Energy Efficiency Analysis of Idealized Coordinated Multi-Point Communication System

Fabien Héliot, Muhammad Ali Imran, and Rahim Tafazolli
Centre for Communication Systems Research, University of Surrey,
Guildford GU2 7HX, UK, Email: F.Heliot@Surrey.ac.uk

***Abstract*— Coordinated multi-point (CoMP) architecture has demonstrated a significant potential of improvement in terms of spectral efficiency and user fairness in comparison with non-coordinated architecture, however, its energy efficiency remains to be evaluated. In this paper, CoMP system is idealized as distributed antenna system by assuming perfect backhauling and cooperative processing. This simplified model allows us to express the capacity of the idealized CoMP system with a simple and accurate closed-form approximation. In addition, a framework for the energy efficiency analysis of CoMP system is introduced, which includes a power consumption model and an energy efficiency metric, i.e. bit-per-joule capacity. This framework along with our closed-form approximation are utilized for assessing both the channel and bit-per-joule capacities of the idealized CoMP system. Results indicate that multi-base-station cooperation can be energy efficient for cell-edge communication and that the backhauling and cooperative processing power should be kept low. Overall, it has been shown that the potential of improvement of CoMP in terms of bit-per-joule capacity is not as high as in terms of channel capacity due to associated energy cost for cooperative processing and backhauling.**

I. INTRODUCTION

In the current context of climate change, growing energy demand and increasing energy price, energy efficiency is becoming a key criteria in the design of communication networks. For instance, during the development of 3GPP systems, such as wideband code division multiple access (WCDMA), the energy consumption issues have received little, if any, attention and, therefore, they were not properly addressed. However, in the future mobile systems, e.g. long term evolution-advanced (LTE-A), the energy consumption will have to be taken into account in order to reduce the carbon footprint of the networks. One of the possible approaches to do so is base station (BS) cooperation, which is more generally referred as coordinated multi-point (CoMP) communication. CoMP has already been comprehensively studied in the literature in terms of spectral efficiency and user fairness [1], [2] and has demonstrated significant enhancements according to these metrics. However, its potential for energy efficiency improvements remains to be assessed and this is one of the aims of this paper.

Traditionally, the efficiency of a communication system is measured in terms of spectral efficiency, which is related to the channel capacity in bits/s. This metric indicates how efficiently a limited frequency spectrum is utilized but does not provides any insight on how efficiently the energy is consumed. In order to evaluate this particular aspect of the communication system, we need a metric that takes into account the energy consumption. Such a metric, the bit-per-joule capacity (bits/J) has first been introduced in [3] and is simply defined as the ratio of the capacity to the rate of energy expenditure, i.e. to the signal power. This metric has been recently used in [4] for analyzing the performance of energy-limited wireless sensor and ad hoc networks. In this paper, it will be utilized for assessing the energy efficiency of CoMP communication.

In CoMP communication, several BSs cooperate to transmit and receive data from multiple mobile stations (MSs) in different cells [1], [5], [6]. The BSs can share information by using high speed reliable connections over wire links, e.g. optical fiber, or wireless line-of-sight microwave links. In conventional systems, the backhaul links are already in use for handling the control and signaling that are required between BSs. The aim of the joint BS signal processing is to cancel or even exploit inter-cell interference. In the uplink, the BSs cooperate to jointly decode all users data. In the downlink, multiple BSs transmit data to one or several MSs for improving the received signal quality and/or pre-cancel interference from other MSs. CoMP communication is considered as a key technology for the future of mobile communication and it has already been included in LTE-A standard [7].

Assuming perfect backhaul links between each BS and an idealistic cooperative processing, the CoMP system model becomes equivalent to a distributed antenna or distributed multiple-input multiple-output (DMIMO) system model [8], which is presented in Section II. DMIMO channel itself can be considered as a special case of correlated MIMO channel. The works in [9], [10] and [11] have provided asymptotic closed-form approximations of the channel capacity for correlated MIMO channel by using random matrix theory and the Stieltjes transform of the empirical distribution of the eigenvalues of the correlated MIMO channel, respectively. Whereas in [6], [12] and [13], closed-form approximations of the DMIMO channel capacity have been explicitly obtained. In [6], a closed-form approximation of the capacity for the uplink of DMIMO system with multiple users has been provided by using results on limiting eigenvalue distributions of large random matrices and assuming a large number of antennas at the BSs and MSs and certain symmetry conditions in the system. Whereas, in [12], a different approach has been followed to obtain a closed-form approximation of the capacity for both uplink and downlink of DMIMO system by considering only a single user and assuming a large number of antennas at the BSs and MS, and high signal-to-noise ratio (SNR) values. Finally, in [13], a more generic and accurate approximation than in [12] has been derived for the single user case by relying as in [9] on random matrix theory. In Section III, we extend our work in [13] for a multi-user scenario and provide a more generic closed-form approximation of the DMIMO capacity than in [6], regardless of the DMIMO system symmetry conditions. In addition, we assess the accuracy of our approximation against Monte-Carlo simulations. In Section IV, we define a framework for the energy efficiency analysis of CoMP system by considering the power consumption model of [14] and the bit-per-joule capacity as an energy efficiency metric. We then modify and utilize the expression that has been derived in Section III for assessing the energy efficiency of idealized CoMP system. Finally, conclusions are drawn in Section V.

II. Distributed MIMO System Model

We consider a DMIMO communication system composed of $m+k$ nodes in different locations, where m BSs equipped with p antennas cooperate to transmit/receive data to/from k MS equipped with q antennas, as illustrated in Fig. 1. We define the matrices $\mathbf{\Sigma}_{i,j}$ and $\mathbf{H}_{i,j}$ as the average path loss/shadowing and the MIMO Rayleigh fading channel, respectively, between the i-th BS and the j-th MS, $i \in \{1,\ldots,m\}$, $j \in \{1,\ldots,k\}$. The equivalent channel model of the system in the uplink is then defined as $\widetilde{\mathbf{H}} = \mathbf{\Sigma} \odot \mathbf{H}$, where

$$\mathbf{\Sigma} = \begin{bmatrix} \mathbf{\Sigma}_{1,1} & \ldots & \mathbf{\Sigma}_{1,k} \\ \vdots & \ddots & \vdots \\ \mathbf{\Sigma}_{m,1} & \ldots & \mathbf{\Sigma}_{m,k} \end{bmatrix}, \mathbf{H} = \begin{bmatrix} \mathbf{H}_{1,1} & \ldots & \mathbf{H}_{1,k} \\ \vdots & \ddots & \vdots \\ \mathbf{H}_{m,1} & \ldots & \mathbf{H}_{m,k} \end{bmatrix}$$

and $\odot$ is the entrywise product between any two matrices. Moreover, $\widetilde{\mathbf{H}} \in \mathbb{C}^{N_r \times N_t}$, $\mathbf{H} \in \mathbb{C}^{N_r \times N_t}$, $\mathbf{\Sigma} \in \mathbb{R}_+^{N_r \times N_t}$ with $\mathbb{R}_+ \triangleq \{x \in \mathbb{R} | x \geq 0\}$, and the total number of transmit and receive antennas of the DMIMO system is defined as N_t and N_r, respectively. In the uplink case $N_t = kq$, $N_r = mp$ and $n = q$, whereas in the downlink case $N_t = mp$, $N_r = kq$ and $n = p$, where n is the number of transmit antenna per node. Accordingly, we assume the linear channel model where the receive signal $\mathbf{r} \in \mathbb{C}^{N_r \times 1}$ can be expressed as

$$\mathbf{r} = \widetilde{\mathbf{H}}\mathbf{s} + \mathbf{n}, \tag{1}$$

with $\mathbf{s} \in \mathbb{C}^{N_t \times 1}$ being the transmit signal with average transmit power P and $\mathbf{n} \in \mathbb{C}^{N_r \times 1}$ being a vector with independent entries of zero-mean complex Gaussian noise. Moreover, we assume that $\mathbf{H}$ is a random matrix having independent and identically distributed (i.i.d.) complex circular Gaussian entries with zero-mean and unit variance. The mutual information (MI) of the composite channel $\widetilde{\mathbf{H}}$, $I(\widetilde{\mathbf{H}})$, and its capacity, C, are respectively defined as follows

$$\begin{aligned} I(\widetilde{\mathbf{H}}) &\triangleq \ln \left| \mathbf{I}_{N_r} + \lambda \widetilde{\mathbf{H}}\widetilde{\mathbf{H}}^\dagger \right| \quad \text{and} \\ C &\triangleq \mathrm{E}_{\mathbf{H}}\{I(\widetilde{\mathbf{H}})\} \qquad \text{(nats/s/Hz)}, \end{aligned} \tag{2}$$

where $\mathbf{I}_{\{.\}}$ is an identity matrix, $|.|$ is the determinant, $\{.\}^\dagger$ is the Hermitian operator and $\mathrm{E}\{.\}$ is the expectation. In addition, $\lambda \triangleq P/(nN)$ and N is the average power of the noise $\mathbf{n}$.

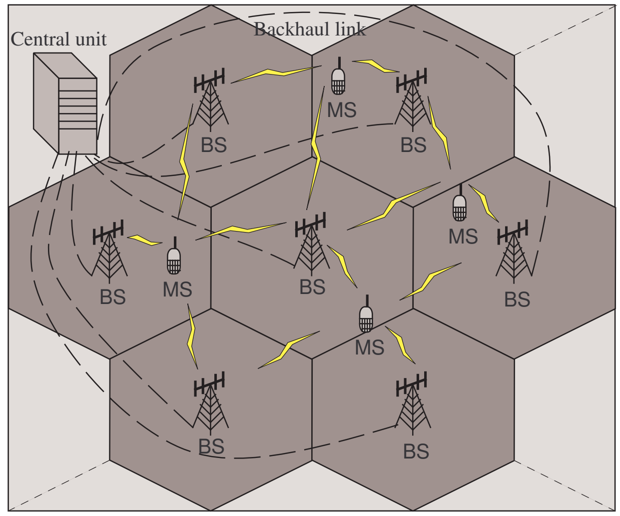

Fig. 1. Distributed MIMO system model

III. Closed-form approximation of the DMIMO capacity in multi-user context

In (9) of [13], we have obtained a closed-form approximation of the DMIMO channel capacity for $m > 1$ and $k = 1$. Here, we revisit the derivation of this expression and extend it for the case where $m, k > 1$.

A. Closed-form approximation derivation

The moment generating function (MGF) of the RV $I(\widetilde{\mathbf{H}})$ can be expressed as $M_{I(\widetilde{\mathbf{H}})}(-u) = \mathrm{E}_{\mathbf{H}}\{\exp[(-u)I(\widetilde{\mathbf{H}})]\}$

$$\begin{aligned} &= \pi^{-N_r N_t} \int_{\mathbb{C}^{N_r \times N_t}} e^{-\|\mathbf{H}\|_F^2} \phi(\mathbf{H})^{-u} d\mathbf{H}, \\ &= \pi^{-N_r N_t} \int_{\mathbb{C}^{N_r \times N_t}} \int_{\mathbb{C}^{N_r \times u}} \int_{\mathbb{C}^{N_t \times u}} e^{-\pi \operatorname{tr}\left[(\mathbf{X}^\dagger \mathbf{X} + \mathbf{Y}^\dagger \mathbf{Y})\right]} \psi(\mathbf{H}) \\ &\times d\mathbf{H} d\mathbf{X} d\mathbf{Y}, \end{aligned} \tag{3}$$

where $\|.\|_F$ and $\operatorname{tr}[.]$ denote the Frobenius norm and the trace operator, respectively; $\phi(\mathbf{H}) = \left| \mathbf{I}_{N_r} + \lambda \widetilde{\mathbf{H}}\widetilde{\mathbf{H}}^\dagger \right|$, $\psi(\mathbf{H}) = \exp\left(-\operatorname{tr}\left[j\left(\widetilde{\mathbf{H}}\mathbf{B}^\dagger + \mathbf{B}\widetilde{\mathbf{H}}^\dagger\right) - \mathbf{H}\mathbf{H}^\dagger\right]\right)$; $\mathbf{X} \in \mathbb{C}^{N_r \times u}$, $\mathbf{Y} \in \mathbb{C}^{N_t \times u}$, u is a dummy variable that is used in the replica method [15]; and $\mathbf{B} \triangleq \pi\sqrt{\lambda}\mathbf{X}\mathbf{Y}^\dagger$, $\mathbf{B} \in \mathbb{C}^{N_r \times N_t}$. By integrating $\psi(\mathbf{H})$ with respect to $\mathbf{H}$, (3) can be rewritten as

$$\begin{aligned} M_{I(\widetilde{\mathbf{H}})}(-u) = &\int_{\mathbb{C}^{N_r \times u}} \int_{\mathbb{C}^{N_t \times u}} e^{-\pi \operatorname{tr}\left[(\mathbf{X}^\dagger \mathbf{X} + \mathbf{Y}^\dagger \mathbf{Y})\right]} \\ &\times e^{-\pi^2 \lambda \operatorname{tr}\left[(\mathbf{\Sigma} \odot \mathbf{X}\mathbf{Y}^\dagger)(\mathbf{\Sigma} \odot \mathbf{X}\mathbf{Y}^\dagger)^\dagger\right]} d\mathbf{X} d\mathbf{Y}. \end{aligned} \tag{4}$$

Let $\mathbf{\Sigma}_{i,j} = \sqrt{\sigma_{i,j}} \mathbf{1}^{p \times q} = \sqrt{\upsilon_i \omega_j} \mathbf{1}^{p \times q} = \mathbf{\Upsilon}_i \mathbf{\Omega}_j^\dagger$, where $\mathbf{\Upsilon}_i = \sqrt{\upsilon_i} \mathbf{1}^{p \times u}$ and $\mathbf{\Omega}_j = \sqrt{\omega_j} \mathbf{1}^{q \times u}$. Then the following equalities $(\mathbf{\Sigma} \odot \mathbf{X}\mathbf{Y}^\dagger) = (\mathbf{\Upsilon} \odot \mathbf{X})(\mathbf{\Omega} \odot \mathbf{Y})^\dagger$ and $(\mathbf{\Sigma}^\dagger \odot \mathbf{X}\mathbf{Y}^\dagger) = (\mathbf{\Omega} \odot \mathbf{X})(\mathbf{\Upsilon}^\dagger \odot \mathbf{Y}^\dagger)$ hold in the uplink and downlink, respectively, with $\mathbf{\Upsilon} = [\mathbf{\Upsilon}_1^\dagger, \ldots, \mathbf{\Upsilon}_m^\dagger]^\dagger$ and $\mathbf{\Omega} = [\mathbf{\Omega}_1^\dagger, \ldots, \mathbf{\Omega}_k^\dagger]^\dagger$. Note that we assume here the same correlation model as in [9], i.e. separable transmit and receive correlations. This assumption is frequently used in MIMO literature for obvious simplification purpose; however, it is not always supported in reality [16]. Using this correlation model, (4) can be re-expressed as

$$M_{I(\widetilde{\mathbf{H}})}(-u)=\int_{\mathbb{C}^{N_r\times u}}\int_{\mathbb{C}^{N_t\times u}} e^{-\pi\,\mathrm{tr}\left[\left(\mathbf{X}^\dagger\mathbf{X}+\mathbf{Y}^\dagger\mathbf{Y}\right)\right]} \times e^{-\pi^2\lambda\,\mathrm{tr}\left[\mathbf{W}\mathbf{Z}^\dagger\mathbf{Z}\mathbf{W}^\dagger\right]} d\mathbf{X}d\mathbf{Y} \quad (5)$$

in the uplink, where $\mathbf{W}\triangleq(\boldsymbol{\Upsilon}\odot\mathbf{X})$ and $\mathbf{Z}\triangleq(\boldsymbol{\Omega}\odot\mathbf{Y})$. Following some simplifications, (5) is modified as

$$M_{I(\widetilde{\mathbf{H}})}(-u)\,(\mathrm{j}2\pi\lambda)^{-u^2}\int_{\mathcal{D}_d^{\mathrm{j}}}\int_{\mathcal{D}_g} e^{\frac{\varphi(\mathbf{D},\mathbf{G})}{\lambda}}d\mathbf{D}d\mathbf{G}, \quad (6)$$

where $\varphi(\mathbf{D},\mathbf{G})\triangleq\mathrm{tr}(\mathbf{DG})-\gamma\alpha\sum_{i=1}^{m}\ln|\mathbf{I}_u+\upsilon_i\mathbf{D}|-\gamma\beta\sum_{j=1}^{k}\ln|\mathbf{I}_u+\omega_j\mathbf{G}|$, $\gamma\triangleq P/N$, $\alpha\triangleq p/n$, $\beta\triangleq q/n$, $\mathbf{D},\mathbf{G}\in\mathbb{C}^{u\times u}$; $\mathcal{D}_d^{\mathrm{j}}\triangleq\mathbf{D}_0+(\mathrm{j}\mathbb{R}^{u\times u})$ and $\mathcal{D}_g\triangleq\mathbf{G}_0+(\mathbb{R}^{u\times u})$, $\mathbf{D}_0,\mathbf{G}_0\in\mathbb{C}^{u\times u}$. At this stage, we apply the multidimensional saddle point integration method [17] for asymptotically computing the integral in (6). We obtain after further derivation steps and simplifications that

$$M_{I(\widetilde{\mathbf{H}})}(-u)\to\exp\left(u\frac{n}{2}\left[\alpha\left(m-\sum_{i=1}^{m}\ln\left(1+d_0\upsilon_i\right)^2+\frac{1}{1+d_0\upsilon_i}\right)+\beta\left(k-\sum_{j=1}^{k}\ln\left(1+g_0\omega_j\right)^2+\frac{1}{1+g_0\omega_j}\right)\right]+\frac{u^2}{2}\left[-\ln\left(1-\widehat{d}_0\widehat{g}_0\right)\right]\right), \quad (7)$$

where $\widehat{d}_0=\alpha\Sigma_{i=1}^{m}\upsilon_i^2(1+d_0\upsilon_i)^{-2}$, $\widehat{g}_0=\beta\Sigma_{j=1}^{k}\omega_j^2(1+g_0\omega_j)^{-2}$, d_0 is the unique positive root of the following degree-mk polynomial $P_{m,k}(d)=$

$$d\prod_{j=1}^{k}f(d,\gamma,\omega_j)-\gamma\beta\prod_{i=1}^{m}(1+d\upsilon_i)\left[\sum_{j=1}^{k}\omega_j\prod_{\substack{h=1\\h\neq j}}^{k}f(d,\gamma,\omega_h)\right], \quad (8)$$

$f(d,\gamma,\omega_j)=\prod_{i=1}^{m}(1+d\upsilon_i)+\gamma\alpha\omega_j\sum_{i=1}^{m}\upsilon_i\prod_{l=1\,l\neq i}^{m}(1+d\upsilon_l)$ and $g_0=\alpha\Sigma_{i=1}^{m}\upsilon_i(d_0+\omega\upsilon_i)^{-1}$. A proof that d_0 is the unique positive root of $P_{m,k}(d)$ has been given in [13] for $k=1$ and it can easily be extended for $k>1$ by using the same approach as in [13]. The value of d_0 can be numerically obtained by computing the companion matrix of $P_{m,k}(d)$ and taking the maximum of its eigenvalue. Knowing that the MGF of any Gaussian RV Z is $M_Z(t)\triangleq\mathrm{E}\{\exp(tZ)\}=\exp\left(t\mu_z+\frac{t^2}{2}\sigma_z^2\right)$, with μ_z and σ_z^2 being the mean and variance of Z, respectively, we conclude by matching (7) with $M_Z(t)$ that $I(\widetilde{\mathbf{H}})$ is asymptotically equivalent to a Gaussian RV and that the capacity of the DMIMO system can be approximated as $C\approx\mu_{I(\widetilde{\mathbf{H}})}=$

$$\widetilde{C}=\frac{nW}{2\ln(2)}\left[\alpha\left(-m+\sum_{i=1}^{m}\ln\left(1+d_0\upsilon_i\right)^2+\frac{1}{1+d_0\upsilon_i}\right)+\beta\left(-k+\sum_{j=1}^{k}\ln\left(1+g_0\omega_j\right)^2+\frac{1}{1+g_0\omega_j}\right)\right] \quad (9)$$

in bits/s for large values of N_r and N_t, where W is the bandwidth. Our approximation $\widetilde{C}$ in (9) can be utilized for both uplink and downlink scenarios with $n=q,\alpha=p/q,\beta=1$ and $n=p,\alpha=1,\beta=q/p$, respectively. Its main purpose is the evaluation and comparison of the channel capacity of idealized CoMP systems in a faster way than time consuming Monte-Carlo simulations, and with a sufficient accuracy such that it can be used in network simulation and optimization. In addition, it can provide upper bounds on the achievable rate of non-idealized CoMP systems. Note that (9) can be seen under certain conditions as a special case of (4.3) in [11].

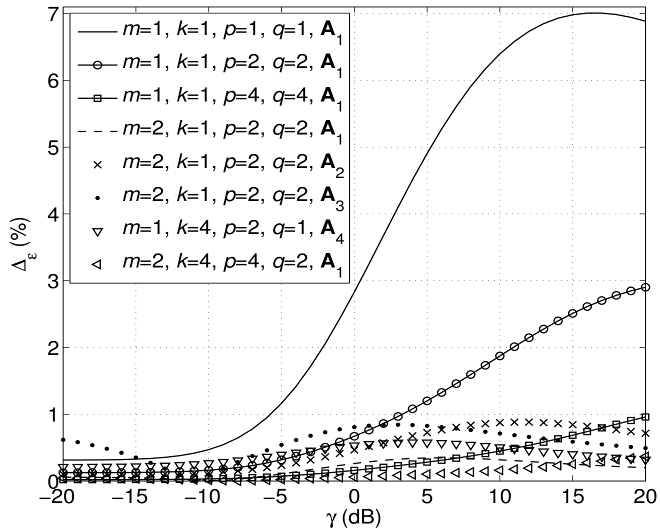

Fig. 2. Accuracy of $\widetilde{C}$ in (9) as a function of γ (dB)

B. Accuracy of our closed-form approximation

In order to numerically assess the accuracy of our approximation, we plot in Fig. 2 $\Delta_\epsilon\triangleq100|C_{\mathrm{MC}}-\widetilde{C}|/C_{\mathrm{MC}}$ vs. γ (dB) for various m, k, p and q values and different $\boldsymbol{\Sigma}$, where Δ_ϵ represents the difference between C_{MC} and $\widetilde{C}$ in percentage, and C_{MC} is the capacity value that is obtained by using Monte-Carlo simulation. Moreover, we define $\boldsymbol{\Sigma}\triangleq\mathbf{A}_i\otimes\mathbf{1}^{p\times q}$, where $\otimes$ is the Kronecker product between any two matrices, and set the various $\mathbf{A}_i$ as follows: $\mathbf{A}_1=\mathbf{1}^{m\times k}$, $\mathbf{A}_2=[1\;\;0.1]^\dagger$, $\mathbf{A}_3=[1\;\;10]^\dagger$ and $\mathbf{A}_4=[0.794\;\;1\;\;0.501\;\;0.631]$ in Fig. 2. Furthermore, we obtained the results for C_{MC} by considering 1×10^6 channel realizations in the Monte-Carlo simulation.

By comparing the first three curves, we can clearly see that the accuracy of the approximation increases with the number of antennas in a traditional MIMO setting, such that C_{MC} and $\widetilde{C}$ differ by less than 1% regardless of the SNR for $p=q=4$. This confirms the assertion made in [10] that the equivalence of $I(\widetilde{\mathbf{H}})$ with a Gaussian RV can be observed in a MIMO system for even a relatively small number of antennas, even though the formal proof is derived by assuming very large number of antennas. The next three curves shows that a 99% accuracy is at least reached in a DMIMO setting when $m=2$, but the accuracy varies as a function of the link qualities between the two BSs and the MS. Overall, the total number of antennas N_r and N_t does not have to be too large for ensuring

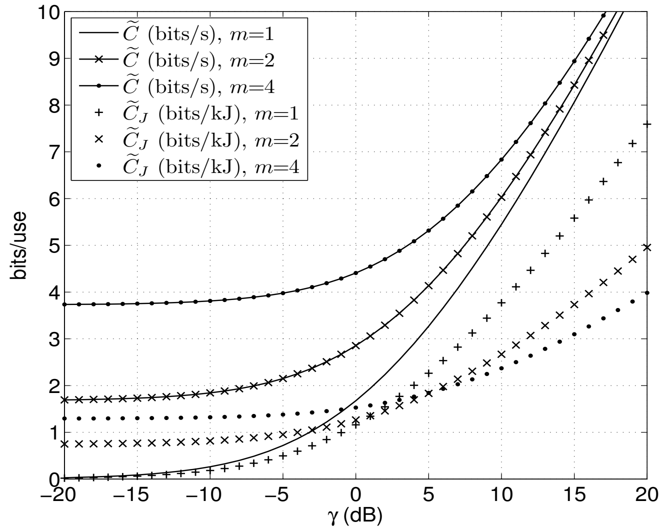

Fig. 3. $\widetilde{C}_J$ and $\widetilde{C}$ comparison of a 1-BS with a 2-BS and 4-BS systems as a function of γ dB in a downlink setting

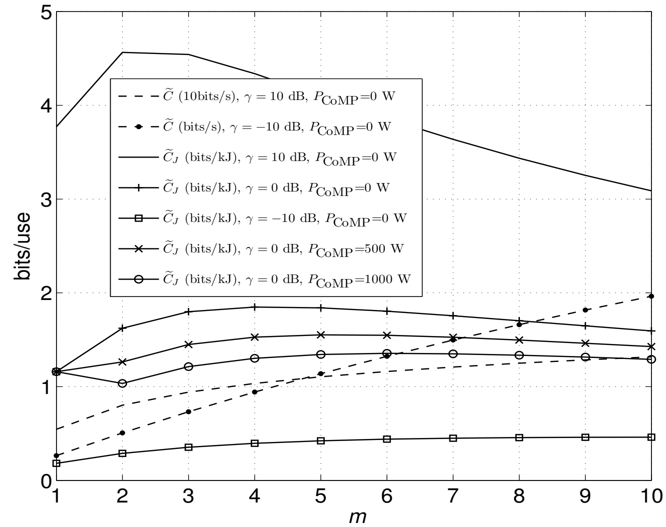

Fig. 4. $\widetilde{C}_J$ variation for an increasing number of BSs m in a downlink scenario

the high accuracy of our approximation, $\widetilde{C}$. Therefore, it can be confidently used for swiftly assessing and comparing the capacity of idealized CoMP systems.

IV. Energy efficiency analysis of CoMP systems

A. Energy efficiency framework

In order to assess the potential of CoMP in terms of energy efficiency, a metric and a power consumption model are defined below.

In this paper, we consider the linear power consumption model given in (1) of [14] for each BS, such that

$$P_{\text{Bs}} = N_{\text{Sector}} N_{\text{PApSec}} (P/\mu_{\text{PA}} + P_{\text{SP}})(1+C_{\text{C}})(1+C_{\text{PSBB}}), \quad (10)$$

where N_{Sector} is the number of sector, N_{PApSec} is the number of power amplifier (PA) per sector, μ_{PA} is the PA efficiency, P_{SP} is the signal processing overhead, C_{C} is the cooling loss and C_{PSBB} is the battery backup and power supply loss. We then defined our CoMP power model in the downlink as

$$P_{\text{T}} = m P_{\text{Bs}} + P_{\text{CoMP}}, \quad (11)$$

where P_{CoMP} is the power that is required for backhauling and coordinating multiple BSs. In the uplink, we simply consider P_{T} as $P_{\text{T}} = k P_{\text{Ms}} + P_{\text{CoMP}}$, where P_{Ms} is the transmit power of each user.

As far as energy efficiency metrics are concerned, the bit-per-joule capacity [3] indicates how efficiently energy is consumed for transmitting information. The bit-per-joule capacity or energy channel capacity is defined as the ratio of the channel capacity to the system consumed power P_{T} such that $C_J = C/P_{\text{T}}$. In our case, we also define $C_J \approx \widetilde{C}_J = \widetilde{C}/P_{\text{T}}$.

B. Simulation results

In our simulation, we have set the various parameters in (10) by using the values related to the model UMTS1 in Table 3 of [14]. In addition, we have set $W = 1$ in (9).

In Fig. 3, we compare the capacity $\widetilde{C}$ and bit-per-joule capacity $\widetilde{C}_J$ of a 1-BS system with a 2-BS and a 4-BS systems according to γ in the downlink scenario. In our simulation, we consider that $P = 40/m$ W such that the total transmit power remains the same for each m-BS scenario. Moreover, we set $k = 1$ (single user case), $p = q = 2$, $P_{\text{CoMP}} = 500$ W and use $\mathbf{A}_1$, $\mathbf{A}_5 = [\sqrt{\gamma}\ \ 1]^\dagger$ and $\mathbf{A}_6 = [\sqrt{\gamma}\ \ 1\ \ 1\ \ 1]^\dagger$ for obtaining $\mathbf{\Sigma}$ when $m = 1$, 2 and 4, respectively. The results show that the 2-BS and 4-BS systems clearly always outperform the 1-BS system in terms of channel capacity. In terms of bit-per-joule capacity, the results show that the 2-BS and 4-BS systems outperform the 1-BS system for low γ values and vice-versa for γ values above 3 dB. For low γ values, the channel capacity of the 1-BS system is close to zero and incidently its bit-per-joule capacity is very low, while the 2 and 4-BS systems take advantage of the macro-diversity [5] and provide around 0.8 and 1.3 bits/kJ, respectively, of extra bit-per-joule capacity. The γ range for which multi-BS systems are more energy efficient than single BS system will increase when P_{CoMP} decreases or the link quality increases.

In Fig. 4, we depict the variation of the energy efficiency as a function of the number of BSs, m, in the downlink scenario and use the following settings to do so: $P = 40/m$, $k = 1$, $p = q = 2$. In addition, we utilise $\mathbf{A}_1$ for obtaining $\mathbf{\Sigma}$ and consider various values of γ and P_{CoMP}. The results first show that $\widetilde{C}_J$ increases with γ and that obviously $\widetilde{C}_J$ decreases as P_{CoMP} increases. Moreover, they indicate that there exists an optimal m value that maximizes $\widetilde{C}_J$ for each setting. More BSs are required for maximizing $\widetilde{C}_J$ when γ is low than when $\widetilde{C}_J$ is high. This is due to the fact that $\widetilde{C}$ is almost linear in m when γ is low and logarithmic in m when γ is high, as it is indicated by the second and first curves of Fig. 4. Similarly, as P_{CoMP} increases, as the optimal value of m increases. For instance the optimal m value for $P_{\text{CoMP}} = 0$ is 4 and becomes 5 and 6 for $P_{\text{CoMP}} = 500$ and 1000 W, respectively.

In Fig. 5, we consider an uplink scenario where k MSs transmit to 1, 2 or 4 BSs. We plot $\widetilde{C}$ and $\widetilde{C}_J$ in function of P_{CoMP} for a 1, 2 and 4-BS systems. We set $k = 4$, $p = 2$,

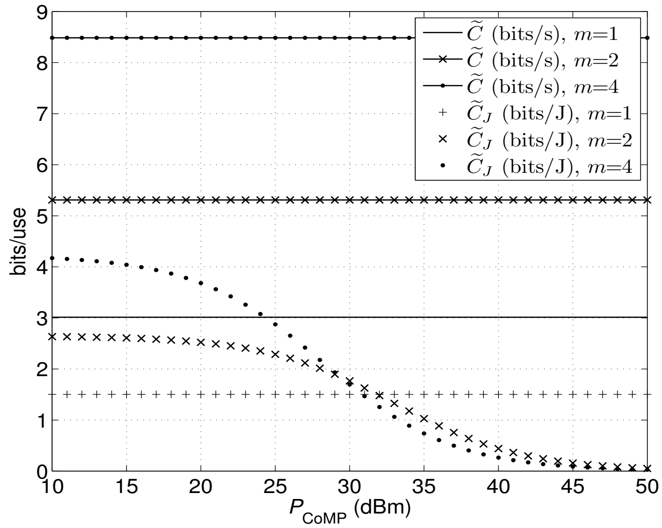

Fig. 5. Uplink: $\widetilde{C}_J$ and $\widetilde{C}$ comparison of a 1-BS with 2 and 4-BSs system as a function of P_{CoMP} in an uplink setting

$q = 1$, $\gamma = 0$ dB, $P_{\text{Ms}} = 27$ dBm (500 mW), and use $\mathbf{A}_4$, $\mathbf{A}_7 = [\mathbf{A}_4^\dagger \ \mathbf{A}_4^\dagger]^\dagger$ and $\mathbf{A}_8 = [\mathbf{A}_4^\dagger \ \mathbf{A}_4^\dagger \ \mathbf{A}_4^\dagger \ \mathbf{A}_4^\dagger]^\dagger$ for obtaining $\mathbf{\Sigma}$ when $m = 1$, 2 and 4, respectively. The 1-BS system exhibits a $\widetilde{C}$ and $\widetilde{C}_J$ of about 3 bits/s and 1.5 bits/J and its $\widetilde{C}_J$ clearly does not vary in function P_{CoMP}, since no backhauling is required in this case. The 2 and 4-BS systems have a fixed $\widetilde{C}$ of about 5.25 and 8.5 bits/s and its $\widetilde{C}_J$ varies in function of P_{CoMP}. The result clearly indicates that as long as P_{CoMP} stays in the order of magnitude of P_{Ms}, the 2 and 4-BS systems are more energy efficient than the 1-BS system.

Overall, the results in Figs. 3, 4 and 5 clearly underline the spectral efficiency gain that CoMP can achieve through macro-diversity, as it has already been shown in [6]. However, making BS cooperate does not come for free, it implies extra cost in terms of energy consumption. In terms of energy efficiency, results show that multi-BS cooperation is most likely to be efficient when the link quality between the BSs and MSs is weak, e.g. cell-edge communication.

V. Conclusion

In this paper, idealized CoMP communication has been assessed in terms of energy efficiency and it has been shown that the potential of improvement of CoMP in terms of bit-per-joule capacity is not as high as in terms of channel capacity. Assuming perfect backhaul links between each BS, CoMP system has been idealized into DMIMO system and the latter model has been utilized to derive a closed-form approximation of its channel capacity. The accuracy of this approximation has been assessed for different numbers of antenna and SNR offset between the various links. Results have indicated that its accuracy is high, even for DMIMO system with small numbers of transmit and receive antennas. A framework for energy efficiency analysis of idealized CoMP system has been introduced that includes a power consumption model and an energy efficiency metric. Our closed-form approximation of the DMIMO capacity has been utilized for assessing both the channel and bit-per-joule capacities of the idealized CoMP system. Results have indicated that multi-BS cooperation is most likely to be efficient when the link quality between the BSs and MSs is weak, e.g. cell-edge communication. In addition, cooperative processing power should be kept low for CoMP to provide energy efficiency gain. In the future, we intend to use a more realistic power model for the backhaul links as well as assuming non-perfect backhauling.

VI. Acknowledgment

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