,c})}\right)$$
$$\triangleq B_{f,c}\log\left(1 + \frac{p_{j,f,c}}{B_{f,c}\gamma_{j,f,c}}\right), \qquad (3)$$

where $B_{f,c} = M_f^c\Delta_B$ is the bandwidth allocated to the fth group, $\rho_{n,\bar{c}} = P_{\text{tx}}^{n,\bar{c}}/B$ denotes the power density of interfering signal from BS_n with transmit power $P_{\text{tx}}^{n,\bar{c}}$, $N_t\alpha_{jn,f,c}$ is the average channel gain from BS_n to $MS_{j,f,c}$, and $\gamma_{j,f,c}$ is the total interference-plus-noise power at $MS_{j,f,c}$.

B. Power Consumption Model

Based on the results of [5], we model the average power consumption of BS_b in the cth cluster as

$$P_{\text{BS}}^{b,c} = \left(\frac{P_{\text{tx}}^{b,c}}{\mu} + P_{\text{sp}}\right)(1 + C_{\text{C}})(1 + C_{\text{PSBB}}) + P_{\text{bh}}, \qquad (4)$$

where $P_{\text{tx}}^{b,c}$, P_{sp} and P_{bh} denote the transmit power per BS, the signal processing power, and the power due to backhauling, respectively, μ denotes power amplifier efficiency, C_{C} reflects the effect of equipment cooling, and C_{PSBB} models the effect of power supply and battery backup.

Let p_{sp} denote a baseline processing power consumed by a Non-CoMP BS, then the signal processing power can be modeled as

$$P_{\text{sp}} = p_{\text{sp}}\left((1 - \xi_1 - \xi_2) + \xi_1 L + \xi_2 L^2\right), \qquad (5)$$

where $\xi_1 L$ and $\xi_2 L^2$ respectively denote the fraction of power consumption due to CoMP channel estimation and SDMA precoding, both of which increase with the cluster size.

The backhaul power P_{bh} is consumed by channel and data sharing amongst cooperative BSs, which is modeled as

$$P_{\text{bh}} = p_{\text{bh}}(\beta_D + \beta_C), \qquad (6)$$

where p_{bh} denotes the power consumption of conveying one-bit information via backhaul, β_D and β_C denote the backhaul traffic due to data and channel sharing for each BS, and $\beta_D = \sum_{f=1}^{F_c}\sum_{j=1}^{J_f^c} R_{j,f,c}$.

III. Power and Subcarrier Allocation Algorithm

In this section, we design power and subcarrier allocation for each user, aimed at minimizing the overall power consumption of the whole network while meeting all users' data rate targets. To this end, we first examine the average power consumption in each cluster, then present a distributed power and subcarrier allocation algorithm.

A. Average Power Consumption per Cluster

Define a row-selection matrix $\mathbf{\Phi}_b$ with all zeros but N_t ones in the positions from $(b-1)N_t+1$ to bN_t on the main diagonal. Then the transmit power of BS_b at an arbitrary subcarrier (say the mth subcarrier) can be obtained from (1) as

$$P_{\text{tx}}^{b,f,m,c} = \text{Tr}\left(\mathbf{\Phi}_b\mathbf{G}_{f,c}\mathbf{G}_{f,c}^H\mathbf{\Phi}_b^H\right)$$
$$= \text{Tr}\left(\mathbf{H}_{f,c}^{\dagger H}\mathbf{\Phi}_b\mathbf{H}_{f,c}^{\dagger}\mathbf{P}_{f,c}\right). \qquad (7)$$

[2]In practice, this assumption is valid when interference averaging mechanisms are employed among clusters.

Assuming that the channels of each user at different subcarriers are i.i.d., the average transmit power of BS_b over M_f^c subcarriers can be expressed as

$$P_{\text{tx}}^{b,f,c} = M_f^c \text{Tr}\left(\mathbb{E}_{\mathbf{h}}\left\{\mathbf{H}_{f,c}^{\dagger H}\mathbf{\Phi}_b\mathbf{H}_{f,c}^{\dagger}\mathbf{P}_{f,c}\right\}\right) \triangleq \mathbf{g}_{f,b,c}\mathbf{p}_{f,c}^T, \quad (8)$$

where $\mathbf{g}_{f,b,c}$ is a vector consisting of the diagonal elements of the matrix $\mathbb{E}_{\mathbf{h}}\left\{\mathbf{H}_{f,c}^{\dagger H}\mathbf{\Phi}_b\mathbf{H}_{f,c}^{\dagger}\right\}$, which can be numerically obtained with channel statistics.

Thus the average transmit power of BS_b is $P_{\text{tx}}^{b,c} = \sum_{f=1}^{F_c} P_{\text{tx}}^{b,f,c}$. From (4) and (6), the overall average power consumption in the cth cluster is obtained as

$$P_{\text{Cluster}}^c = \Big(\frac{1}{\mu}\sum_{b=1}^{L} P_{\text{tx}}^{b,c} + LP_{\text{sp}}\Big)(1+C_{\text{C}})(1+C_{\text{PSBB}}) + Lp_{\text{bh}}\Big(\sum_{f=1}^{F_c}\sum_{j=1}^{J_f^c} R_{j,f,c} + \beta_C\Big). \quad (9)$$

B. Power and Subcarrier Allocation

Let $\epsilon_{j,f,c}$ denote the data rate target of $\text{MS}_{j,f,c}$. Then the power and subcarrier allocation problem that minimizes the network power consumption with minimum data rate constraints can be formulated as follows,

$$\min_{M_f^c, p_{j,f,c}} \sum_{c=1}^{N_c} P_{\text{Cluster}}^c \quad (10a)$$

$$s.\ t. \quad B_{f,c}\log\left(1+\frac{p_{j,f,c}}{B_{f,c}\gamma_{j,f,c}}\right) \geq \epsilon_{j,f,c}, \quad (10b)$$

$$\sum_{f=1}^{F_c} \mathbf{g}_{f,b,c}\mathbf{p}_{f,c}^T \leq P_{\text{tx}}^{\max}, \quad (10c)$$

$$\sum_{f=1}^{F_c} M_f^c \leq \frac{B}{\Delta_B}, \quad (10d)$$

$$B_{f,c} = M_f^c\Delta_B, p_{j,f,c} \geq 0, \quad (10e)$$

$$M_f^c \in \mathbb{Z}_+, \quad (10f)$$

where (10c) reflects the per-BS power constraints (PBPC), $P_{\text{tx}}^{\max}$ is the maximum transmit power per BS, N_c is the number of clusters, and $\mathbb{Z}_+$ denotes the set of all positive integers.

Problem (10) is a joint optimization problem over N_c clusters. Since the cooperation between clusters is not allowed, we propose a distributed power and subcarrier allocation solution. The basic idea is to decompose (10) into a set of single-cluster problems, in each of which the power and subcarrier allocation for users in each cell is iteratively updated by fixing the powers from the interfering BSs, i.e., $\gamma_{j,f,c}$ in (10b) is fixed.

When optimizing the power and subcarrier allocation for the users in the cth cluster, it can be easily shown that P_{Cluster}^c is minimized if the equality in constraint (10b) holds, i.e., $R_{j,f,c} = \epsilon_{j,f,c}$. This is because P_{Cluster}^c increases monotonously with $p_{j,f,c}$ and $R_{j,f,c}$ while $R_{j,f,c}$ increases with $p_{j,f,c}$. Then by discarding the constant items in P_{Cluster}^c given by (9), the objective function in the cth cluster becomes $\sum_{b=1}^{L} P_{\text{tx}}^{b,c}$. However, the optimization of power and subcarrier allocation is still a combinational optimization problem involving integer variables M_f^c and real variables $p_{j,f,c}$. The optimal solution can be found by exhaustive searching, but the complexity is prohibitive. The difficulty comes from the non-convex discrete subcarrier assignment restriction. Therefore, we relax the problem and consider a continuous subcarrier allocation. Then we can reformulate the problem as

$$\min_{M_f^c, p_{j,f,c}} \sum_{b=1}^{L} P_{\text{tx}}^{b,c} \quad (11a)$$

$$s.\ t. \quad \text{Constraints (10b)}\sim\text{(10e)},\ M_f^c \geq 0. \quad (11b)$$

Problem (11) is a convex optimization problem, which can be solved by efficient optimization methods [8]. With the optimal continuous M_f^{c*}, a suboptimal integral solution to the original problem can be obtained by first rounding down M_f^{c*} to a nearest discrete number and then judiciously allocating the rest of subcarriers across users. In the scenario we consider, the number of subcarriers far exceeds the number of users, which implies that the number of subcarriers allocated to each user group can be large. Therefore, the discretization of M_f^{c*} will only slightly affect the system performance.

We summarize the proposed power and subcarrier allocation algorithm in Table I. To solve problem (11) in the cth cluster during each iteration, the knowledge of interference-plus-noise power, $\gamma_{j,f,c}$ defined in (3), is necessary at active BSs. This information can be estimated by $\text{MS}_{j,f,c}$ and fed back to BSs without relying on the cooperation among clusters. Therefore, the algorithm can be implemented across multiple clusters in a distributed fashion.

TABLE I
DISTRIBUTED POWER AND SUBCARRIER ALLOCATION ALGORITHM

1. **Initialization:** set $i=0$, $P_{\text{tx}}^{c(0)}=0$, and $\rho_{b,c}^{(0)}=0$ for $b=1,\ldots,L$ and $c=1,\ldots,N_c$.
2. **Cluster-wise Iteration:** At the ith iteration, set $i \leftarrow i+1$.
   for $c=1,\ldots,N_c$
   - Optimize power and subcarrier allocation in the cth cluster based on $\rho_{b,\bar{c}}^{(i-1)}$ for $\bar{c}\neq c$ by solving problem (11).
   - Compute the average transmit power of BS_b, $P_{\text{tx}}^{b,c(i)}$, and the overall transmit power in the cth cluster, $P_{\text{tx}}^{c(i)}$.
   - Update the power density of all active BSs, $\rho_{b,c}^{(i)} = P_{\text{tx}}^{b,c(i)}/B$.

   end
3. **Repeat:** Iterate step 2 until one of the following situations occurs:
   - The required accuracy is reached, i.e., $\max_c \frac{P_{\text{tx}}^{c(i)}-P_{\text{tx}}^{c(i-1)}}{P_{\text{tx}}^{c(i-1)}} \leq \delta$, where δ is a specific threshold.
   - Problem (11) becomes infeasible since the PBPC are not satisfied. An outage event will be counted in this case.

C. Convergence Discussion

The proposed algorithm turns into the traditional multicell power and subcarrier allocation problem when $L=1$. Its convergence has been proven by [9] under the framework based on *standard interference function*, which can be considered as the mapping function of BSs' transmit power between two consecutive iterations. When $L>1$, convergence behavior of the algorithm becomes complicated, because multiple cooperative BSs rather than a single BS will adjust their power according to the change of transmit power of interfering BSs.

When a large number of users are uniformly distributed in each cluster, the transmit power of all involved BSs will become close due to the symmetry amongst them, i.e., $P_{\text{tx}}^{b,c(i)} \approx$

TABLE II
SIMULATION PARAMETERS

Number of antennas at BS, N_t	4
Number of users in each cell, K	4
Number of clusters, N_c	7
BS-to-BS distance	500 m
Path loss model, in dB	36.3 + 3.76log(d), d >50 m
Shadowing, standard deviation	Log-normal, 8 dB
Small-scale channels	i.i.d. Rayleigh fading
Maximum transmit power, $P_{\text{tx}}^{\max}$	46 dBm
Systems bandwidth, B	5 MHz
Thermal noise power density	-174 dBm/Hz
Receiver noise figure	9 dB
Power amplifier efficiency, μ	38%
Cooling percent, C_{C}	29%
Power supply battery backup, C_{PSBB}	11%
Baseline signal processing power, p_{sp}	2∼50 W
Signal processing power fraction, ξ_1, ξ_2	$\xi_1 = \xi_2 = \xi$ = 0.01 or 0.001
Power efficiency of backhaul, p_{bh}	0.1 W/Mbps

$\frac{1}{L}P_{\text{tx}}^{c(i)}$. Then it is readily to show that the interference function is approximately *standard*, since the interference function with respect to $P_{\text{tx}}^{c(i)}$ is *standard* by considering each cluster as a "super cell". Therefore, the proposed algorithm converges with a high probability. In general cases, the exact convergence analysis is difficult. However, later simulation results show that the algorithm always converges, even for a few users.

D. Extension to Non-CoMP and BS All-on Scenarios

According to whether CoMP or BS sleeping is employed, four possible combined scenarios are denoted as *Sleeping/CoMP*, *Sleeping/Non-CoMP*, *All-on/CoMP*, and *All-on/Non-CoMP*. Although the proposed algorithm considers the *Sleeping/CoMP* scenario, we remark that it can be straightforwardly applied in *All-on/CoMP* scenario where each cluster has $L+1$ active BSs, and also in *All-on/Non-CoMP* scenario by setting cluster size to 1.

In *Sleeping/Non-CoMP* scenario, users in the coverage of the sleeping BS are first assigned to active BSs in the same cluster. The resulting network can be regarded as the scenario *All-on/Non-CoMP*, then the proposed algorithm is applicable. It should be pointed out that though CoMP is not used in this scenario, the cluster size still affects the network performance, since it determines the received signal power of users in the coverage of the sleeping BS achieved by serving BS selection.

IV. SIMULATION RESULTS

In this section, we evaluate the EE of BS sleeping and CoMP via simulations by comparing the performance of the four relevant scenarios. In Non-CoMP systems, we consider that each BS serve only one user in the same time-frequency resource with maximal ratio transmission (MRT). In CoMP systems, we employ the random-scheduling based ORS to generate F_c user groups as follows:

- Denote the set of users in the cth cluster as $\mathcal{S}_c$. For the fth group, $1 \le f \le F_c - 1$, randomly pick and remove L users from $\mathcal{S}_c$. This allows a fair comparison between CoMP and Non-CoMP systems in a sense that each active BS serves one user on average.

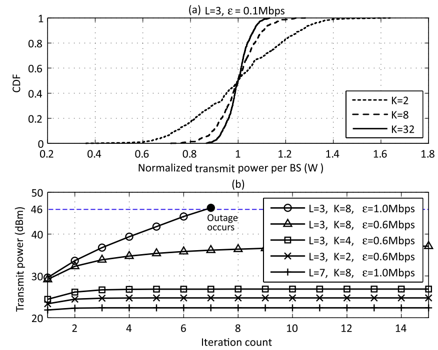

Fig. 2. CDF of normalized transmit power per BS, $P_{\text{tx}}^{b,c}/\mathbb{E}\{P_{\text{tx}}^{b,c}\}$, and convergence behavior of the proposed algorithm.

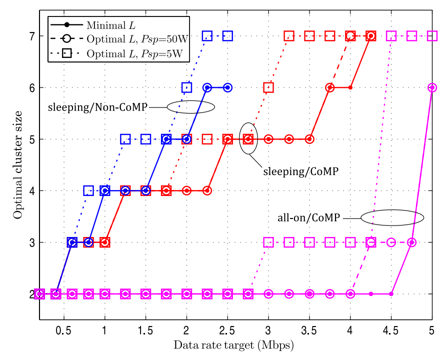

Fig. 3. Optimal cluster size $(L+1)$ versus data rate targets, $\xi = 0.001$.

- The remaining $K(L+1) - (F_c - 1)L$ users constitute the F_cth group.

The use of random-scheduling associated with ZFBF usually results in a somewhat pessimistic EE, which can be considered as a performance lower bound of CoMP.

Simulation parameters are listed in Table II. In simulations, equal data rate target for all users is considered, denoted by ϵ, the threshold in the algorithm is set to 0.01, the outage probability is required to be less than 10%, and backhaul traffic is counted only for data sharing. We employ cluster wraparound to prevent network edge effects by ensuring that each cell is surrounded by two rings of interfering cells. All the results are averaged over 20 drops.

We first examine the convergence behavior of the proposed algorithm. Fig. 2(a) plots the cumulative distribution function (CDF) of normalized transmit power per BS. It can be seen that the dispersion of transmit power of different BSs reduces with the increase of user number K, which ensures the convergence of the algorithm for large K according to the discussion in Section III-C. Yet even when K is not large (which is the case we considered), Fig. 2(b) shows the convergence of the algorithm with various data rate targets and cluster size unless an outage event occurs due to violating the PBPC.

The optimal cluster size achieving the highest EE in three revelent scenarios is shown in Fig. 3, where the energy efficiency is defined as the ratio of sum data rate to the overall power consumption in each cluster. The optimal cluster size is found from 1 to 7 (i.e., at most one-ring cell cooperation) by comparing the corresponding EE. The impact of BS sleeping and CoMP on cluster size can be seen respectively from the results in *Sleeping/Non-CoMP* and *All-on/CoMP* scenarios. First, a minimal cluster size is required in both scenarios due to the BS transmit power constraint. The size depends on the required data rate target. For instance, the minimal cluster size is 5 for BS sleeping and 2 for CoMP when $\epsilon = 2$ Mbps. Second, the optimal cluster size depends on the signal processing power P_{sp}. For large P_{sp} (e.g., $P_{\text{sp}} = 50$ W), both BS sleeping and CoMP prefer a small cluster size. In this case, P_{sp} dominates the overall power consumption compared with transmit power. Therefore, BS sleeping prefers switching off more BSs to save more energy, and CoMP prefers a small cluster size to reduce the extra power consumption due to complex signal processing. For small P_{sp} (e.g., $P_{\text{sp}} = 5$ W), a large cluster size is preferred, which value relies on the balancing between transmit power and signal processing power. Similar results can be observed in *Sleeping/CoMP* scenario, since P_{sp} influences the optimal cluster size for both BS sleeping and CoMP in the same way.

Figure 4 shows the EE in the four considered scenarios versus different data rate targets. It can be observed that different data rate targets can be supported by the four strategies due to the BS transmit power constraint. For low data rate targets, BS sleeping is always useful since the increase of transmit power of active BSs is much less than the saving of signal processing power. The benefit of CoMP depends on its extra power consumption. When the fraction of signal processing power is small (e.g., $\xi = 0.001$ in *Sleeping/CoMP* scenario), CoMP provides high EE for high data rate users. As expected, the EE of CoMP decreases with the growth of ξ. Moreover, for large ξ (e.g., $\xi = 0.01$ in *All-on/CoMP* and *Sleeping/CoMP* scenarios), high data rate does not necessarily result in high EE, since the increasing number of active cooperative BSs to support the data rate will lead to much more energy consumption.

The EE gain of employing BS sleeping or/and CoMP compared to the *All-on/Non-CoMP* strategy is illustrated in Fig. 5. For small ϵ (e.g., $\epsilon = 1$ Mbps), again BS sleeping is always beneficial and the energy efficiency gain increases with the growth of P_{sp}. However, merely employing CoMP (*All-on/CoMP*) can not improve the EE in this case since the resulting transmit power saving is less than the extra signal processing power. The contribution of CoMP can be observed when ϵ is large (e.g., $\epsilon = 4$ Mbps). As expected, the gain decreases with the increase of P_{sp}. Yet by combining CoMP with BS sleeping, a gain of 10% can be obtained for large P_{sp}. The results of *Sleeping/Non-CoMP* are not shown when $\epsilon = 4$ Mbps, because this data rate target can not be supported.

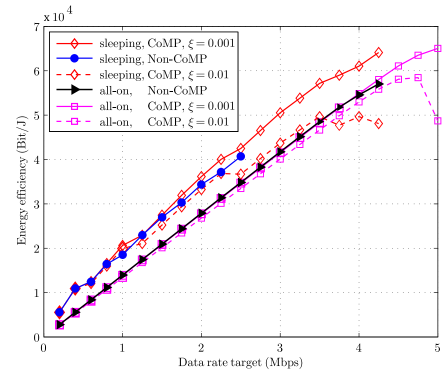

Fig. 4. EE versus data rate targets. Optimal cluster size, P_{sp} = 50 W.

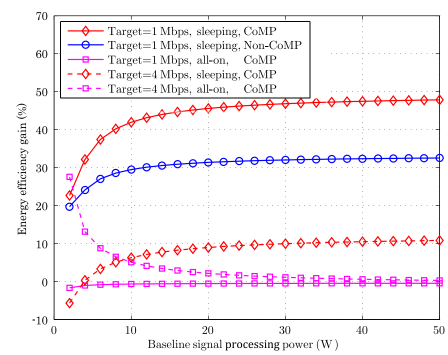

Fig. 5. EE gain of BS sleeping and CoMP. Optimal cluster size, $\xi = 0.001$.

V. Conclusions

The energy efficiency of both BS sleeping and CoMP has been investigated in this paper. We proposed a joint power and subcarrier allocation algorithm aimed at minimizing network power consumption with minimum data rate constraints. Our results show that the combination of BS sleeping and CoMP can improve network energy efficiency, but CoMP itself is only energy efficient for low extra power consumption. BS sleeping is useful only for low data rates, while CoMP extends the benefits of BS sleeping to a wide range of data rates. When signal processing power is 50 W, *Sleeping/CoMP* provides an energy efficiency gain of 48% and 10% for data rate targets of 1 Mbps and 4 Mbps compared to *All-on/Non-CoMP* strategy.

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