On the Energy Efficiency-Spectral Efficiency Trade-Off in the Uplink of CoMP System

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***Abstract*—In this paper, we derive a generic closed-form approximation (CFA) of the energy efficiency-spectral efficiency (EE-SE) trade-off for the uplink of coordinated multi-point (CoMP) system and demonstrate its accuracy for both idealistic and realistic power consumption models (PCMs). We utilize our CFA to compare CoMP against conventional non-cooperative system with orthogonal multiple access. In the idealistic PCM, CoMP is more energy efficient than non-cooperative system due to a reduction in power consumption; whereas in the realistic PCM, CoMP can also be more energy efficient but due to an improvement in SE and mainly for cell-edge communication and small cell deployment.**

***Index Terms*—Energy efficiency, Spectral efficiency, Trade-off, CoMP system.**

I. Introduction

The need for network operators to reduce their CO_2 emissions and energy related operating expenses (OPEX) is currently steering research in communication towards more energy efficient networks. Until recently, the main metric for designing communication networks has been the spectral efficiency (SE), which measures how efficiently a limited frequency spectrum is utilized but fails to account for how efficiently the energy is consumed. The latter can be measured by means of an energy efficiency (EE) metric such as the bits-per-joule capacity [1], which measures the maximum amount of bits that can be delivered by the network per Joule it consumed to do so or by using an energy consumption metric such as the traditional energy-per-bit to noise spectral density [2]. A metric is not sufficient on its own for accurately assessing the EE of a network, indeed, its power consumption must be adequately modeled. In the literature, two forms of power consumption model (PCM) can be identified for characterizing the EE of a communication network: the idealistic PCM which only considers transmit power [1], [2] and; the realistic PCM which accounts for the total power consumption of the network by including the transmit and processing powers, cooling loss, etc., in its model [3]–[6].

According to Shannon's capacity theorem, maximizing the EE while maximizing the SE are conflicting objectives and, hence, a trade-off exists between these two metrics [1]. In coordinated multi-point (CoMP) system, which is a generic name for base station (BS) cooperation, this EE-SE trade-off has been defined in [7] for the case of single antenna at all nodes and by considering solely the idealistic PCM. Moreover, the expression of [7] is based on the linear approximation technique of [2], which is only accurate in the low-power/SE regime.

In this paper, we derive a novel and accurate closed-form approximation (CFA) of the EE-SE trade-off for the uplink of multiple-input multiple-output (MIMO) symmetrical CoMP system with uniformly distributed users and a perfect backhaul link. In comparison with the linear approximation in [7], our CFA is accurate for a wider range of SE values and can thus be utilized to obtain the EE gain of CoMP over the non-cooperative scheme. In Sections II, we present the symmetrical CoMP model. Section III introduces the EE-SE trade-off concept based on both PCMs and also presents the derivation of our EE-SE trade-off CFA. As an application for our CFA, we derive in Section IV the EE gain of CoMP over the non-cooperative approach for both PCMs and utilize this criterion for establishing analytically and by simulations the EE potential of CoMP. Numerical results are presented in Section V. In the idealistic PCM, CoMP is more energy efficient than non-cooperation due to a reduction in power consumption; whereas in the realistic PCM, CoMP can also be more energy efficient but mainly for cell-edge communication, small cell deployment and as a result of SE improvement. Finally, conclusions are drawn in Section VI. Some preliminary results on the EE-SE trade-off for the Wyner uplink model are presented in [8]. In this work, we consider a more realistic uplink channel model and provide a detailed analysis of the EE gain of CoMP over the non-cooperation approach.

II. System Model

We consider the uplink of a symmetrical CoMP system where K user terminals (UTs), which are uniformly distributed in each cell, transmit signals over Rayleigh fading channels to M BSs, which fully cooperate to decode these signals. Each UT and each BS is equipped with t and r antennas, respectively. The aggregate received signal vector $\mathbf{y} \in \mathbb{C}^{Mr\times 1}$ can be expressed as

$$\mathbf{y} = \tilde{\mathbf{H}}\mathbf{x} + \mathbf{z}, \quad (1)$$

where $\mathbf{x} \in \mathbb{C}^{KMt\times 1}$ is the transmit signal vector and $\mathbf{z} \in \mathbb{C}^{Mr\times 1}$ being a vector with independent entries of zero-mean complex Gaussian noise. The channel matrix can be expressed as $\tilde{\mathbf{H}} = \mathbf{\Omega}_V \odot \mathbf{H}_V$, where $\mathbf{H}_V$ is a $Mr \times KMt$ matrix with i.i.d. random variables having zero mean and unit variance,

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$\mathbf{\Omega}_V$ is a $Mr \times KMt$ deterministic distance dependent pathloss matrix and $\odot$ denotes the Hadamard product. Considering the multiple antennas at each UT and BS, $\mathbf{\Omega}_V = \mathbf{\Omega} \otimes \mathbf{J}$, where $\otimes$ denotes the Kronecker product, $\mathbf{J}$ is a $r \times t$ matrix with all its elements equal to one and $\mathbf{\Omega}$ is a $M \times KM$ matrix which meets the doubly-regular characteristic [9] such that

$$\mathbf{\Omega} = \begin{bmatrix} \boldsymbol{\omega}_0 & \boldsymbol{\omega}_1 & \boldsymbol{\omega}_2 & \cdots & \boldsymbol{\omega}_{M-1} \\ \boldsymbol{\omega}_{-1} & \boldsymbol{\omega}_0 & \boldsymbol{\omega}_1 & & \vdots \\ \boldsymbol{\omega}_{-2} & \boldsymbol{\omega}_{-1} & \boldsymbol{\omega}_0 & \ddots & \boldsymbol{\omega}_2 \\ \vdots & & \ddots & \ddots & \boldsymbol{\omega}_1 \\ \boldsymbol{\omega}_{-M+1} & \cdots & \boldsymbol{\omega}_{-2} & \boldsymbol{\omega}_{-1} & \boldsymbol{\omega}_0 \end{bmatrix}, \quad (2)$$

and

$$\lim_{M\to\infty} \frac{1}{M} \sum_{i=0}^{M-1} \mathbf{\Omega}_{i,j} = \lim_{M\to\infty} \frac{1}{M} \sum_{j=0}^{M-1} \mathbf{\Omega}_{i,j} \ , \quad (3)$$

where $\boldsymbol{\omega}_m = [\omega_1^m \cdots \omega_K^m]$ is a $1 \times K$ vector containing the pathloss factor between all UTs in the m^{th} cell and a reference BS. Each element in $\boldsymbol{\omega}_m$ is obtained from the power-law pathloss model given as $\sqrt{L_0\left(1 + d_k^m/d_0\right)^{-\eta}}$, where d_k^m is the distance to the reference BS, η is the path loss exponent, L_0 is the power loss at a reference distance d_0. In addition, the k^{th} UT transmits its signal with a power P_k and, without loss of generality, we assume that all UTs transmit with equal power, i.e. $P_k = P \ \forall \ \{k = 1, \ldots, K\}$. Moreover, the UTs transmit power is normalized by the noise power N such that $\gamma = P/N$ and $\bar{\gamma} \triangleq K\gamma$. The ergodic per-cell SE of the uplink channel is given in [7] as

$$\bar{S} = f(\bar{\gamma}) = \frac{1}{M}\mathbb{E}_{\tilde{H}}\left\{\log_2\!\Big(\mathrm{I}_M + \frac{\bar{\gamma}}{Kt}\tilde{\mathbf{H}}\tilde{\mathbf{H}}^\dagger\Big)\right\} \quad (4)$$

in bits/s/Hz, where $\mathrm{I}_{\{\}}$ is an identity matrix and, moreover, the asymptotic per-cell SE with doubly-regular channel can be approximated as [10]

$$\bar{S} \approx \tilde{f}(\bar{\gamma}) = \ Kt\Big[\log_2\!\big(1 + y - \mathcal{F}(y,\beta)\big) + \frac{1}{\beta}\log_2\!\big(1 + y\beta - \mathcal{F}(y,\beta)\big) - \frac{\log_2(e)}{y\beta}\mathcal{F}(y,\beta)\Big], \quad (5)$$

where $\mathcal{F}(y,\beta) = \frac{1}{4}\Big[\sqrt{1+y(1+\sqrt{\beta})^2} - \sqrt{1+y(1-\sqrt{\beta})^2}\Big]^2$ and $y = \frac{\|\mathbf{\Omega}\|^2\bar{\gamma}}{KM\beta}$. In addition, $\beta = Kt/r$ is the ratio of the horizontal to the vertical dimension of $\tilde{\mathbf{H}}$ and $\| \quad \|$ is the frobenius norm.

III. EE-SE Trade-off for the Uplink of CoMP

A. EE-SE Trade-off definition

Given that the K UTs of a cell achieve a per-cell sum-rate R (bits/s) by consuming a power P_T (Watts), the EE and the energy consumption index of each cell can be defined as $\mathcal{C}_J = \frac{R}{P_T}$ in terms of the bit-per-joule capacity and as $E_b = \frac{P_T}{R}$ in terms of the energy-per-bit, respectively. Note that $P_T = KP$ when assuming the idealistic power model [1], [2]. Given that $S = \frac{R}{W}$ (bits/s/Hz) is the achievable SE, hence, we can express $\bar{\gamma}$ both in terms of SE and EE as follows

$$\bar{\gamma} = \frac{P_T}{N_0 W} = S\frac{E_b}{N_0} = \frac{S}{N_0\mathcal{C}_J}. \quad (6)$$

Inserting (6) into (4), the EE-SE trade-off for the uplink of CoMP can be defined as

$$\mathcal{C}_J \ = \frac{S}{N_0 f^{-1}(\bar{S})} \ , \quad (7)$$

where f^{-1} is the inverse function of f in (4). Equation (7) indicates that the EE-SE trade-off can be formulated by finding an explicit expression for $f^{-1}(\bar{S})$. For example, $f^{-1}(\bar{S})$ can easily be obtained for point-to-point AWGN channel as in [1], however, this is not as straightforward for more complex channel scenarios such as CoMP. Instead, approximating $f^{-1}(\bar{S})$ can turn out to be an effective solution for formulating the EE-SE trade-off in closed-form, as it has been shown in [2] and [7] for the low-SE regime. An improved approach will be to design a tight CFA of $f(\gamma)$ i.e. $f(\gamma) \approx \tilde{f}(\gamma)$, such that our CFA has an explicit accurate solution for $\tilde{f}^{-1}(\bar{S}) \approx f^{-1}(\bar{S})$, regardless of the value of $\bar{S}$.

B. Realistic EE-SE Trade-off for the Uplink of CoMP

In a realistic CoMP system, the total UT transmit power, KP, is not the only consumed power. Some other power components must be taken into account such as the UT circuit power, BS processing and backhaul powers. Adapting the PCMs of [4]–[6] to the uplink of CoMP, we can express the realistic total consumed power per cell as

$$P_T = K\left(\frac{P}{\varsigma} + tP_c\right) + bP_{sp} + cP_{bh}, \quad (8)$$

where $0 \leq P \leq P_{max}$, P_c and $\varsigma \in [0,1]$ are the circuit power and amplifier efficiency of each UT, respectively, while P_{sp} and P_{bh} denote the BS signal processing power and additional backhauling induced power for supporting CoMP, respectively. In addition, the parameter $b = (1 + c_c)(1 + c_{dc})(1 + c_{ms})$ accounts for the cooling, DC-DC and main supply losses [3], i.e. c_c, c_{dc} and c_{ms} respectively, and c is the ratio of the number of backhaul links to the number of BSs [4]. The power P_{sp} is given in [4] by

$$P_{sp} = r.p_{sp}\left((0.9 - v) + 0.1M + vM^2\right), \quad (9)$$

where p_{sp} is the base value of the signal processing power and $\left((0.9 - v) + 0.1M + vM^2\right)$ is the additional processing cost as a result of joint processing. Note that 10% and v% (where v is between 1 and 10%) of p_{sp} are used for channel estimation and MIMO processing, respectively. The backhaul power P_{bh} is given as $P_{bh} = \frac{C_{ul}}{C_{bh}}p_b$ Watts, where C_{bh} is the capacity of the backhaul link with dissipation power p_b. In the non-cooperative scenario, $c = 0$ and $P_{sp} = r.p_{sp}$ [3]. Inserting (8) into (6), the uplink of CoMP EE-SE trade-off in (7) can be generalized as

$$\mathcal{C}_J = \frac{S}{N_0}\left[\frac{f^{-1}(\bar{S})}{\varsigma} + \frac{tKP_c + bP_{sp} + cP_{bh}(\bar{S})}{N}\right]^{-1} \quad (10)$$

C. EE-SE Trade-off Closed-Form Approximation for the Uplink of CoMP

In the uplink of CoMP, obtaining a closed form expression for the EE-SE trade-off from $f(\bar{\gamma})$ is not feasible. Instead, we utilize $\tilde{f}(\bar{\gamma})$ whose inverse function, i.e. $\tilde{f}(\bar{S})$, can be expressed into a closed-form. From (5), we denote $q_0 = \frac{\bar{\beta}}{w\left(1+y/\bar{\beta}-\mathcal{F}\left(y,1/\bar{\beta}\right)\right)}$ and $r_0 = \frac{1}{w\left(1+y-\mathcal{F}\left(y,1/\bar{\beta}\right)\right)}$ such that $q_0 r_0 = \frac{\mathcal{F}\left(y,1/\bar{\beta}\right)}{y\beta}$. Expanding $\mathcal{F}(y,\beta)$, q_0 and r_0 can be re-expressed as in (E.41) of [11], i.e. $q_0 \triangleq \frac{\bar{\beta}-1-w^2+\sqrt{(\bar{\beta}-1-w^2)^2+4w^2\bar{\beta}}}{2w}$ and $r_0 \triangleq \frac{1-\bar{\beta}-w^2+\sqrt{(1-\bar{\beta}-w^2)^2+4w^2}}{2w}$, respectively, and (5) can be simplified as

$$\bar{S} \approx Kt\left[\bar{\beta}\log_2\!\left(\frac{\bar{\beta}}{wq_0}\right) + \log_2\!\left(\frac{1}{wr_0}\right) - q_0 r_0 \log_2(e)\right], \quad (11)$$

where $w = 1/\sqrt{y/\bar{\beta}}$, $\bar{\beta} = \frac{1}{\beta}$ and, hence, (5) and (11) are equivalent. For the case that $K = 1$ and $w = 1/\sqrt{\gamma}$, equation (11) is exactly the definition of the CFA for the MIMO Rayleigh fading channel SE given in [11]. Using this expression, we have recently derived in [12] an accurate CFA of the MIMO EE-SE trade-off. Since we have shown here that (5) is equivalent to (11), we can utilize our approach of [12] for deriving an accurate CFA of the inverse of $\tilde{f}(\bar{\gamma})$ as

$$\tilde{f}^{-1}(\bar{S}) = \frac{\beta\left(\left[1+\frac{1}{W_0\left(g_t(\bar{S})\right)}\right]\left[1+\frac{1}{W_0\left(g_r(\bar{S})\right)}\right]-1\right)}{2q\left(\mathbf{\Omega}\right)M(1+\beta)} \quad (12)$$

where $g_t\left(\bar{S}\right) \triangleq -2^{-\left(\frac{\bar{S}+h(\bar{S})}{2Kt}+1\right)}e^{-\frac{1}{2}}$, $g_r\left(\bar{S}\right) \triangleq -2^{-\left(\frac{\bar{S}-h(\bar{S})}{2r}+1\right)}e^{-\frac{1}{2}}$, $q(\mathbf{\Omega}) = \frac{\|\mathbf{\Omega}\|^2}{KM^2}$ and $W_0\left(x\right)$ is the real branch of the Lambert function [13]. In addition, the function $h\left(\bar{S}\right)$ is expressed as

$$h\left(\bar{S}\right) = \begin{cases} \zeta\alpha\log_2\!\left(1-\eta_0\left[1-\cosh\left(\frac{\bar{S}\log_e(2)}{\alpha\eta_2}\right)^{\eta_1}\right]\right) & 0.5<\beta<2 \\ \zeta\left[\bar{S}-\alpha\eta_1\log_2\!\left(\frac{2}{1+e^{\frac{-2\bar{S}\log_e(2)}{\alpha\eta_1}}}\right)\right] & \beta\le 0.5 \text{ or } \beta\ge 2 \end{cases} \quad (13)$$

where $\alpha = \min\left(Kt, r\right)$, $\zeta = -\mathrm{sgn}\left(\ln\left(\beta\right)\right)$ and $\mathrm{sgn}(x) = -1, 0$ or 1 if $x<0, x=0$ or $x>0$ such that $h(x)=0$ when $\beta = 1$. Note that the values of the parameters η_0, η_1 and η_2 can be obtained from [12]. By inserting $\tilde{f}^{-1}(\bar{S}) \approx f^{-1}(\bar{S})$ into (10), we obtain our generalized accurate CFA of the EE-SE trade-off for the uplink of CoMP with uniformly distributed UTs.

IV. Energy Efficiency Gain of CoMP over Non-cooperation

In order to evaluate how CoMP compares with the conventional non-cooperative approach in terms of EE, we define G_E as the EE gain of CoMP over the non-cooperative system. In comparison with CoMP which involves cooperation of BSs and joint decoding of all users' signal, in the non-cooperative system, each BS decodes users' in their respective cell via single user decoding (SUD) without cooperation of BSs. Note that the EE gain can result from a decrease of consumed power, $G_{E\bar{S}}$, or an increase of SE, G_{EP}, as explained below.

Definition The EE gain $(G_{E\bar{S}})$ is the ratio of the total power consumed by the non-cooperative system to that of CoMP when both systems achieve the same $\bar{S}$ and are affected by the same level of noise at their receivers.

Based on this definition and (10), we express $G_{E\bar{S}}$ as

$$G_{E\bar{S}} = \frac{\frac{f_{nc}^{-1}(\bar{S})}{\varsigma} + \frac{tKP_c+bP_{sp}^{nc}}{N}}{\frac{f_{bc}^{-1}}{\varsigma}\left(\bar{S}\right) + \frac{tKP_c+bP_{sp}+cP_{bh}(\bar{S})}{N}}, \quad (14)$$

where the function $f_{bc}^{-1}\left(\bar{S}\right)$ is obtained from our CFA in (12) while $f_{nc}^{-1}\left(\bar{S}\right)$ can be obtained numerically from the CFA of the SE for the SUD scenario given in (56) & (57) of [14]. In the low-SE regime, $G_{E\bar{S}}$ can be simplified into the expression given later in (16), when $b = c = P_c = 0$. The overall maximum transmit power for K UTs when $\varsigma = 1$, KP_{max} has an order of magnitude of $K/2$ Watts, whereas $bP_{sp}^{nc} \simeq 56r$ Watts, according to Table I. Thus if $K \ll 100r$, $f_{nc}^{-1} \ll \frac{tKP_c+bP_{sp}^{nc}}{N}$ as well as $f_{bc}^{-1} \ll \frac{tKP_c+bP_{sp}+cP_{bh}(\bar{S})}{N}$ and $G_{E\bar{S}}$ would simplify as $\frac{tKP_c+bP_{sp}^{nc}}{tKP_c+bP_{sp}+cP_{bh}(\bar{S})}$. Since $(bP_{sp}+cP_{bh}(\bar{S})) > bP_{sp}^{nc}$, it implies that CoMP is surely less EE than non-cooperation for such range of K values. Consequently, we also investigate the EE gain due to an increase in SE when using CoMP.

Definition The EE gain (G_{EP}) is the ratio of the EE of CoMP to that of the non-cooperative system when the UTs transmit at the same power and both systems experience the same level of noise at the receiver.

$$G_{EP} = G_{EP,Th}\frac{KP+\varsigma(tKP_c+bP_{sp}^{nc})}{KP+\varsigma\left(tKP_c+bP_{sp}+cP_{bh}(\bar{S})\right)}, \quad (15)$$

where $G_{EP,Th} = R_{bc}/R_{nc}$ is the idealistic SE gain, R_{bc} and R_{nc}, are the achievable per-cell sum-rate of CoMP and non-cooperative systems, respectively. In order to get insights into this ratio and to establish the range of $\bar{S}$ values for which CoMP is energy efficient, we derive the low and high-SE approximations of G_{EP}. From the low-SE approximation of CoMP EE-SE trade-off in (21) and that of the non-cooperative system with orthogonal multiple access scheme given in (32) of [14], we proved in the appendix that the low-SE approximation of $G_{EP,Th}$ is given by

$$G_{EP,Th}^0 \approx \frac{Mq\left(\mathbf{\Omega}\right)}{\left|\alpha_k^{n1}\right|^2}. \quad (16)$$

Moreover, the asymptotic approximation of $G_{EP,Th}$ based on the high-SE approximation of the capacity of the symmetrical CoMP and non-cooperative systems in [14] can be expressed

TABLE I
PARAMETERS FOR THE SYSTEM AND POWER MODELS

Realistic PCM Parameters [4]–[6]		**System Parameters**	
Parameter	Value	Parameter	Value
p_{sp}	42.5 W	W	5 MHz
v	1	N_0	−169 dBm/Hz
c_c	0.12	L_0	34.5 dB
c_{dc}	0.08	η	3.5
c_{ms}	0.09	d_0	1 m
C_{bh}	100 Mbit/s	P_{max}	27 dBm
p_b	50 W	Fading	Rayleigh flat fading
c	1		
P_c	100 mW		
ς	1		

as

$$G^{\infty}_{EP,Th} \approx \begin{cases} \dfrac{\log_2(Mq(\mathbf{\Omega})\bar{\gamma})}{\log_2\left(1+\dfrac{\left|\alpha_k^{n1}\right|^2}{\sum_{m=2}^{M}\left|\alpha_k^{nm}\right|^2}\right)} & \beta \to \infty \\[2ex] \dfrac{\log_2\frac{(Mq(\mathbf{\Omega})\bar{\gamma})}{\beta}}{\log_2\frac{\left|\alpha_k^{n1}\right|^2\bar{\gamma}}{\beta}} & \frac{1}{\beta} \to \infty. \end{cases} \tag{17}$$

Inserting (16) and (17) into (15), we obtain G^0_{EP} and G^{∞}_{EP}, the lower and upper limits of G_{EP}, respectively. We observe that at low SE, $G^0_{EP,Th} \geq 1 \, \forall \beta$, while at high SE, for $\beta \to \infty$, and $1/\beta \to \infty$, the asymptotic $G^{\infty}_{EP,Th} \geq 1$. This clearly confirms that CoMP can be more energy efficient than non-cooperative system because of the extra SE it generates.

V. Numerical Results

In this section, we present numerical results for the EE-SE trade-off and the EE gain of CoMP based on the idealistic and realistic PCMs. We consider that $b = c = P_c = 0$ and $\varsigma = 1$ for the idealistic PCM and use the PCM parameters of Table I for the realistic PCM. Moreover, we assume an inter-site distance (ISD) of 1 km between BSs, $K = 50$ uniformly distributed UTs within each cell and the system parameters of Table I. We also ensure that the relative distance between each UT and its serving BS, denoted rd_{UT-BS}, is always greater than 0.05 ($rd_{UT-BS} = 0/1$: UT collocated with BS / UT at cell edge, respectively).

In Figs. 1 and 2, we compare our CFA in equation (12) with the low-SE approximation approach of [7] and the nearly-exact EE obtained from (4) according to both the idealistic and realistic PCMs, respectively. We can easily obtain the total intra-cell SNR $\bar{\gamma} = f^{-1}(\bar{S})$ for a given $\bar{S}$ by using a linear search algorithm on (4) such that the target $\bar{S}$ differ from the actual $\bar{S}$ by less than 10^{-5} bits/s/Hz. Then we plotted the nearly-exact EE as a function of the per-cell SE $\bar{S}$ by inserting $f^{-1}(\bar{S})$ and $S = \bar{S}$ in (7) and (10) for the idealistic and realistic PCMs, respectively. Results in both figures show the tight fitness between our EE-SE trade-off CFA in (12) and the nearly-exact EE for various antenna and BS settings, which in turn graphically demonstrates the high accuracy of our CFA. Whereas, it can be observed in Fig. 1 that the low-power approximation approach of [7] is mainly accurate in the low-SE regime. As compared with the idealistic scenario where not transmitting is the optimal approach in terms of EE,

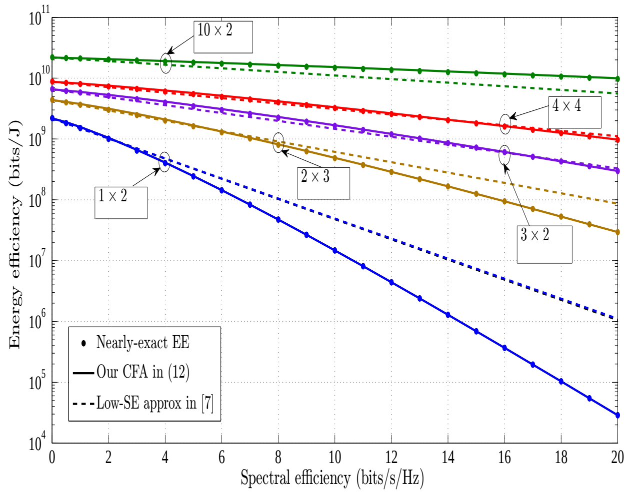

Fig. 1. *Comparison of our EE-SE CFA in (12) with Low-power approximation and the nearly-exact $\frac{E_b}{N_0}$ based on the idealistic PCM.*

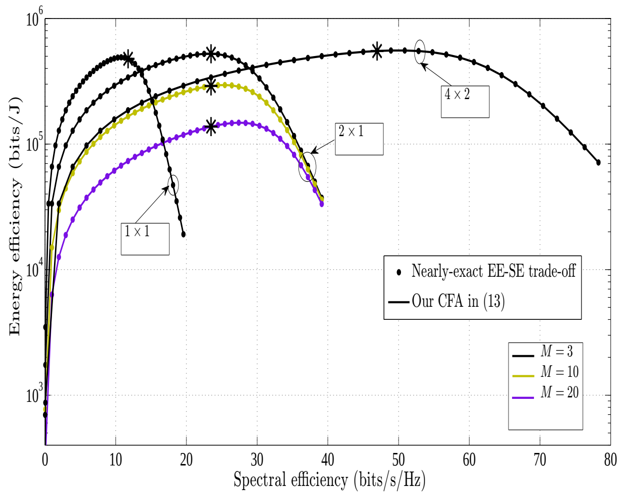

Fig. 2. *EE-SE trade-off based on the realistic PCM, the star marker indicates the EE-SE trade-off point for which $P = P_{max}$.*

in the realistic case, there exists an optimal transmit power that maximizes the EE.

In Figs. 3, 4 and 5, we consider a scenario in which only one UT is active per-cell at every time due to the use of an orthogonal multiple access scheme within the cell. We first compare in Fig. 3 $G_{E\bar{S}}$ and G_{EP} for both PCMs. This figure indicates that when the idealistic PCM is considered CoMP is always more energy efficient than the non-cooperative system, and a higher gain is achieved via reduction in power consumption. Whereas, for the realistic PCM, CoMP's EE gain is achieved for cell edge, i.e. $0.8 \leq rd_{UT-BS} \leq 1$, and small number of cooperating BSs, i.e. $M = 3$, and only through its SE improvement capability. In addition, Fig. 3 shows that no EE gain can be achieved via power reduction in the realistic PCM and, hence, our next results focus on the EE gain due to SE improvement, G_{EP}.

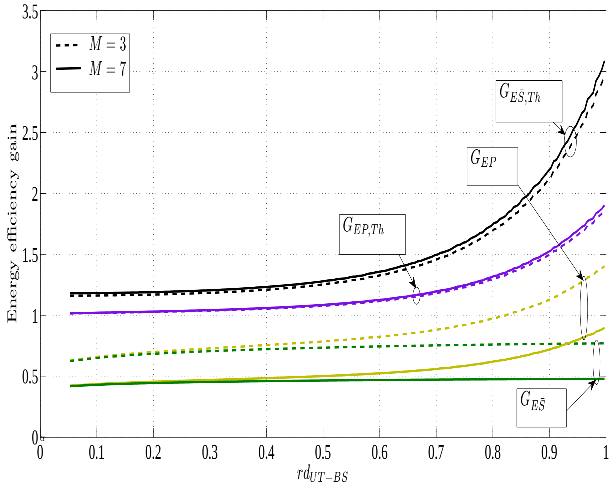

Fig. 3. *Energy efficiency gain of BS cooperation over the non cooperative approach as a function of UT position for $M = 3, 7$ and a 2×1 antenna configuration.*

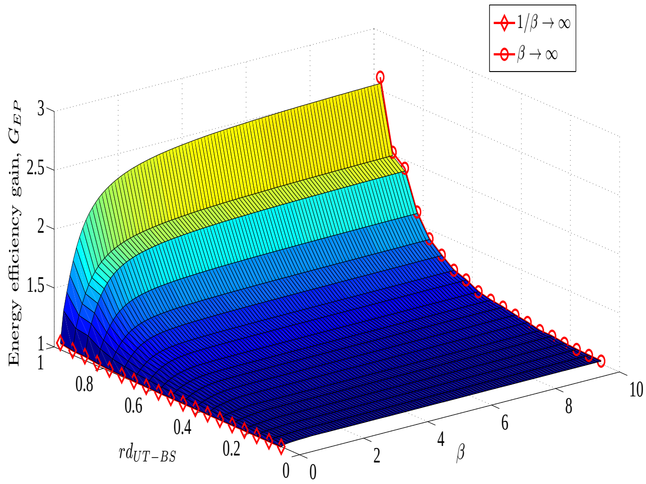

Fig. 4. *EE gain of BS cooperation over the non-cooperative system against antenna configuration ratio β for various UT position.*

We plot in Fig. 4 $G_{EP,Th}$ as a function of β and the relative UT distance to its serving BS rd_{UT-BS}. Results show that $G_{EP,Th}$ increases sharply for values of β between $0 - 1$ regardless of the UT position. Indeed, we know from [14] that an increase of β from 0 to 1 results in a sharp increase in SE for the uplink of CoMP system; whereas in the non-cooperative case, the SE increases modestly for values of β which are far lower than 1 depending on the strength of the inter-cell interference at the BS. In addition, our approximations of $G_{EP,Th}$ at $\beta \to \infty$ and $1/\beta \to \infty$ in (17) are tight.

In Fig. 5, UTs are placed at cell edge ($rd_{UT-BS} = 0.95$) and G_{EP} is plotted by considering the realistic PCM for various numbers of cooperating BSs and antenna configurations. It can be observed that reducing β from $\beta = 1$ in (2×2) to $\beta = \frac{2}{3}$, in (3×2) results in a decrease in G_{EP} since increasing r is beneficial in terms of SE for the non-cooperative system, whereas CoMP performance is only slightly increased. In addition, increasing β from $\beta = 1$ in (2×2) to $\beta = \frac{3}{2}$ in (2×3) leads to an increase in G_{EP} since no improvement in SE is achieved by the non-cooperative system when increasing β beyond 1, whereas CoMP performance increases. The results also show that for large ISD, which corresponds to low received power at the BS, the realistic G_{EP} performance converges to its lower limit G_{EP}^0. Furthermore, as it is also indicated in Fig. 3, increasing the number of cooperating BSs leads to a reduction in the EE gain as a result of the sharp increase in both the backhaul and processing powers of CoMP, whereas, the SE increases marginally especially for $M > 3$ in the circular cellular grid layout.

VI. Conclusion

In this paper, we have derived an accurate CFA of the EE-SE trade-off for the uplink of CoMP with uniformly distributed UTs, MIMO Rayleigh fading channel and two

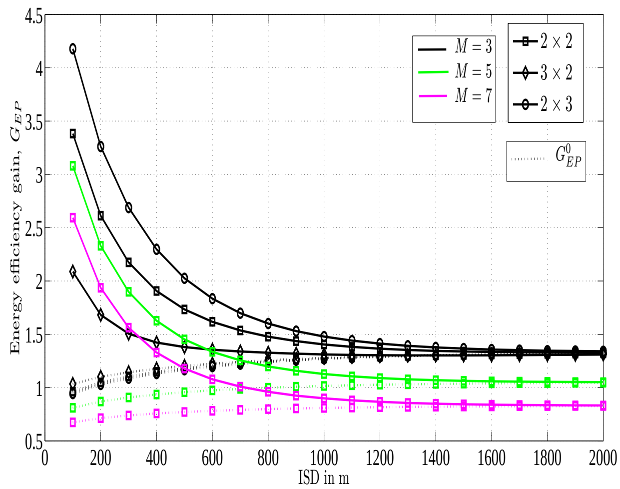

Fig. 5. *Realistic EE gain against the inter-site distance for various antenna configurations and cooperating BSs.*

types of PCM. We first demonstrate its accuracy for various antenna configurations, numbers of cooperating BSs and a wider range of SE values than the approximation in [7]. We then utilized our CFA to investigate the EE gain of CoMP over the non-cooperative system.

The main findings of this paper can be summarized as follows: in the idealistic PCM, EE gain can be achieved by both power reduction and SE improvement when using CoMP and higher gains are obtained by power reduction. In a realistic PCM, the contrary happens and, hence, increasing the EE in the uplink of CoMP must be approached via SE improvement. CoMP is more energy efficient than non-cooperative system for cell edge communication, large β and small cell deployment. Finally, in the realistic PCM, there exists an optimal SE value that maximizes the EE of CoMP system for any given antenna and node settings.

APPENDIX

A. Derivation Insight: (16)

Assuming that $\bar{S} \sim 0$ in the uplink of CoMP, then $g_t\left(\bar{S}\right) \overset{0}{\sim} -2^{-\left(\frac{\bar{S}}{2Kt}+1\right)}e^{-\frac{1}{2}}$, which simplifies as $-\frac{1}{2}\left(1-\frac{S\ln(2)}{Kt}\right) \times e^{-\frac{1}{2}\left(1-\frac{S\ln(2)}{Kt}\right)}$, and in turn is equivalent to

$$W_0(g_{\bar{t}}(\bar{S})) \overset{0}{\sim} -\frac{1}{2}\left(1-\frac{S\ln(2)}{Kt}\right). \quad (18)$$

Similarly,

$$W_0(g_r(\bar{S})) \overset{0}{\sim} -\frac{1}{2}\left(1-\frac{S\ln(2)}{r}\right). \quad (19)$$

Inserting (18) and (19) into (12) when $\bar{S} \sim 0$, we obtain that

$$\tilde{f}(\bar{S}) = \frac{\bar{S}\beta\ln(2)(r+Kt)}{q(\mathbf{\Omega})M(1+\beta)Kt}, \quad (20)$$

which simplifies as

$$\tilde{f}(\bar{S}) \approx \frac{\bar{S}\ln(2)}{q(\mathbf{\Omega})Mr}, \quad (21)$$

such that the capacity at the low-SE regime is

$$R_c^0 \approx \frac{Wq(\mathbf{\Omega})Mrf^{-1}(\bar{S})}{\ln(2)}. \quad (22)$$

In the non-cooperative case, when considering that each BS performs SUD, i.e. $M-1$ interfering signals, the low-SE approximation of the achievable rate is obtained from (32) of [14] as

$$R_{nc}^0 \approx Wr\log_2(e)\left(\frac{\left|\alpha_k^{n1}\right|^2 P}{N}\right)^2\left[\frac{N+\sum_{m=2}^{M}\left|\alpha_k^{nm}\right|^2 P}{\left|\alpha_k^{n1}\right|^2 P}-A\right] \quad (23)$$

where $A=\frac{1}{2}\left(1+\frac{1}{\beta}\right)$. The idealistic EE gain $G_{EP,th}^0$ is such that $G_{EP,th}^0=\frac{R_c^0}{R_{nc}^0}$. Using (22) and (23), we obtain

$$G_{EP,Th}^0 = \frac{NMq(\mathbf{\Omega})}{\left|\alpha_k^{n1}\right|^2\left(N+\sum_{m=2}^{M}\left|\alpha_k^{nm}\right|^2 P-\left|\alpha_k^{n1}\right|^2 PA\right)}. \quad (24)$$

Finally, since the low-SE regime corresponds to the low-power regime, it implies that $P \to 0$ at low-SE and (16) has been derived by solving $\lim_{P\to 0} G_{EP,th}^0$.

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