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Improving network energy efficiency through cooperative idling in the multi-cell systems

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Abstract

Network energy efficiency (NEE) is considered as the metric to address the energy efficiency problem in the cooperative multi-cell systems in this article. At first, three typical schemes with different levels of cooperation, i.e., interference aware game theory, inter-cell interference cancellation, and multi-cell joint processing, are discussed. For both unconstrained and constrained case, efficient power control strategies are developed to maximize the NEE. During the optimization, both the optimization objects and strategies are distinct because of different levels of data and channel state information at the transmitter sharing. In order to further improve NEE, a novel cooperative idling (CI) scheme is proposed through cooperatively switching some BSs into micro-sleep and guaranteeing the data transmission with the other active BSs' cooperative transmission. Simulation results indicate that cooperation can improve both NEE and network capacity and demonstrate that CI can further improve the NEE significantly.

Keywords: network energy efficiency, cooperative idling, multi-cell systems

1 Introduction

Data service has become the key application in the next generation wireless networks, such as 3GPP-LTE and WiMAX. Unlike the voice service, exploiting the delay tolerance of data service can save significant energy during the low load scenario, which attracts a lot of attentions for the green communications [1,2]. In order to minimize the energy consumption while exploiting the delay tolerance, "Bits per-Joule" energy efficiency (EE) should be applied as the optimization metric.

There is a rich body of works [1-16] focusing on maximizing the link energy efficiency (LEE) of the single cell systems. The literatures on LEE can be mainly divided into two classes. The first one focuses on the LEE of frequency selective channels [3-8] and the second one mainly considers the LEE of MIMO systems [2,9-15]. Moreover, [16] provided the analytical foundation for analyzing the LEE. As indicated by these literatures, power allocation and link adaptation are the key technologies to improve LEE through compromising capacity, transmit power related power amplifier (PA) power,

and circuit power. When MIMO channels can be separated into parallel sub-channels after precoding or detection, e.g., based on zero-forcing precoding or singular value decomposition (SVD), the similar power allocation and link adaptation in the frequency selective channels can be applied to the MIMO systems [4]. However, compared with the single cell scenario, the EE problem is distinct in the multi-cell systems as there are multiple transmitters and the LEE cannot express the systems' EE accurately. The pioneering study of Miao et al. [17] considered the EE of the uplink multi-cell systems and proposed an interference aware non-cooperative scheme based on the game theory. But compared with the uplink channels in which transmitters (users) are difficult to cooperate, the feature of transmitters' (base stations, BS) backhaul connection makes it possible to cooperate for the transmitters in the downlink systems.

There are a lot of literatures considering the cooperative multi-cell downlink systems from a standpoint of spectral efficiency (SE). As combating the inter-cell interference is the key challenge faced in the multi-cell cellular systems, BS cooperation (so called coordinated multi-point, CoMP) has attracted a lot of attention these days to meet this challenge. Cooperation can

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combat or even exploit the inter-cell interference to improve the capacity, some examples of which are [18-22]. According to different levels of data and channel state information at the transmitter (CSIT) sharing in the cooperative BS cluster, different cooperation schemes should be applied. For example, with full CSIT and data sharing, the cooperative BS cluster is equivalent to a 'super' BS and the CoMP system is similar with a single cell downlink MIMO system where global precoding can be employed. With only local CSIT and no data sharing, inter-cell interference cancellation (ICIC) [19] is a promising technology. If there are full data sharing but only local CSIT available, the distributed virtual SINR (DVSINR) based precoding is an efficient way [20].

However, to the best of the authors' knowledge, there are few literatures considering EE in the cooperative downlink multi-cell systems and this article is a pioneering study discussing this topic. Network energy efficiency (NEE) is addressed as the performance metric to evaluate the EE of the CoMP systems, which is defined as sum capacity in the cooperative cluster divided by the total BS power consumption of the cluster. Here BS power consumption includes both transmit power and constant part power which accounts for the circuit, signal processing, cooling etc. NEE denotes the average total delivered bits per-unit energy in the whole cluster, and hence can better represent the EE in the multi-cell networks. Correspondingly, we denote network capacity (NC) as the sum capacity in the cooperative cluster.

Unconstrained maximizing NEE problem is addressed at first and the energy efficient transmit power optimization with different levels of cooperation is discussed. Compared with the SE design, the key challenge of energy efficient design is power control. Cooperative or non-cooperative power control acting at each BS are mainly determined by the levels of CSIT and data sharing. Three transmission strategies with different levels of sharing are taken into account. The first scheme, i.e., interference aware game theory (IA-GT) requires only the CSIT and data of each BS's own cell. The second scheme, i.e., inter-cell interference cancellation (ICIC) requires local CSIT and needs no data sharing. And the third scheme, i.e., multi-cell joint processing (MC-JP), needs the highest level of cooperation, in which both CSIT and data sharing are required. When full CSIT is not available in IA-GT and ICIC, NEE calculation is not available at each BS, and hence, different optimization object at each BS and non-cooperative power control should be utilized. When full CSIT is available at the central unit (CU) in MC-JP, NEE is exploited as the global optimization object. Joint precoding and cooperative power control should be used to fully exploit the inter-cell interference and the highest NEE and NC can be both acquired.

Next, we extend the NEE optimization to the case with each users' rate constraint to make the EE transmission useful under the quality of service (QoS) constraints and reveal the tradeoff between NEE and NC. To maximize the constrained NEE, modified power control strategies are developed to solve the problem for the above three schemes.

Interestingly, for the three schemes, higher level of cooperation can increase both NEE and NC because of better exploiting inter-cell interference. Nevertheless, according to the definition of NEE which is denoted as the total capacity divided by the total power consumption, increasing capacity through cooperation, and decreasing the constant power consumption part are two direct strategies to improve the NEE. Therefore, only exploiting the inter-cell interference is not enough. How to jointly employ the two strategies is addressed then and a novel cooperative idling (CI) scheme is proposed to employ micro-sleep cooperatively in the both data and CSIT sharing scenario. Through cooperatively turning some BSs in the cooperative cluster into micro-sleep, and utilizing cooperative transmission of the rest active BSs in the cluster to guarantee all users' data transmission through multiuser MIMO (MU-MIMO), the power consumption can be further decreased while fulfilling the rate constraints. Hence, the NEE is improved significantly. CI is different from the dynamical BS energy saving, e.g., cell zooming [23]. Dynamical BS energy saving switches off BSs from a network level and the neighbors of the turned off BSs need to increase the transmit power or adjust the antenna tilts to compensate the coverage. However, CI is absolutely distinct from it. In CI, the cooperative micro-sleep BSs need to transmit the common, pilot, and synchronization channels to guarantee the coverage and only avoid the the data transmission to save the circuit and signal processing power. Compared with the single-cell micro-sleep (also called discontinuous transmission, DTX [24]), CI extends the realization into a cooperative feature to exploit it more flexibly through transferring the whole data transmission in the cluster to the active BSs. So the single-cell micro-sleep can be treated as a special case of CI. Simulation results show that in the low rate constraint case, CI can significantly improve the NEE, while in the high rate constraint case, CI would degenerate to MC-JP. This indicates that CI is more suitable in the low load to aggregate the data transmission to enable significant micro-sleep, and hence, further improves the NEE. CI is promising for the future green cellular networks.

The rest of this article is organized as follows: Section 2 introduces the system model. Section 3 discusses the NEE optimization with different schemes, i.e., IA-GT, ICIC, and MC-JP and section 4 develops the modified

power allocation schemes under rate constraints. The novel CI scheme is proposed in section 5 and then Section 6 gives the simulation results. Finally, Section 7 concludes this article.

Regarding the notation, bold face letters refer to vectors (lower case) or matrices (upper case). Notation $E(A)$ and $Tr(A)$ denote the expectation and trace operation of matrix A, respectively. The superscript H and T represent the conjugate transpose and transpose operation, respectively.

2 System model

The multi-cell system consists a cooperative cluster with M BSs assigned with the same carrier frequency and the BSs are connected with a CU. Each BS is equipped with J antennas. Only one active user is served in each cell at each time slot with precoding at the BS. For simplification, we assume that each user is deployed with only a single antenna. The BS closest to the user is called as home BS, while other BSs are called as neighbor BSs. Denote the channel from the ith BS to the jth user as $\mathbf{h}_{i,j} \in \mathbb{C}^{1 \times J}$, $i,j = 1,...,M$ and denote the transmitted signal from BS i as $x_i \in \mathbb{C}^{J \times 1}$, and then the received signal at the user j can be denoted as

$$\gamma_j = \sum_{i=1}^{M} \mathbf{h}_{i,j} x_i + n_j, \tag{1}$$

in which n_j is the noise at the user j and the noise power is denoted as N_0. The transmit power of BS i is denoted as $\mathbb{E}(x_i^H x_i) = P_{t,i}$. About the channel mode, we denote

$$\mathbf{h}_{i,j} = \zeta_{i,j} \hat{\mathbf{h}}_{i,j} = \Phi_{i,j} d_{i,j}^{-\lambda} \Psi_{i,j} \hat{\mathbf{h}}_{i,j}. \tag{2}$$

$\zeta_{i,j} = \Phi_{i,j} d_{i,j}^{-\lambda} \Psi_{i,j}$ is the large scale fading including pathloss and shadowing fading, in which $d_{i,j}$, λ denote the distance from the BS i to the user j and the path loss exponent, respectively. The random variable $\Psi_{i,j}$ accounts for the shadowing process. The terms $\Phi_{i,j}$ denotes the pathloss parameters to further adapt the model which accounts for the BS and MS antenna heights, carrier frequency, propagation conditions, and reference distance. $\hat{\mathbf{h}}_{i,j}$ denotes the small scale fading channel, we assume the channel experiences flat fading and is well modeled as a spatially white Gaussian channel, with each entry $\mathcal{CN}(0, 1)$.

The BS power model during transmission is motivated by [25]. Except for the transmit power, the dynamic power P_{Dyn} and static power P_{Sta} account for the power consumed by signal processing, A/D converter, feeder, antenna, power supply, battery backup, cooling etc., in which dynamic power is dependent of the bandwidth, antenna number, and static power is a constant variable.

As shown in [13], the power model at BS i is denoted as

$$P_{\text{total},i} = \frac{P_{t,i}}{\eta} + P_{Dyn} + P_{Sta}, $$
$$P_{Dyn} = JP_{cir} + p_{ac,bw}W + Jp_{sp,bw}W, \tag{3}$$

where η is the RF efficiency, W is the bandwidth. Here, we assume that the active bandwidth W and antenna number J for each BS are fixed, so the dynamic and static power can be totally referred to a constant power $P_{con} = P_{Dyn} + P_{Sta}$. The power model of BS i during transmission can be rewritten as

$$P_{\text{total},i} = \frac{P_{t,i}}{\eta} + P_{con}. \tag{4}$$

In this article, perfect CSIT is assumed and the effect of CSIT imperfections is beyond the scope of this article.

As the purpose of this article is to discuss the EE in the multi-cell systems, the performance metric need to be defined. NEE is the EE metric in this article, which is defined as the total capacity can be delivered in the multi-cell network divided by the total BS power consumption.

$$\text{NEE} = \frac{\sum_{j=1}^{M} R_j}{\sum_{i=1}^{M} P_{\text{total},i}}, \tag{5}$$

in which R_j is the achievable capacity of user j. Correspondingly, NC is defined as the total capacity delivered in the multi-cell network, which can be denoted as

$$\text{NC} = \sum_{j=1}^{M} R_j. \tag{6}$$

For comparison, LEE for each link is defined as the link capacity divided by the BS's power consumption. It is always applied as the optimization metric for the link [1-14]. For the BS i, LEE can be denoted as

$$\text{LEE}_i = \frac{R_i}{P_{\text{total},i}}, \tag{7}$$

where R_i is the capacity of the user whose home BS is i.

It is worthwhile to note that the cell edge performance is another key performance metric in the multi-cell systems. However, it is not addressed in this article and it will be left for the future study.

3 Maximizing network energy efficiency with different level of cooperation

In this section, unconstrained NEE optimization of different schemes with distinct cooperation levels is considered. We formulate the maximizing NEE problem at

first, and then three schemes, i.e., IA-GT, ICIC, and MC-JP are taken into account. IA-GT requires only both the CSIT and data of BSs' own cell and performs selfish eigen-beamforming. Hence, non-cooperative power control should be employed in IA-GT. ICIC requires local CSIT and needs no data sharing. Each BS proactively cancel its own interference to other cells in the cooperative cluster and non-cooperative power control is utilized in ICIC. MC-JP requires full data and CSIT sharing and the cooperative cluster can be treated as a"super BS". We consider global zero-forcing beamforming there and cooperative power control is available.

3.1 Problem formulation

The problem is formulated in this subsection where NEE is the optimization object. As precoding design is based on eigen-beamforming and zero-forcing beamforming, respectively, as shown above, only the transmit power $P_{t,i}$ needs to be optimized. The optimization problem can be defined as

$$\mathbb{P}1 : \max_{\{P_{t,i}\}_{i=1}^{M}:P_{t,i}\geq 0} \text{NEE}. \tag{8}$$

In the above problem, NEE is first addressed as the performance metric to represent the EE of the multi-cell systems. Although NEE have been considered in the uplink multi-cell channels [17], we believe that it is more suitable for the downlink multi-cell systems because of the two reasons as follows. For one thing, maximizing the NEE needs the global information in the cooperative multi-cell system but the users are difficult to get these global information to control their power cooperatively in the uplink systems. For another, battery limitation is important for the users in the uplink channels and the remaining battery energy is always different for each user, and hence, NEE maximizing cannot indicate the EE requirement of each users, respectively. Therefore, designing to maximize the LEE is more suitable for the uplink systems. Things change for the downlink systems. First, backhaul connection among different BSs makes it possible to exchange the CSIT and data information to preform joint optimization, especially CU in the CoMP systems can help the cooperation. Second, different from the battery limitation in the user side, the total power consumption is more important for the BSs, so NEE is provided with practical significance for the downlink cellular networks. Hence, NEE can better externalize the network behavior compared with the previous LEE.

Considering different capability of backhaul connection, limited CSIT and data sharing are also taken into account. Interestingly, maximizing LEE with limited CSIT and data sharing is a sub-optimal choice without

extra information exchanging. We discuss these issues later.

3.2 Different transmission schemes

The solution of problem $\mathbb{P}1$ with three different schemes are discussed in this subsection.

3.2.1 Interference aware game theory

IA-GT is a non-cooperative transmission scheme. In this scheme, only the CSIT between the home BS to its dominated user is available for each BS and no data sharing is available. Each BS selfishly determines the precoding vector based on the eigen-beamforming. If the signal for user i is denoted as s_i, precoding vector is denoted as $\mathbf{f}_i$, then the transmitted signal at BS i is

$$x_i = \mathbf{f}_i s_i = \mathbf{h}_{i,i}^H / ||\mathbf{h}_{i,i}|| s_i. \tag{9}$$

The SINR of user i can be denoted as

$$\text{SINR}_i = \frac{P_{t,i}|\mathbf{h}_{i,i}\mathbf{f}_i|^2}{N_0 + \sum_{j=1,j\neq i}^{M} P_{t,j}|\mathbf{h}_{j,i}\mathbf{f}_j|^2}. \tag{10}$$

In this case, problem $\mathbb{P}1$ can be rewritten as

$$\mathbb{P}1 : \max_{\{P_{t,i}\}_{i=1}^{M}:P_{t,i}\geq 0} \frac{\sum_{i=1}^{M} W \log \left\{ 1 + \frac{P_{t,i}|\mathbf{h}_{i,i}\mathbf{f}_i|^2}{N_0 + \sum_{j=1,j\neq i}^{M} P_{t,j}|\mathbf{h}_{j,i}\mathbf{f}_j|^2} \right\}}{\sum_{i=1}^{M} P_{\text{total},i}}. \tag{11}$$

As data and CSIT sharing is not available in IA-GT, joint optimizing above problem is impractical in IA-GT. A sub-optimal but practical solution is that each user optimize its own transmit power $P_{t,i}$ as follows excluding other cells' rate.

$$\max_{P_{t,i}:P_{t,i}\geq 0} \frac{W \log \left\{ 1 + \frac{P_{t,i}|\mathbf{h}_{i,i}\mathbf{f}_i|^2}{N_0 + \sum_{j=1,j\neq i}^{M} P_{t,j}|\mathbf{h}_{j,i}\mathbf{f}_j|^2} \right\}}{P_{\text{total},i} + \sum_{j=1,j\neq i}^{M} P_{\text{total},j}}. \tag{12}$$

In order to optimize (12), inter-cell interference $\sum_{j=1,j\neq i}^{M} P_{t,j}|\mathbf{h}_{j,i}\mathbf{f}_j|^2$ and other BSs' power consumption $\sum_{j=1,j\neq i}^{M} P_{\text{total},j}$ are required except for the own cell's CSIT. Fortunately, the noise and inter-cell interference level of the previous slot can be measured at the user side, so only other BSs' power consumption $\sum_{j=1,j\neq i}^{M} P_{\text{total},j}$ affects the optimization (12). Motivated by Björnson et al. [20], we provide two simple strategies to

meet this challenge, which both lead to maximizing LEE at each BS. In the first strategy, each BS should assume that the BS itself is the only BS in the cluster, thus it should be set as $\sum_{j=1,j\neq i}^{M} P_{total,j} = 0$ in the denominator. Although the assumption is simple and sub-optimal, it is robust because the effect of other BSs' power parts are all excluded whether their impact is positive or negative. In the second strategy, the system should be assumed to be symmetrical at each BS, which means the user in each BS experiences the similar channel condition. Thus, the optimized power at each BS should be the same in the symmetrical scenario and it is set that $P_{total,j} = P_{total,i}, \forall j \neq i$. Interestingly, for the above both strategies, the optimization object at BS i is equivalent to the LEE after some simple calculation, which can be denoted as follows:

$$\max_{P_{t,i}} LEE_i = \frac{W \log \left\{ 1 + \dfrac{P_{t,i}|\mathbf{h}_{i,i}\mathbf{f}_i|^2}{N_0 + \sum\limits_{j=1,j\neq i}^{M} P_{t,j}|\mathbf{h}_{j,i}\mathbf{f}_j|^2} \right\}}{P_{total,i}}. \quad (13)$$

When each BS optimizes LEE according to above equation, the interference level of other cells would change, and hence, the other BSs' LEE would be affected. Thus, when each BS optimizes its own LEE, Pareto-efficient Nash equilibrium, which is defined as the point where no BS can unilaterally improve its LEE without decreasing any other BS's LEE, is expected to be achieved. Fortunately, we find that the optimization (13) is similar with the uplink multi-cell systems [17]. Therefore, the practical non-cooperative power control strategy based on the game theory in [17] can be directly applied here to achieve the Pareto-efficient Nash equilibrium. During the power control procedure, no cooperation is needed and each BS only need to get the interference level and then maximize its own LEE.

We should notice that here although other BSs' power consumption part is left out to help the distributed optimization (13) at each BS, the NEE in (11) should be employed as the performance metric to express the systems' EE. In the simulation, we optimize the power according to (13) and then calculate the NEE based on (11). The same principle is applied in the other schemes in the rest of the article.

3.2.2 Inter-cell interference cancellation

ICIC is a scheme in which each BS proactively cancel its own interference to other cells. Only local CSIT is required and no data sharing is needed. Zero-forcing precoding is considered to cancel the inter-cell interference and $J \geq M$ should be assumed to guarantee the matrices' degree of freedom. Denote

$\hat{\mathbf{H}}_i = \left[\mathbf{h}_{i,1}^T, ..., \mathbf{h}_{i,i-1}^T, \mathbf{h}_{i,i+1}^T, ...\mathbf{h}_{i,M}^T\right]^T$. The precoding vector $\mathbf{f}_i$ in ICIC is the normalized version of the following vector

$$\mathbf{w}_i = \left(I - \frac{\hat{\mathbf{H}}_i^H \hat{\mathbf{H}}_i}{||\hat{\mathbf{H}}_i||^2} \right) \mathbf{h}_{i,i}^H, \quad (14)$$

and it can be denoted as $\mathbf{f}_i = \frac{\mathbf{w}_i}{||\mathbf{w}_i||}$. As perfect CSIT is assumed at the transmitter, the inter-cell interference can be perfectly canceled, and then the SINR can be denoted as :

$$SINR_i = \frac{P_{t,i}|\mathbf{h}_{i,i}\mathbf{f}_i|^2}{N_0}. \quad (15)$$

In this case, problem $\mathbb{P}1$ can be rewritten as:

$$\mathbb{P}1 : \max_{\{P_{t,i}\}_{i=1}^{M}:P_{t,i}\geq 0} \frac{\sum\limits_{i=1}^{M} W \log \left\{ 1 + \dfrac{P_{t,i}|\mathbf{h}_{i,i}\mathbf{f}_i|^2}{N_0} \right\}}{\sum\limits_{i=1}^{M} P_{total,i}}. \quad (16)$$

Different from IA-GT, changing transmit power $P_{t,i}$ would not change other cells' interference level here, and hence, would not affect $SINR_j, j \neq i$. Therefore, for each BS, the optimal transmit power derivation should be based on the following criteria.

$$\max_{\{P_{t,i}\}:P_{t,i}\geq 0} \frac{W \log \left\{ 1 + \dfrac{P_{t,i}|\mathbf{h}_{i,i}\mathbf{f}_i|^2}{N_0} \right\}}{P_{total,i} + \sum\limits_{j=1,j\neq i}^{M} P_{total,j}}. \quad (17)$$

In order to perform the above optimization, the other cells' power consumption information is required, which is similar with the optimization in IA-GT (12). In order to realize it in a distributed manner, we apply the same strategies as in section 3.2.1, i.e., setting $\sum_{j=1,j\neq i}^{M} P_{total,j} = 0$ or assuming a symmetrical scenario with $P_{total,j} = P_{total,i}, \forall j \neq i$. For both strategies, the optimization object is changed as LEE_i again which can be denoted as follows.

$$\max_{\{P_{t,i}\}:P_{t,i}\geq 0} LEE_i = \frac{W \log \left\{ 1 + \dfrac{P_{t,i}|\mathbf{h}_{i,i}\mathbf{f}_i|^2}{N_0} \right\}}{P_{total,i}}. \quad (18)$$

The LEE optimization of a MIMO channels can be directly applied here. For more details, the readers can be referred in our previous study [13].

It is worthwhile here that the interference cannot be fully canceled if the CSIT is not perfect. In that case, the SINR formula of ICIC should not be (15) but be (10) and non-cooperative power control strategy based on the game theory in [17] is applicable in order to

optimize NEE, which is similar with section 3.2.1. Another critical issue in the imperfect CSIT case is that the capacity cannot be perfectly known before the transmission, the so-called capacity estimation mechanism is important for the capacity predication and for the EE optimization. About the capacity estimation, [13] discussed it in the single cell MIMO systems in detail and it can be simply extended here.

3.2.3 Multi-cell joint processing

Full CSIT and data sharing are assumed in MC-JP. As full cooperation is available in MC-JP, the multi-cell system can be viewed as a multi-user MIMO system which consists of a single "super-BS" deployed with JM transmit antennas and M single antenna receivers. CU gathers the whole data and CSIT information and then controls each BS's precoding and power allocation. Globally zero-forcing beamforming is applied.

Denote the channel matrix from all BSs to the M users as $\mathbf{H} \in \mathbb{C}^{M \times MJ}$ and then the precoding matrix is denoted as :

$$\mathbf{F} = \mathbf{H}^{H}(\mathbf{H}\mathbf{H}^{H})^{-1}. \tag{19}$$

And then the SINR of user i is

$$\mathrm{SINR}_i = \frac{P_{t,i}\lambda_i}{N_0}, \tag{20}$$

in which $\lambda_i = \frac{1}{(\mathbf{H}\mathbf{H}^{H})^{-1}_{i,i}}$ and here $P_{t,i}$ is the total power for user i. The NEE optimization problem with MC-JP can be rewritten as:

$$\mathbb{P}1 : \max_{\{P_{t,i}\}_{i=1}^{M}:P_{t,i}\geq 0} \frac{\sum_{i=1}^{M} W \log \left(1 + \frac{P_{t,i}\lambda_i}{N_0}\right)}{\sum_{i=1}^{M} P_{\mathrm{total},i}}. \tag{21}$$

As full CSIT and data sharing are available at the CU, NEE with different transmit power can be calculated. This feature in MC-JP indicates that the power control can be applied cooperatively. Fortunately, the maximizing NEE problem (21) is equivalent to the LEE maximizing in the frequency selective channels [4]. And then the binary search assisted ascent (BSAA) algorithm in [4] should be applied directly here. Compared with ICIC and IA-GT, MC-JP benefits from two aspects. For one thing, cooperative precoding can fully exploit the interference to further increase the SINR. For another, cooperative power control can better balance the capacity and power consumption. And hence MC-JP leads to higher NEE.

4 Constrained network energy efficiency optimization

Previous section discusses the unconstrained NEE maximizing problem. However, it is well known that maximizing EE would decrease SE in some sense. Therefore, considering the NEE maximizing problem with rate constraints can help to reveal the tradeoff between EE and SE and find the optimal EE with QoS constraints. We formulate the optimization problem with rate constraint as

$$\mathbb{P}2 : \max_{\{P_{t,i}\}_{j=1}^{M}:P_{t,i}\geq 0} \mathrm{NEE} = \frac{\sum_{j=1}^{M} R_j}{\sum_{i=1}^{M} P_{\mathrm{total},i}}, \tag{22}$$

$$\mathrm{s.t.} R_j \geq R_{j,\min}, \quad j = 1, ..., M,$$

where $R_{j,\min}$ denotes the rate constraint of user j. In this section, we will discuss the solution under the constraints.

4.1 Interference aware game theory

For ease of description, we denote the unconstrained solution of problem $\mathbb{P}1$ as $P^{*}_{t,i}, i = 1, ..., M$. Meanwhile, in IA-GT, we formulate the rate constraints as equations, which are denoted as follows by substituting (10) into the constraints.

$$W \log \left(1 + \frac{P_{t,i}|\mathbf{h}_{i,i}\mathbf{f}_i|^2}{N_0 + \sum_{j=1,j\neq i}^{M} P_{t,j}|\mathbf{h}_{j,i}\mathbf{f}_j|^2}\right) = R_{i,\min}, \quad i = 1, ..., M. \tag{23}$$

As the above equations are linear equations with M unknowns, they can be solved by some simple algorithms such as Gaussian elimination algorithm. We denote the solution of the above equations as $P^{+}_{t,i}, i = 1, ..., M. P^{+}_{t,i}$ represents the minimum transmit power for user i to guarantee the rate constraint. It is important to indicate that not any rate constraints are feasible because of the existence of inter-cell interference, so checking the feasibility before the optimization is necessary [26]. Here, when any $R_{i,\min}, i = 1,..., M$ is not achievable, the derived $P^{+}_{t,i}$ would not be all positive. In that case, the rate constraints are not feasible. This situation occurs when the system becomes interference limited and then any transmit power increasing cannot further increase the capacity.

After checking the feasibility and obtaining both $P^{+}_{t,i}$ and $P^{*}_{t,i}$, the solution should be derived. As only distributed power control at each BS can be employed here, the joint optimization is not applicable. Similar with section 3.2.1, Pareto-efficient Nash equilibrium is expected to be achieved and the equilibrium point is illustrated as follows.

If $P^{+}_{t,i} < P^{*}_{t,i}$ holds for all $i = 1,..., M$, then $P^{*}_{t,i}$ can achieve the globally Pareto-efficient Nash equilibrium. If there is any $j \in \{1,..., M\}$ fulfilling $P^{+}_{t,j} > P^{*}_{t,j}$, then

$P_{t,i}^+, i = 1, ..., M$ can achieve the Pareto-efficient Nash equilibrium. The first conclusion is straightforward according to section 3.2.1. About the second one, the reason can be illustrated as follows which is motivated by MeshkatiH et al. [27]. According to [17], the LEE of BS j is monotonously decreasing as a function of $P_{t,j}$ when $P_{t,j} \geq P_{t,j}^*$. Thus, for BS j with $P_{t,j}^+ > P_{t,j}^*$, $P_{t,j}^+$ is the feasible optimal transmit power with maximum LEE. For the BSs with $P_{t,i}^+ < P_{t,i}^*$, $P_{t,i}^+$ is not globally optimal and increasing $P_{t,i}$ can further increase BS i's LEE. However, BS i's transmit power increasing would increase the interference levels of BS j's user, thus BS j would increase its transmit power $P_{t,j}$ to fulfill the rate constraint. Unfortunately, increasing $P_{t,j}$ would cause BS j's LEE decreasing. Therefore, BS i's LEE cannot be increased without decreasing BS j's LEE. Thus, $P_{t,i}^+, i = 1, ..., M$ achieve Pareto-efficient Nash equilibrium. Above all, the solution can be denoted as follows.

If $P_{t,i}^+ < P_{t,i}^*$ holds for all $i = 1,..., M$,

$$P_{t,i}^{\text{opt}} = P_{t,i}^*, \quad i = 1, ..., M. \tag{24}$$

If $P_{t,i}^+ < P_{t,i}^*$ holds for any $i \in \{1,..., M\}$,

$$P_{t,i}^{\text{opt}} = P_{t,i}^+, \quad i = 1, ..., M. \tag{25}$$

4.2 Inter-cell interference cancellation

For ICIC, we also denote the unconstrained solution of problem $\mathbb{P}1$ in last section as $P_{t,i}^*, i = 1, ..., M$. Substituting (15) into the constraints, the rate constraints can be denoted as

$$W \log \left(1 + \frac{P_{t,i}|\mathbf{h}_{i,i}\mathbf{f}_i|^2}{N_0} \right) \geq R_{i,\text{min}}, \quad i = 1, ..., M. \tag{26}$$

Change the inequality as an equation, then the solutions are denoted as

$$P_{t,i}^+ = \left(2^{\frac{R_{i,\text{min}}}{W}} - 1 \right) \frac{N_0}{|\mathbf{h}_{i,i}\mathbf{f}_i|^2}, \quad i = 1, ..., M. \tag{27}$$

Compared with IA-GT, the solution of LEE optimization in ICIC are separately derived for each BS as shown in section 3.2.2. Therefore, the result in the single cell MIMO systems [14] can be directly applied there, and then the optimal solution can be denoted as

$$P_{t,i}^{\text{opt}} = \max \left(P_{t,i}^*, P_{t,i}^+ \right), \quad i = 1, ..., M. \tag{28}$$

4.3 Multi-cell joint processing

In MC-JP, the rate constraints are

$$W \log \left(1 + \frac{P_{t,i}\lambda_i}{N_0} \right) \geq R_{i,\text{min}}, \quad i = 1, ..., M. \tag{29}$$

Also denote the solutions of the equations as

$$P_{t,i}^+ = \left(2^{\frac{R_{i,\text{min}}}{W}} - 1 \right) \frac{N_0}{\lambda_i}, \quad i = 1, ..., M, \tag{30}$$

and then the rate constraints become

$$P_{t,i} \geq P_{t,i}^+, \quad i = 1, ..., M. \tag{31}$$

In order to solve problem $\mathbb{P}2$, some simple modifications are needed when applying BASS. For problem $\mathbb{P}1$, the maximum value between the refreshed one and zero is chosen for each transmit power (it is rate in [4]) during each iteration as shown in TABLE II in [4]. However, to solve problem $\mathbb{P}2$, the maximum value between the refreshed power and $P_{t,i}^+$ is chosen for each transmit power (it is rate in [4]) during each iteration. After the simple modification, the solution of problem $\mathbb{P}2$ can be derived.

5 Cooperative idling

It is worthwhile to note the truth that EE is denoted as the capacity divided by the power consumption, so improving capacity and decreasing power consumption are the two main methods to improve EE. In the previous discussion, the first method is employed, where higher cooperation leads to higher NEE because of capacity increasing through exploiting interference. Look at the second method then. It is observed that the NEE can be further improved if the constant power consumption part can be decreased.

In the multi-cell system, dynamically switching off BSs in a long-term can decrease the total power consumption during the low load period [23,28]. However, this technology always acts in the network level and needs to switch off the whole cell while the neighbor BSs need to apply some self-organizing network (SON) features, e.g., increasing transmit power or changing the antenna tilt, to compensate the coverage hole. In our study, the NEE maximizing is realized in a short-term in the physical layer and it is expected that the cell coverage should not be changed. Fortunately, we note that micro-sleep technology is promising to decrease the power consumption in short term, in which PA can be switched off during the no data transmission period. Motivated by the above aspects, a novel CI scheme is proposed. The CI utilizes the micro-sleep cooperatively to decrease the constant power consumption of BSs while guaranteeing the users' QoS, thus, it can improve the NEE significantly. Before introducing CI, we will review the micro-sleep technology at first.

5.1 Brief introduction of micro-sleep

Figure 1 depicts the example of micro-sleep and active mode. Here, active means that user data is trans mitting.

And micro-sleep means that when there is no user data transmitting, the BS should turn off the PA and signal processing component to save power. We can see from Figure 1 that the system information channels, e.g., common channels, pilot channels, and synchronization channels, need to be always transmitted to guarantee the cell coverage. In order to improve the potential of energy saving, the sending of system information need to be reduced or only sent on request [28]. Some standardization example can be found in 3GPP [24], which is called as DTX there. During the micro-sleep period, we denote the power consumption as P_{idle}, which includes the power consumption of system information sending etc.

5.2 Cooperative idling

Cooperative idling is a cooperative implementation of micro-sleep in the CoMP systems, in which full CSIT and data sharing are required. The basic idea of CI with two cells is illustrated in Figure 2, which can be easily extend to the multi-cell case. There are two BSs in Figure 2 and home BS of user 1 and 2 are BS 1 and 2, respectively. There are both data requested in user 1 and 2 in this slot. In the previous three conventional schemes, both BS 1 and 2 should be active to serve the two users. In IA-GT and ICIC, user 1 would receive the data from BS 1 and user 2 would receive the data from BS 2, respectively. In MC-JP, the users would receive data from both BSs simultaneously. As both users can receive signal from each BS, the NEE can be improved if we can guarantee the data transmission through one BS and idle the other one into micro-sleep to save energy. Motivated by this idea, CI is proposed and can be explained as follows. The CU would determine which BS should be idled and which one should be active according to the rate requirements and channel environment in the whole cluster at first. We assume that BS 1 is decided to be idle and BS 2 should be active to guarantee the data transmission in Figure 2. After that, the

CU would idle BS 1, i.e., turn BS 1 into micro-sleep, and meanwhile schedule the other active BS i.e., BS 2 to transmit the desired data to the both users through MU-MIMO.[a] As micro-sleep is employed cooperatively and the power consumption during micro-sleep P_{idle} is always much smaller than P_{con}, significant power saving and NEE improvement can be acquired.

The main feature of CI and its difference from BS switching off is that CI would not change the cell coverage and can be realized in a short-term, such as several milliseconds. Meanwhile, different from the conventional single cell micro-sleep where the status is determined by the BS itself, the status of BSs in CI is controlled by the CU and the determination is according to the rate requirements and channel environment in the whole cluster. Moreover, it is amazing to point out that CI can also decrease the data sharing in the backhaul. After CU makes decision to idle some BSs into micro-sleep mode, the user data would not be forwarded to these idle BSs.

In a more general multi-cell case, the CI scheme would idle several BSs into micro-sleep and serves the users whose home BSs are idled by the rest active BSs. Which BSs should be idled and which BSs should be active are the key challenge in CI. As full CSIT and data sharing are assumed in CI which indicates that the CU gathers the whole information, the optimal solution is exhaust search. Through calculating and comparing the NEE of the all possible active BS set, the optimal active BS set can be determined. The procedure of CI with exhaust search can be described as follows, in which the expression of NEE is modified by introducing the idling power P_{idle}.

1. For any BS set $\mathcal{A} \subseteq \{1, ..., M\}$, temporarily active the BSs in $\mathcal{A}$ and idling the rest BSs. And then calculate the maximum NEE as $\text{NEE}_{\mathcal{A},\max}$ as follows:
   - Denote the channel matrix from all BSs in $\mathcal{A}$ to the M users is $\mathbf{H}_{\mathcal{A}} \in \mathbb{C}^{M \times |\mathcal{A}|J}$, where $|\mathcal{A}|$ denotes
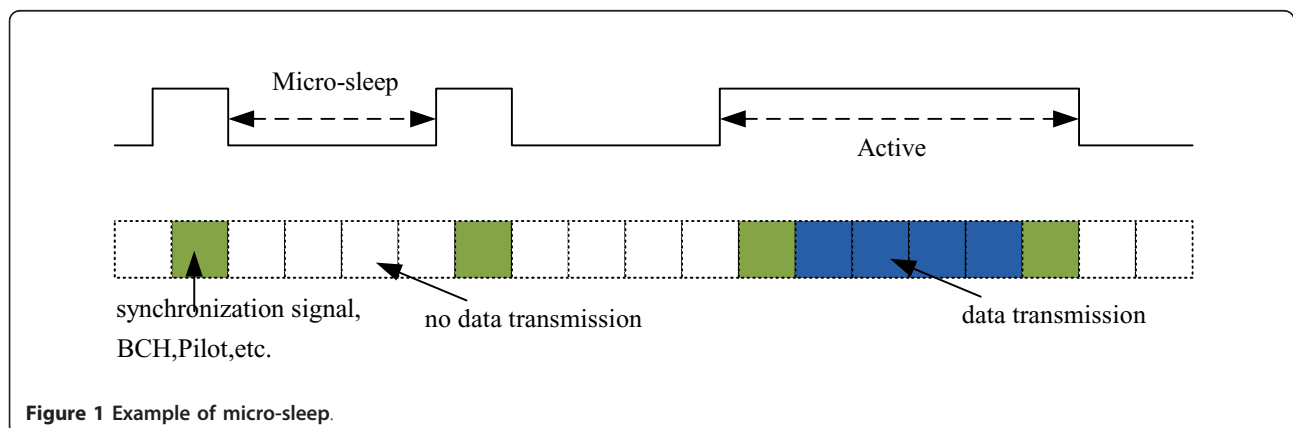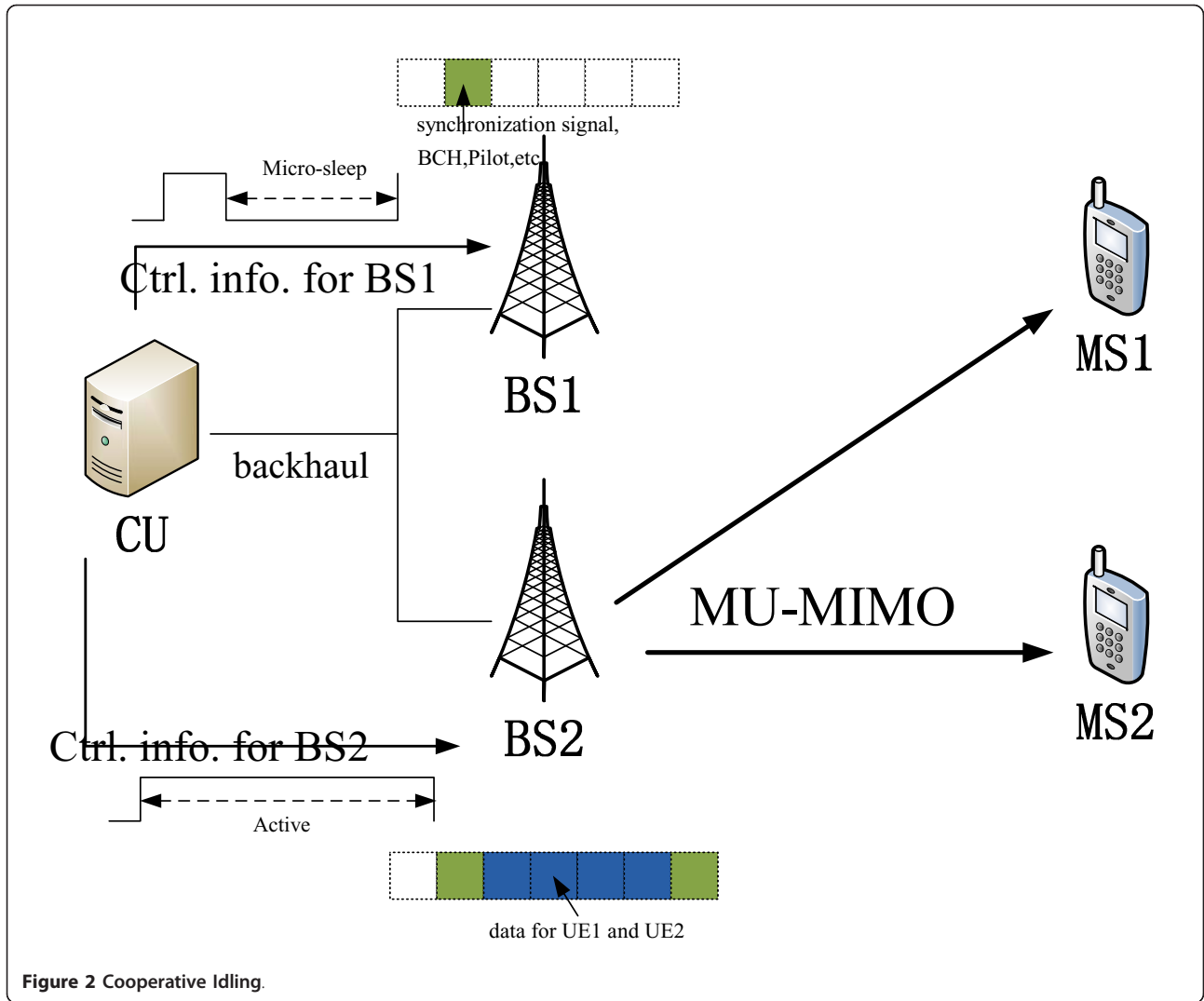

Figure 1 Example of micro-sleep.

Figure 2 Cooperative Idling.

the BS number in $\mathcal{A}.|\mathcal{A}|J \geq M$ should be guaranteed.

• Precoding matrix should be designed according to zero-forcing beamforming as

$$\mathbf{F}_i = \mathbf{H}_{\mathcal{A}}^{\mathrm{H}}(\mathbf{H}_{\mathcal{A}}\mathbf{H}_{\mathcal{A}}^{\mathrm{H}})^{-1}. \tag{32}$$

and the SINR of user j is

$$\mathrm{SINR}_j = \frac{P_{t,j}\lambda_j}{N_0}, \tag{33}$$

in which $P_{t,j}$ is the transmit power allocated to user j, $\lambda_j = \frac{1}{(\mathbf{H}_{\mathcal{A}}\mathbf{H}_{\mathcal{A}}^{\mathrm{H}})_{j,j}^{-1}}$.

• Introducing the idling power P_{idle}, and then the NEE maximizing can be denoted as

$$\mathrm{NEE}_{\mathcal{A},\max} = \max_{\{P_{t,j}\}_{j=1}^{M}:P_{t,j}\geq 0} \mathrm{NEE}_{\mathcal{A}}, \tag{34}$$

where

$$\mathrm{NEE}_{\mathcal{A}} = \frac{\sum_{j=1}^{M} W \log\left(1 + \frac{P_{t,j}\lambda_j}{N_0}\right)}{\sum_{j\in\mathcal{A}} P_{\mathrm{total},i} + \sum_{j\notin\mathcal{A}} P_{\mathrm{idle}}}. \tag{35}$$

Although P_{idle} is introduced, the expression here is similar as MC-JP. Therefore, BSAA and modified BSAA algorithms can also be applied here for the unconstrained and constrained case to maximize NEE here.

2. Compared all NEE with possible active BS set and choose optimal active BS set with the maximum NEE as follows:

$$\mathcal{A}_{\mathrm{opt}} = \arg\max_{\mathcal{A}\subseteq\{1,\dots,M\}} \mathrm{NEE}_{\mathcal{A},\max}. \tag{36}$$

Although employing the exhaust search scheme to determine the active and idle BSs in the cluster here is straightforward, the results can provide insights about the performance gain of CI. During the exhaust search, the CU need to calculate the NEE of each possible active BS set, the search size can be approximated as

$$\sum_{i=1}^{M} C_M^i = \sum_{i=1}^{M} \frac{M!}{i!(M-i)!}. \tag{37}$$

When the BS in the cluster is limited, the complexity would be acceptable, for instance, the search size is eight when $M = 3$. However, the complexity will increase exponentially as the BS number increases. When the BS number becomes large, developing low complexity schemes is very significant to decrease the complexity and computing power. The complexity of the exhaust search comes from two parts. For one thing, the search size increases significantly as shown above. For another, the calculation of maximum NEE in (34) needs iteration when apply BSAA or modified BSAA. This situation is similar with the energy efficient mode switching and user scheduling in MU-MIMO systems [14], where the complexity reduction is obtained through successive selection schemes. The successive selection schemes in [14] can decrease the search size. Moreover, the schemes in [14] exclude the impact of transmit power on the EE based on some approximations, thus they can also avoid calculating the maximum EE with iteration for every possible set. For CI, the low complexity schemes can be obtained through a similar way as in [14]. We may need to choose the active BSs according to a successive manner to decrease the search size at first, and then try to exclude the impact of transmit power on NEE via approximating the NEE formula to avoid calculating the maximum NEE with iterative BSAA or modified BSAA for every possible set. This is a very interesting and important issue to realize the CI practical when M is large, which we will leave for the future study. During the simulation, as $M \leq 3$ is considered, the complexity of applying CI with exhaust search is acceptable.

6 Simulation results
This section provides the simulation results. In the simulation, bandwidth is set as 5 MHz, $\eta = 0.38, P_{idle} = 30W, P_{cir} = 66.4W, P_{Sta} = 36.4W, p_{sp,bw} = 3.32 \mu$ W/Hz, and $p_{ac,bw} = 1.82 \mu$ W/Hz, noise density is set as -174Bm/Hz, the pathloss model is set as 128.1 + 37.6$\log_{10} d_{i,j}$. Although the power needed for exchanging the information in these schemes should be considered to make the comparison fair, the model of the data exchanging is difficult to get as it is affected by the

backhaul connection type etc. We omit this impact here and it should be considered in the future study.

Figures 3, 4, 5, 6, 7, 8 and 9 depict the simulation results in a two-cell network where $J = 4$, $M = 2$. In the two-cell network, BSs are located in $(-R, 0)$ and $(R, 0)$ and two users are generated between the two BSs. User1 is located in $(-\mu_1 R, 0)$ and user2 is located in $(\mu_2 R, 0)$, in which $0 \leq \mu_1 \leq 1$ and $0 \leq \mu_2 \leq 1$. In the simulation, $R = 1$ km. In order to illustrate the effect of idling BSs on both NEE and NC, Figures 3, 4, 5, 6, 7 and 8 depict the NEE and NC when one BS of the two is idled. Here, the one BS who can provide higher NEE out of the two is chosen to be active.

In Figures 3, 4, 5 and 6, the unconstrained case is plotted. Figure 3 depicts the NEE versus μ_2, in which $\mu_1 = 0.9$. We can see that NEE increases as μ_2 changes from 0.1 to 0.9. That is because user2 is more close to BS2 when μ_2 gets larger and then the inter-cell interference decreases. Non-cooperative IA-GT performs worst in this figure and the performance gain between ICIC and IA-GT comes from the SINR increase because of interference cancellation. MC-JP further improves NEE compared with ICIC. The increasing comes from two reasons. The first one comes from the SINR improvement through exploiting the inter-cell interference and the second one comes from the joint EE power control. The exciting result here is that CI preforms best. Through idling one of the two BSs to decrease the constant power consumption, CI even outperforms MC-JP. This result indicates that only increasing SINR through combatting interference is not enough from the EE point of view. Through decreasing the constant power simultaneously, higher NEE can be achieved in CI. However, the NEE gap between CI and MC-JP decreases when μ_2 increases. That is because μ_2 increasing means that user2 is much closer to BS2. In this case, CI can not benefit from the pathloss decreasing between user2 and BS2, so the gap becomes smaller. Figure 4 depicts the corresponding NC with the optimal NEE. Unfortunately, CI has the smallest NC because of smaller multiplexing and diversity gain caused by less transmit antennas. This result shows us that CI is much more suitable to the low load scenario. If QoS constraint is considered, the use of CI or other schemes should be determined based on the rate requirement, which is shown later. Figures 5 and 6 depict the NEE and NC versus μ_2, in which $\mu_1 = 0.1$. As $\mu_1 = 0.1$ means the user1 is more close to the cell edge, cooperation would lead to higher performance gain. Significant performance is gained by CI there. Interestingly, CI has higher NC than IA-GT. That is because interference becomes huge when users are in the cell edge and CI can avoid the inter-cell interference.
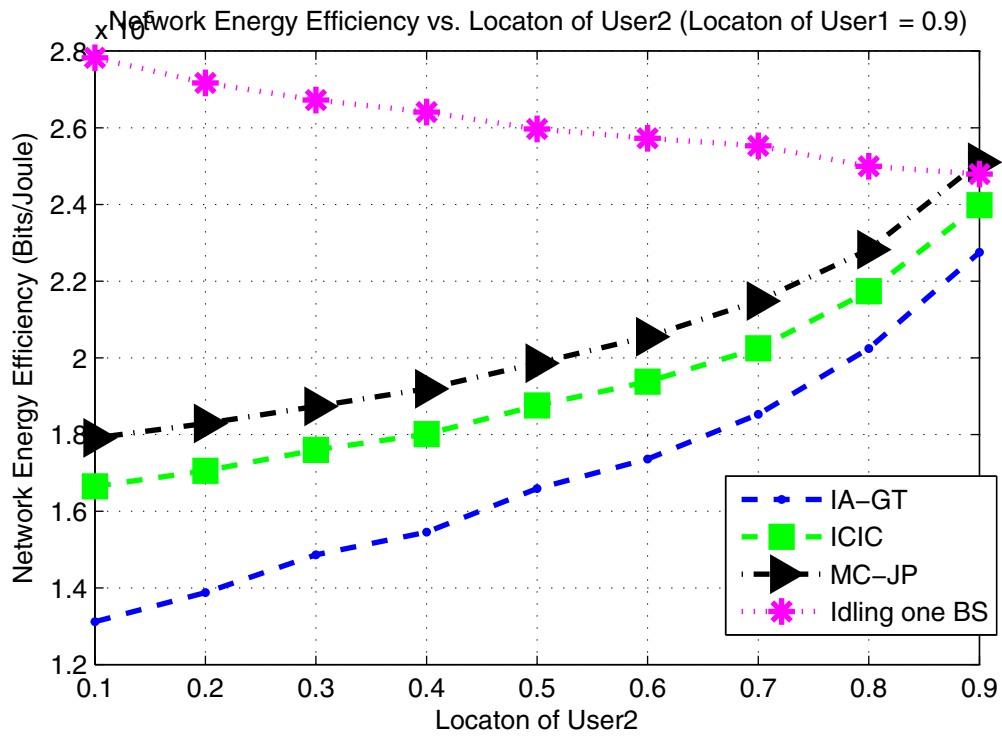
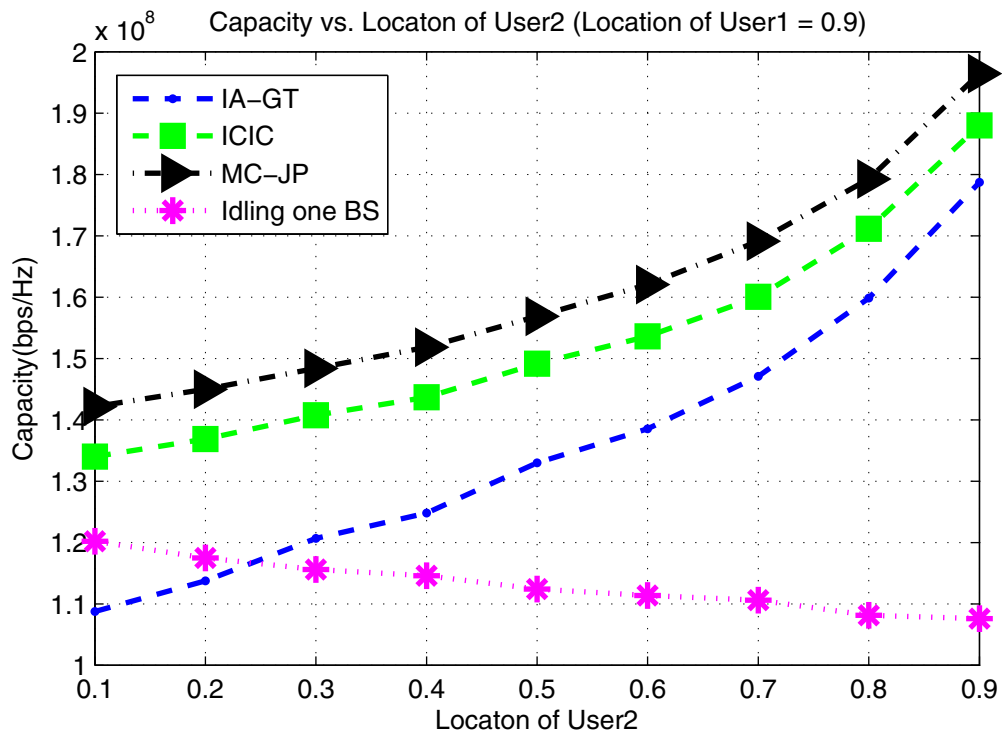**Figure 3 Network energy efficiency versus location of user2 when user1 is at 0.9**.

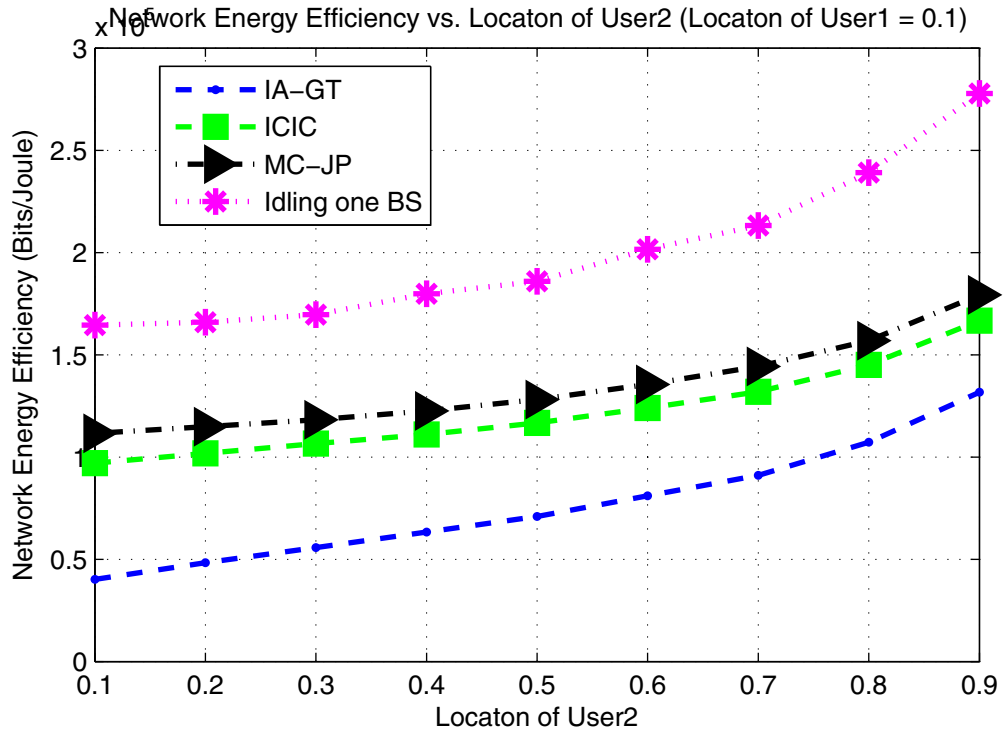**Figure 4 Network capacity versus location of user2 when user1 is at 0.9**.

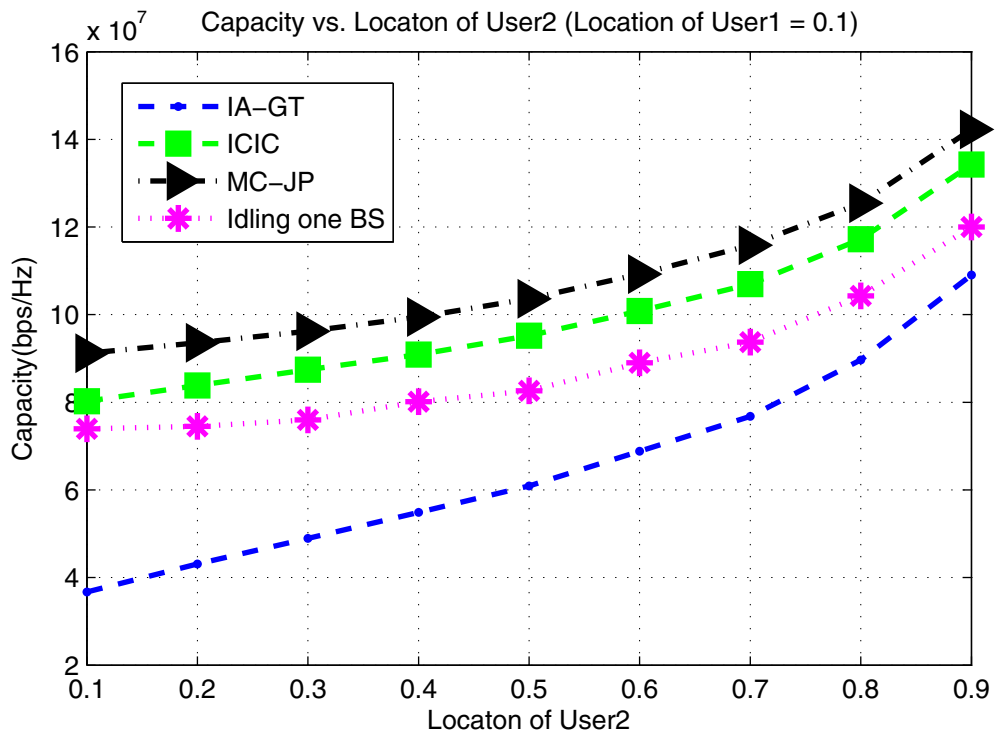**Figure 5 Network energy efficiency versus location of user2 when user1 is at 0.1**.

Figure 6 Network capacity versus location of user2 when user1 is at 0.1.

Figures 7 and 8 show the results with different rate constraints. In the simulation, $R_{i,\min}$ of all users are set as the same. Note that IA-GT cannot always achieve the rate constraints, especially when the rate constraint is high. MC-JP performs always better than ICIC and IA-GT. We can see that idling one BS can significantly increase the NEE when the rate constraints are small. However, the performance of idling one BS decreases seriously when rate constraint becomes large. Especially in Figure 8, idling one BS performs worst when $R_{i,\min}$ is larger than 5×10^7 bps. The reason is that the transmit power would dominate the total power consumption when $R_{i,\min}$ is large and then active more BSs would benefit. Fortunately, as BS idling is controlled adaptively by CU in CI and the CI would degenerate to the MC-JP in this case. Figure 9 is an example in which users are located randomly between the two BSs and the performance of CI is shown. We can see that CI performs better in the low rate constraint case and performs the same as MC-JP when rate constraint increases.

In order to externalize the performance of the network, we plot the NEE in the multi-cell systems. Figure 10 plots the network layout in the simulation. The three BSs in the center are set as the cooperative cluster and the nine BSs outside are set as the interference cells. The inter-site distance is set as 1 km. In Figure 11 and 12, average NEE versus each user's rate constrain is plotted and $R_{i,\min}$ of all users are set as the same in the simulation. It is set as $J = 4$ in Figure 11 and $J = 8$ in Figure 12. It is similar as the simulation in the two cells that CI performs better than MC-JP in the low rate constraint scenarios and degenerates to MC-JP when rate constraint becomes large. However, IA-GT performs better than ICIC in Figure 11. That is because when J is comparable with M, the matrix degree of freedom would be used for canceling the interference in ICIC and then the diversity gain decreases. When $J = 8$ in Figure 12, there are enough degrees of freedom there, and hence ICIC performs better than IA-GT.

Figure 13 and 14 show us the average NEE versus cell size. Here, cell size means inter-site distance and no rate constraint is considered. We can see the performance gain of CI in the pictures. Interestingly, IA-GT performs better than ICIC in Figure 13 and the performance gap between IA-GT and ICIC becomes slight when cell size increases. That is because interference becomes more significant with denser network deployment and then ICIC is better in the small cell size
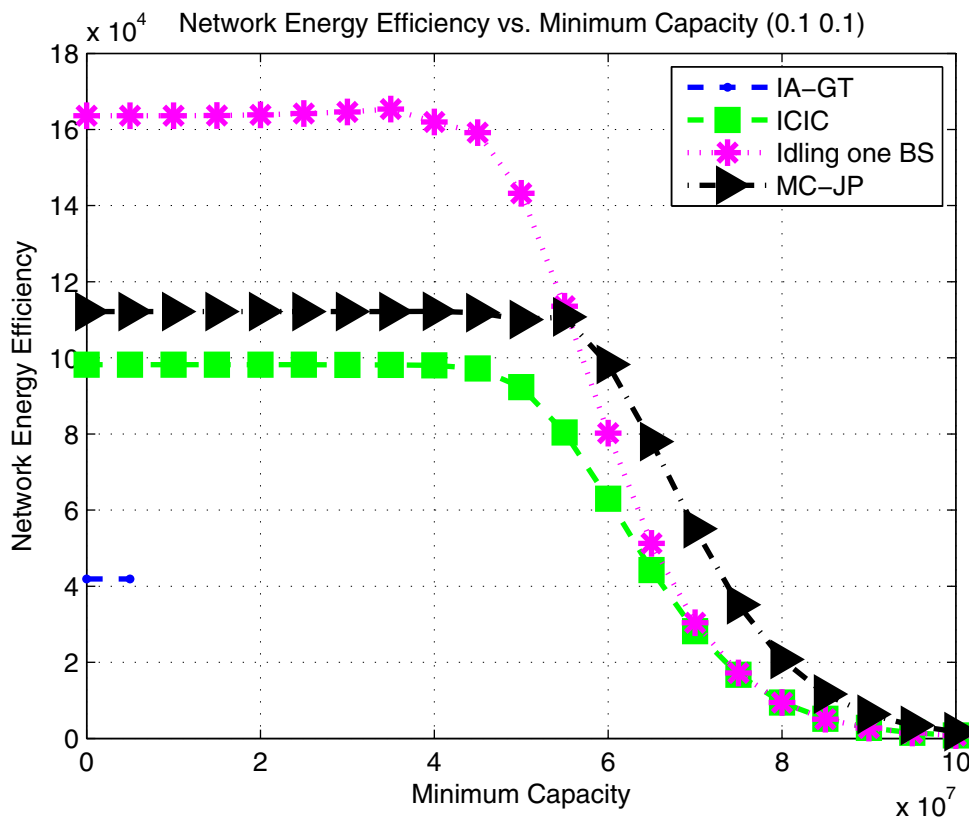

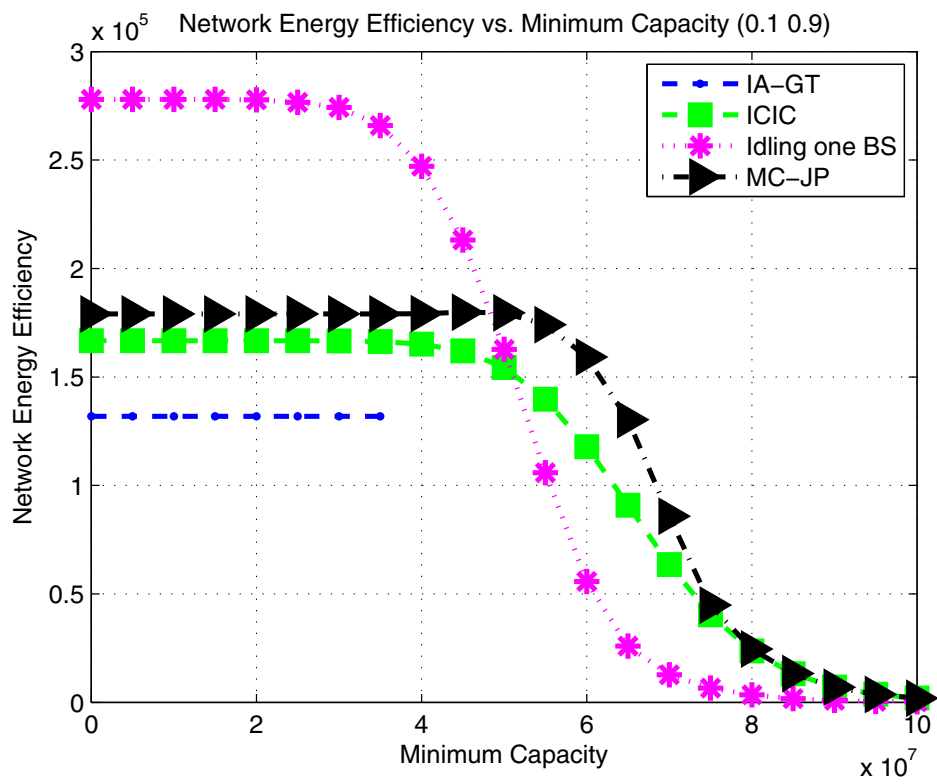**Figure 7 Network energy efficiency versus rate constraint, user locations: 0.1, 0.1.**

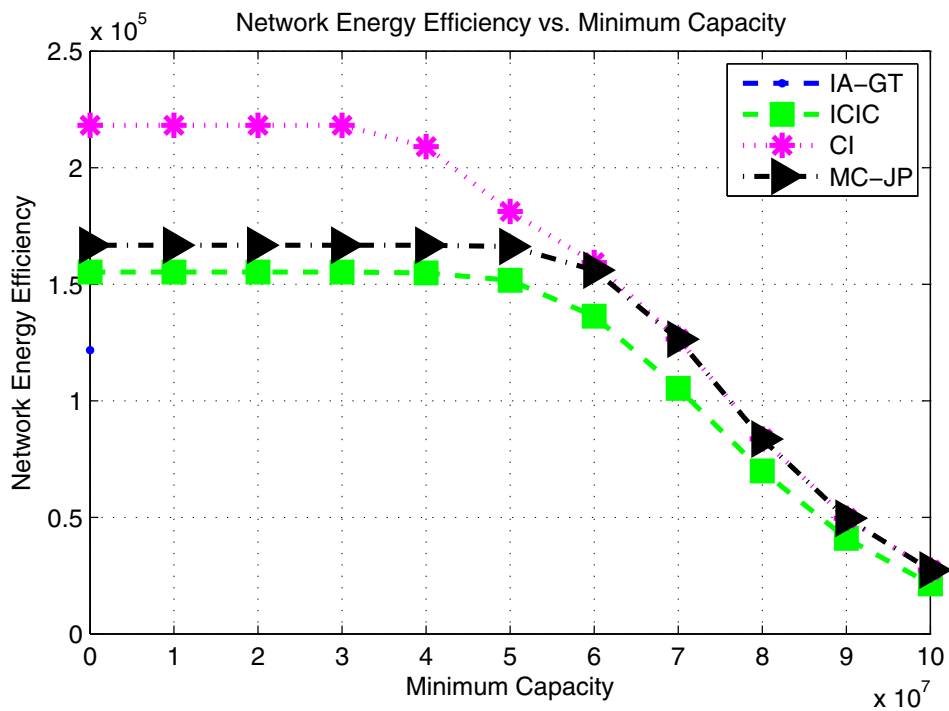**Figure 8 Network energy efficiency versus rate constraint, user locations: 0.1, 0.9**.

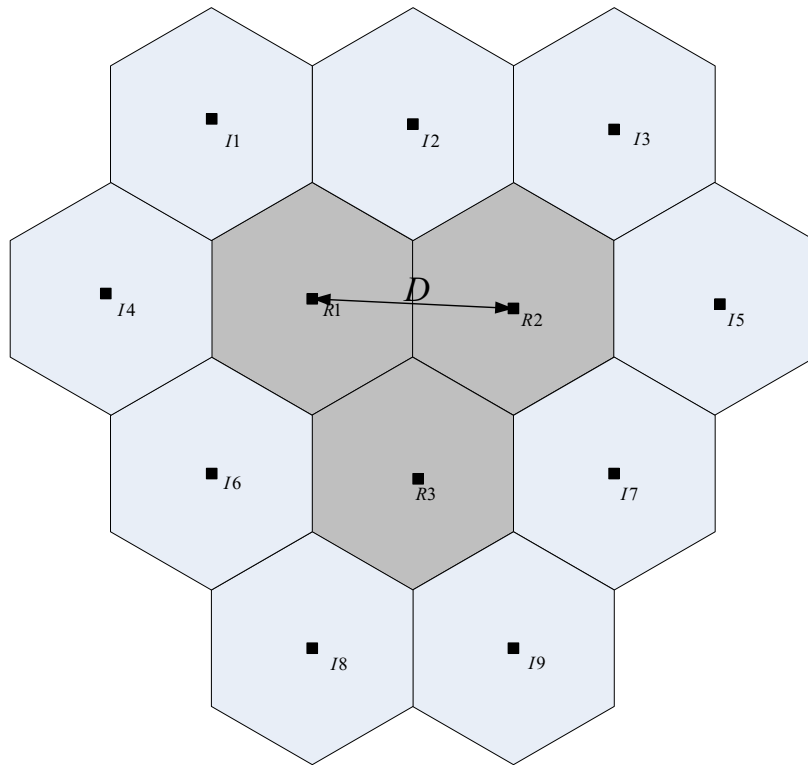**Figure 9 Average network energy efficiency in a two-cell system**.
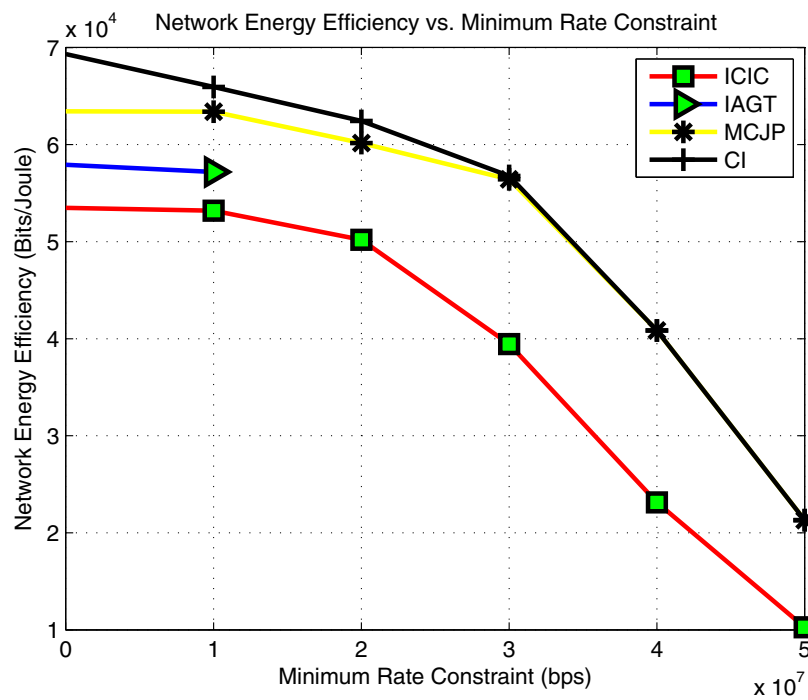
Figure 10 Three cell network layout.

Figure 11 Average network energy efficiency versus rate constraint in a three-cell system: 4 transmit antennas.
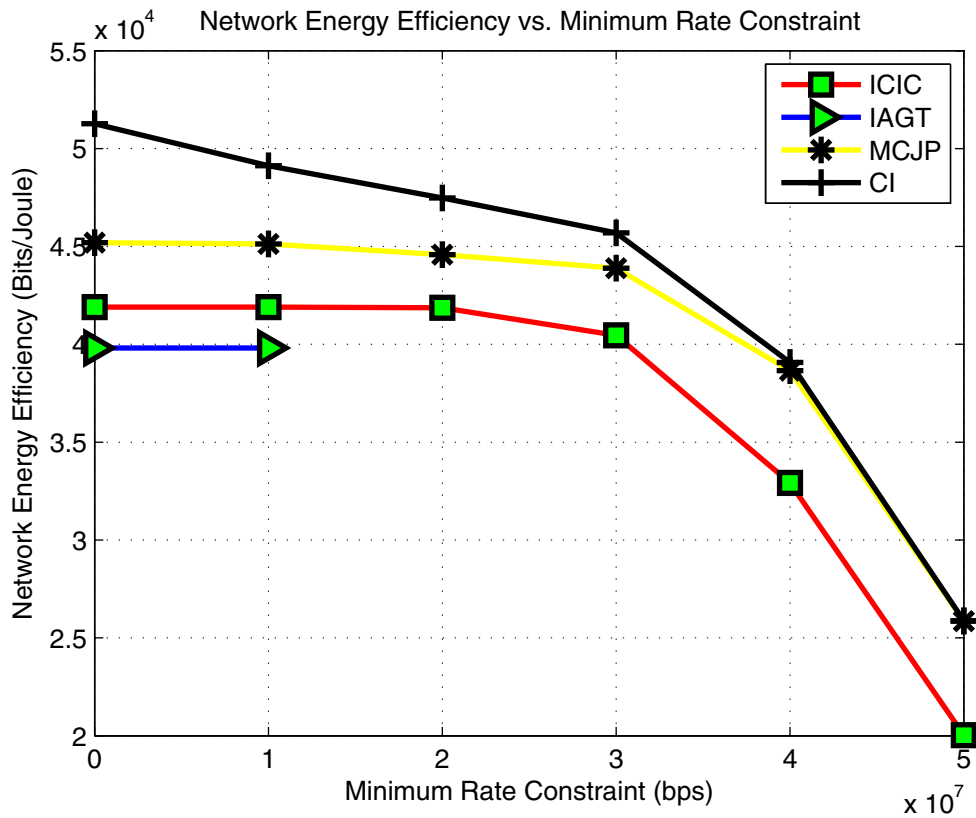
Figure 12 Average network energy efficiency versus rate constraint in a three-cell system: 8 transmit antennas.
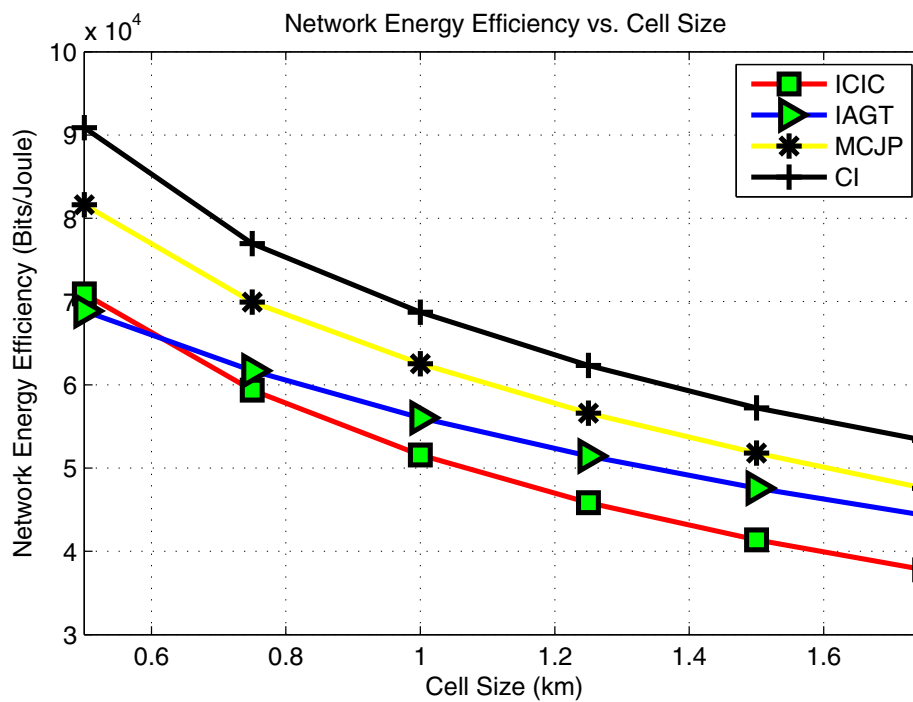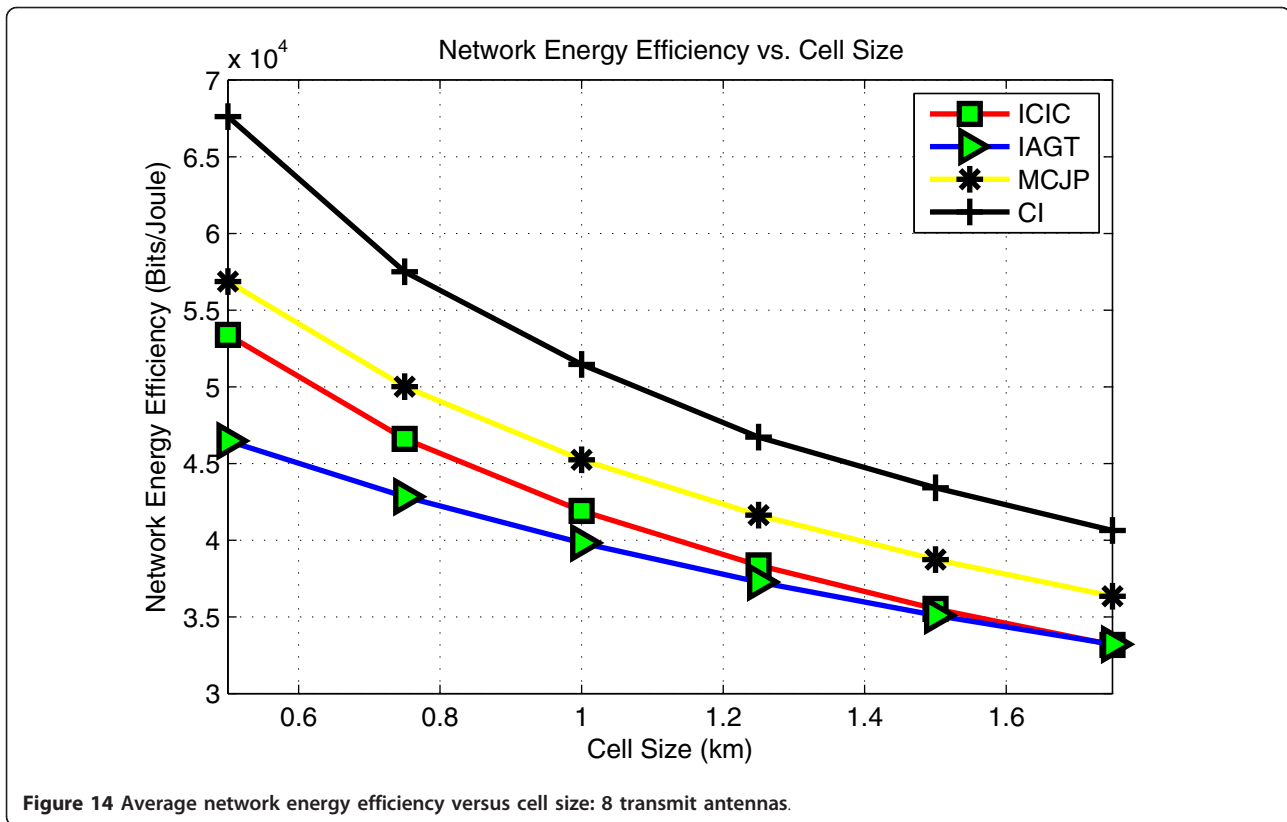

Figure 13 Average network energy efficiency versus cell size: 4 transmit antennas.

Figure 14 Average network energy efficiency versus cell size: 8 transmit antennas.

scenario. But channel strength dominates the performance in the large cell size scenario, therefore, IA-GT benefits then. Here, we can conclude that a mode switching between IA-GT and ICIC is necessary from NEE point of view and some example of SE aware mode switching can be found in [19].

7 Conclusion

Maximizing NEE problem in the multi-cell network is addressed in this article. Optimal NEE schemes with different levels of cooperation are discussed and then a novel CI scheme is proposed to further improve the NEE. Simulation results confirms the performance gain of CI and it is promising to improve EE, especially in the low load scenarios.

Endnotes

[a]Note that other multiple access technologies such as TDMA, FDMA are also can be applied here to enable CI.

Abbreviations

NEE: Network energy efficiency; EE: energy efficiency; IA-GT:interference aware game theory; ICIC: inter-cell interference cancellation; MC-JP: multi-cell joint processing; CSIT: channel state information at the transmitter; CI: cooperative idling; NC: network capacity; LEE: link energy efficiency; PA: power amplifier; SVD: singular value decomposition; BS: base stations; SE: spectral effieicncy; CoMP: coordinated multipoint; SINR: signal to interference noise ratio; DVSINR: distributed virtual SINR; CU: central unit; QoS: quality of service; MIMO: multiple input multiple output; MU-MIMO: multiuser MIMO; DTX: discontinuous transmission; SON: self-organizing network.

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Competing interests

The authors declare that they have no competing interests.

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