Location-Aware Coordinated Multipoint Transmission in OFDMA Networks

Ahmed Hamdi Sakr, Hesham ElSawy, and Ekram Hossain

Abstract—We propose a novel Location-Aware multicell Cooperation (LAC) scheme for downlink transmission in OFDMA-based networks. Compared to the traditional multicell cooperation, the proposed scheme only uses coordinated multipoint (CoMP) transmission to serve users with poor SINR. On the other hand, users with good SINR conditions are served via multiuser MIMO by a single base station (BS). The proposed scheme uses a joint zero-forcing beamforming with semi-orthogonal user selection (ZFBF-SUS) transmission along with optimized power allocation in a semi-distributed manner to maximize the overall system energy efficiency (i.e., the average data rate per unit power [bps/Watt], or equivalently, average number of successfully transmitted bits per energy unit [bit/Joule]). Numerical results show that the proposed scheme outperforms the scheme that uses cooperation to serve all users, in terms of energy efficiency as well as system capacity and fairness.

I. INTRODUCTION

Multiple-input multiple-output (MIMO) has been of a great interest as a key technology for wireless system to roughly increase the capacity linearly with the minimum number of transmit and receive antennas [1]. Unfortunately, the complexity at mobile equipments limits the gain of this technique. Multiuser MIMO (MU-MIMO) and coordinated multipoint (CoMP) transmission (also referred as network-MIMO) are two forms of MIMO in which multiple users with a single receive antenna can be served simultaneously in the same subcarrier [2]. Both schemes boost the capacity by exploiting the spatial multiplexing gain, while shifting the processing burden and complexity to the transmitter side. MU-MIMO is mainly used to mitigate the intra-cell interference, while CoMP is used to alleviate the inter-cell interference especially for cell-edge users. In CoMP, multiple BSs share users’ data, via backhaul network, to form a single virtual BS with a large antenna array to serve these users. In both schemes, beamforming such as ZFBF is used to cancel out the interference resulting from serving multiple users on the same subcarrier [3].

Unfortunately, the deployment of these technologies to satisfy the ever-increasing user demand, increases the energy consumption which will significantly contribute to the global greenhouse gas emissions [4]. Therefore, energy efficiency is as important as system capacity in the design of resource allocation schemes for cellular networks. In the context of energy-efficient MIMO systems, [5] proposes an multicell cooperative ZFBF scheme in which all BSs use CoMP transmission to maximize the energy efficiency while considering the backhaul link capacity limitations. In [6], a MU-MIMO resource allocation scheme in a single-cell with multiple-antenna BS scenario is discussed to minimize the transmit power that satisfies given data rate requirements. The authors in [7] consider a two-tier scenario in which cooperating macro BSs are overlaid with clusters of cooperating femtocells where the energy efficiency is maximized under cross-tier interference constraints.

Motivated by the performance gains achieved by multicell cooperation and in order to increase the energy efficiency, we propose a Location-Aware multicell Cooperation (LAC) scheme for downlink OFDMA networks. Unlike conventional CoMP systems in which all users are served via cooperation, the main idea of LAC is to alleviate the burden of using cooperation to serve cell-centre users who already receive a high signal-to-interference-plus-noise ratio (SINR). For downlink transmission, this scheme exploits the dependency of SINR on users’ locations to control the tradeoff among capacity, fairness, and energy efficiency via selecting the appropriate mode of operation for the users (i.e., CoMP mode or non-CoMP mode). Based on the location of a user, the system chooses to serve this user via CoMP using all the BSs or via MU-MIMO by the nearest BS. Incorporating mode selection to the system design gives higher degrees of freedom in the resource allocation which improves the system performance.

We present a design paradigm for LAC scheme with the objective of maximizing the system energy efficiency. We perform mode selection, subcarrier allocation, precoding weight allocation, as well as power allocation. The results show that our scheme outperforms the conventional CoMP systems in terms of system capacity, fairness, and energy efficiency.

The contributions of this work are summarized as follows:

- We propose a novel LAC scheme for downlink MIMO-OFDMA networks. In the proposed scheme, cell-edge users are served via CoMP transmissions by multiple BSs, while cell-centre users are served via MU-MIMO transmissions by a single BS, cf. Fig. 1.
- We provide a semi-distributed resource allocation scheme that maximizes the system energy efficiency while considering both the total circuit power consumption and the limited capacity of the backhaul network.
- We show that LAC scheme is promising for improving spectral efficiency, energy efficiency, and fairness of MIMO-OFDMA systems compared to conventional schemes that use CoMP to serve all users in a cluster of cells.

Fig. 1. OFDMA downlink network with $M = 3$ BSs where each BS has $A = 3$ antennas.
II. System Model

A. Network Model

We consider a downlink multiuser MIMO-OFDMA network consisting of $M$ BSs and $K$ mobile users. Each BS is equipped with $A$ antennas where each user terminal has a single receive antenna. The BSs adopt a LAC scheme in which the complete set of users is split into two non-overlapping subsets, namely, non-CoMP users and CoMP users. CoMP users are served cooperatively by $M$ antennas where, for simplicity, the antenna with the best channel condition from each BS is selected. On the other hand, the non-CoMP users are served by MU-MIMO transmissions from their nearest BS, cf. Fig. 1. All BSs are assumed to communicate via a capacity-limited mesh backhaul network to exchange CoMP users’ data.

For a generic user, the mode of operation, i.e., non-CoMP or CoMP mode, is selected based on the average received SINR. In general, the distance of the user from her BS is a good indicator of her average received SINR. Therefore, the user is classified based on her distance from the nearest BS and a threshold radius $r_t$. In other words, a generic user is served by non-CoMP transmissions if her distance to the nearest BS is less than $r_t$; otherwise, the user is considered a CoMP user. We define $\alpha$ as the ratio between the non-CoMP transmission coverage area and the cell coverage area, i.e., $\alpha = \frac{r_t^2}{\pi r^2}$.

B. Channel Model and Capacity

For interference coordination, the total bandwidth $B$ is partitioned into two disjoint sets of subcarriers, $\mathcal{F}_c$ and $\mathcal{F}_n$, for CoMP and non-CoMP transmissions, respectively. Note that any subcarrier in $\mathcal{F}_n$ can be reused by any BS to serve its non-CoMP users while a subcarrier $n$ in $\mathcal{F}_c$ is used by all BSs to serve the same CoMP user. This spectrum partitioning, along with the distance-based mode selection, provides exclusion regions to protect both CoMP and non-CoMP users. Let $|\mathcal{F}_c| = N_c$, $|\mathcal{F}_n| = N_n$, and $N_c + N_n = N$, the size of each set is determined dynamically and proportional to the total number of CoMP and non-CoMP users such that $N_n = \lfloor N_c \times N \rfloor$ and $N_c = N - N_n$ where $K_i$ is the total number of non-CoMP users in the system and $\lfloor \cdot \rfloor$ denotes the set cardinality. Complete CSI is assumed at each BS and that the channel coherent time is greater than or equal to the frame duration.

For a non-CoMP user $k$ served by BS $m$ in subcarrier $n$ in $\mathcal{F}_n$, there are two sources of interference, namely, $i_{1,k}^n$ and $i_{2,k}^n$. While $i_{1,k}^n$ results from other non-CoMP users who share the same subcarrier in the same cell, $i_{2,k}^n$ results from non-CoMP transmissions in the other BSs. Hence, $i_{1,k}^n = \sum_{a=1}^{A} \sum_{j \in S_m \setminus k} \sqrt{p_{j,a}^n h_{j,a}^n w_{j,a}^n s_j^n}$, (1) $i_{2,k}^n = \sum_{a=1}^{A} \sum_{j \in S_m} \sqrt{p_{j,a}^n h_{j,a}^n w_{j,a}^n s_j^n}$, (2) $i_{3,k}^n = \sum_{m=1}^{M} \sum_{j \neq k} \sqrt{p_{j,m}^n h_{j,m}^n w_{j,m}^n s_j^n}$, (3) On the other hand, $i_{3,k}^n$ is the interference that affects CoMP transmissions due to sharing the same subcarrier $n$ in $\mathcal{F}_c$ by multiple CoMP users. That is, $i_{3,k}^n = \sum_{m=1}^{M} \sum_{j \in S_m} \sqrt{p_{j,m}^n h_{j,m}^n w_{j,m}^n s_j^n}$.

Note that, $p_{k,a}^n$ is the transmit power to non-CoMP user $k$ by antenna $a$ from its serving BS in subcarrier $n$, while $p_{k,m}^n$ is the transmit power to CoMP user $k$ by BS $m$ in subcarrier $n$. $h_{j,a}^n$ is the total channel gain (i.e., including both small-scale fading and path-loss) of subcarrier $n$ between CoMP user $k$ and non-CoMP user $a$ from its serving BS. $h_{j,m}^n$ is the best channel gain of subcarrier $n$ between CoMP user $k$ and CoMP users, respectively. $S_m$ is the set of non-CoMP users who are served by BS $m$ and share subcarrier $n$, while $S_c$ is the set of CoMP users who share subcarrier $n$. $s_k^n$ is the transmitted symbol for user $k$ in subcarrier $n$.

The received SINR at a user $k$ in subcarrier $n$ is given by

$$\text{SINR}_k^n = \left\{ \begin{array}{ll} \frac{\sum_{a=1}^{A} \sqrt{p_{k,a}^n h_{k,a}^n w_{k,a}^n s_k^n}^2}{\sum_{m=1}^{M} \sqrt{p_{k,m}^n h_{k,m}^n w_{k,m}^n} + \sigma_z^2} & , n \in \mathcal{F}_c, \\ \frac{\sum_{m=1}^{M} \sqrt{p_{k,m}^n h_{k,m}^n w_{k,m}^n} + \sigma_z^2}{\sum_{m=1}^{M} \sqrt{p_{k,m}^n h_{k,m}^n w_{k,m}^n}} & , n \in \mathcal{F}_n \end{array} \right. \quad (4)$$

where $\sigma_z^2$ is the variance of AWGN with zero mean and $I_{1,n}^k$, $I_{2,n}^k$, and $I_{3,n}^k$ are the interference powers based on (1), (2), and (3), respectively. Note that the numerator represents the useful coded signal power received at user $k$ in subcarrier $n$.

Using (4), we can express the channel capacity for user $k$ in subcarrier $n$ as

$$C_k^n = \frac{B}{N} \log_2 \left( 1 + \text{SINR}_k^n \right). \quad (5)$$

The total system capacity can therefore be obtained as follows

$$C_{\text{tot}} = \sum_{n \in \mathcal{F}_c} \sum_{k \in S_c^n} C_k^n + \sum_{m=1}^{M} \sum_{n \in \mathcal{F}_c} \sum_{k \in S_m^n} C_k^n = C_{\text{CoMP}} + C_{\text{non-CoMP}}. \quad (6)$$

C. Power Consumption Model

For the system described above, the total power consumption is given by

$$P_{\text{tot}} = P_{BH} + \sum_{m=1}^{M} \left( P_C + P_{\text{CoMP},m} + P_{\text{non-CoMP},m} \right), \quad (7)$$

where

$$P_{\text{CoMP},m} = \eta \sum_{n \in \mathcal{F}_c} \sum_{k \in S_m^n} \left| w_{k,m}^n \right|^2, \quad (8)$$

$$P_{\text{non-CoMP},m} = \eta \sum_{n \in \mathcal{F}_n} \sum_{a=1}^{A} \sum_{k \in S_m^n} \left| w_{k,a}^n \right|^2. \quad (9)$$

The power consumption model consists of a linear part which is proportional to the RF transmit power, a constant part that includes all signal processing power, and another constant part $P_{BH}$ which represents the total power consumption in the backhaul network [8]. $\eta \geq 1$ is the power amplifier inefficiency constant and $P_C$ is the signal processing power per BS.
D. Energy Efficiency Metric

We define the system energy efficiency as the average number of successfully transmitted bits per energy unit (bit/Joule) or, equivalently, the average data rate per power unit (bps/Watt), i.e.,

$$\text{EE} = \frac{C_{\text{tot}}}{P_{\text{tot}}},$$  \hspace{1cm} (10)

where $C_{\text{tot}}$ and $P_{\text{tot}}$ are given by (6) and (7), respectively.

III. PROBLEM FORMULATION

The objective is to perform resource allocation to maximize the energy efficiency of the network subject to backhaul capacity limitations and a total power budget. In this context, resource allocation (RA) means power allocation $\mathcal{P}$, precoding coefficient allocation $\mathcal{W}$, and subcarrier allocation $\mathcal{S}$.

A. Problem Decomposition

We propose a semi-distributed energy-efficient RA algorithm in which the problem is decomposed into two phases. In the first phase, each BS performs RA individually for its non-CoMP users, then it passes the values of $C_{\text{non-CoMP}}^m$ and $P_{\text{non-CoMP}}^m$ to a central unit to proceed with the second phase. In the second phase, the central unit allocates resources for all the CoMP users.

1) RA for Non-CoMP Users: In order to solve the RA problem for the non-CoMP users distributively, we ignore the effect of $i_{2,k}^n$, i.e., $I_{2,k}^n \approx 0$. This assumption is reasonable due to the exclusion region that separates the non-CoMP coverage regions, cf. Fig. 1. Then, we have $M$ different optimization problems, one problem per each BS. Our objective is to maximize the energy efficiency, however, it was shown in [5] that when the transmit power budget is low, maximizing the spectral efficiency leads to maximizing the energy efficiency. Therefore, we maximize $C_{\text{non-CoMP}}^m$ while limiting the total power available for the non-CoMP transmissions. Limiting the transmit power also reduces the effect of ignoring $i_{2,k}^n$.

For any BS $m$, the RA problem for the non-CoMP users can be written as

$$\max_{\mathcal{P}, \mathcal{W}, \mathcal{S}_m} \quad C_{\text{non-CoMP}}^m$$ \hspace{1cm} (11)

s.t. \hspace{0.5cm} \sum_{n \in \mathcal{F}_n} \sum_{a=1}^A \sum_{k \in \mathcal{S}_n^m} p_{k,a}^n |w_{k,a}^n|^2 \leq P_{th}, \quad \forall n \in \mathcal{F}_n, \hspace{1cm} (12)

$$|\mathcal{S}_n^m| \leq A, \quad \forall n \in \mathcal{F}_n, \hspace{1cm} (13)

$$p_{k,a}^n \geq 0, \quad \forall n, k, \hspace{1cm} (14)

where $P_{th}$ is a threshold to limit the total transmit power used by BS $m$ for non-CoMP transmissions. Note that $P_{th}$ also controls the amount of interference introduced to the other non-CoMP transmissions at neighboring BSs. (13) guarantees that each subcarrier is reused by a maximum of $A$ users for proper MU-MIMO transmissions.

2) RA for CoMP Users: For given $C_{\text{non-CoMP}}^m$ and $P_{\text{non-CoMP}}^m$, RA for CoMP users is performed in order to maximize the overall system energy efficiency defined in (10), and hence the problem can be written as

$$\max_{\mathcal{P}, \mathcal{W}, \mathcal{S}_m} \quad \text{EE}$$ \hspace{1cm} (15)

s.t. \hspace{0.5cm} \sum_{n \in \mathcal{F}_n} \sum_{k \in \mathcal{S}_n^m} \sum_{a=1}^A p_{k,a}^n |w_{k,a}^n|^2 \leq P_T - P_{th}, \quad \forall m, \hspace{1cm} (16)

$$\sum_{n \in \mathcal{F}_n} \sum_{k \in \mathcal{S}_n^m} C_k^n \leq R_{\text{max}}, \quad \forall m, \hspace{1cm} (17)

$$|\mathcal{S}_n^m| \leq M, \quad \forall n \in \mathcal{F}_c, \hspace{1cm} (18)

$$P_{k,a}^n \geq 0, \forall n, k, \hspace{1cm} (19)

where (16) is the total power budget constraint and $P_T$ is the maximum allowable transmit power by any BS. (18) is to ensure that no more than $M$ users are simultaneously selected to use any subcarrier. $R_{\text{max}}$ is the maximum backhaul link capacity and $\mathcal{U}_m$ is the set of users assigned to BS $m$.

IV. SOLUTION METHODOLOGY

The problems in (11) and (15) are mixed-combinatorial non-convex which are computationally huge and it is infeasible to obtain the optimal solution. Therefore, to solve these problems sub-optimally, we adopt a three-step approach. In the first two steps, based on [9], a semi-orthogonal user selection (SUS) scheme and zero-forcing beamforming (ZFBF) are used to obtain $\mathcal{S}$ and $\mathcal{W}$, respectively. In the third step, for a given $\mathcal{S}$ and $\mathcal{W}$, the problem reduces to a power allocation problem which can be solved by different methods.

A. Zero-forcing Beamforming with Semi-orthogonal User Selection (ZFBF-SUS) Scheme

This scheme performs precoding coefficient and subcarrier allocation at the same time. The main idea of the scheme is to achieve the capacity of CoMP and MU-MIMO by grouping the semi-orthogonal users to be simultaneously served on the same subcarrier; i.e., $\mathcal{S}$, while canceling out the interference by using ZFBF; i.e., $\mathcal{W}$. This scheme imposes an additional constraint on the problems, (11) and (15), such that the resulting set of users selected to transmit on any subcarrier $n$ are distinct. In addition, this scheme satisfies (13) and (18) where no more than $A$ or $M$ users are allowed to share the same subcarrier. Another benefit of ZFBF-SUS scheme is that it cancels out the interference between the CoMP users who share the same subcarrier, as well as, the non-CoMP users who share the same subcarrier at the same cell. Hence, $I_{2,k}^n = 0$. The algorithm can be found in [9] where it also has been shown that its performance is asymptotically optimal with low complexity.

To decouple the power allocation from the calculation of ZFBF coefficients, an additional constraint is added to the problems, (11) and (15). That is, on any subcarrier, the transmit powers to a certain CoMP (non-CoMP) user from the $M$ BSs ($A$ antennas) are the same, i.e.,

$$\begin{cases} p_{k,a}^n = p_{k,A}^n, & \forall a \in \{1, 2, \ldots, A\} \\ p_{k,m}^n = p_{k,M}^n, & \forall m \in \{1, 2, \ldots, M\} \end{cases}$$ \hspace{1cm} (20)

Now, we can rewrite the SINR as

$$\text{SINR}_k^n = \begin{cases} \frac{\sum_{a=1}^A h_{k,a}^n w_{k,a}^n \cdot p_{k,A}^n}{\sigma_z^2}, & n \in \mathcal{F}_n \\ \frac{\sum_{m=1}^M h_{k,m}^n w_{k,m} \cdot p_{k,M}^n}{\sigma_z^2}, & n \in \mathcal{F}_c \end{cases}$$ \hspace{1cm} (21)
B. Power Allocation Schemes

1) Non-CoMP Transmissions: We use Lagrangian relaxation $L_1(P, \lambda)$ of the primal problem (11) to obtain the dual problem as given by

$$\min_{\lambda} \max_P L_1(P, \lambda),$$

where $\lambda$ is the Lagrangian multiplier of (12), KKT conditions are necessary and sufficient to get the optimal solution of the dual problem (22). Therefore, we can obtain a closed-form solution for the power allocation for given $S_n$ and $W_m$ as

$$p_{k,A}^\ast = \left[ \frac{B}{N \ln(2)} - \frac{\sigma_n^2}{\sum_{i=1}^M h_{k,i}^n w_{n,i}} \right]^+, \quad (23)$$

The solution in (23) is in the form of multi-level water-filling and can be solved iteratively using the subgradient method [10]. However, we propose a less complex greedy algorithm to solve the problem. The algorithm is summarized in Table I, where $L$ is the number of power levels which controls the precision and speed of the solution. $\Delta c_n^k$ denotes the data rate gain achieved by assigning one additional power level to user $k$ in subcarrier $n$. The algorithm maximizes the capacity by adding one more power level, $\Delta p$, to user $k$ in subcarrier $n$ that has the maximum data rate gain $\Delta c_n^k$.

2) CoMP Transmissions: For given $W$ and $S$, the objective function in (15) is in a fractional form and non-convex in general; however, according to [11], it can be transformed into an equivalent form with the same optimal decision parameters, i.e., $P^\ast$, as stated in the following theorem.

**Theorem 1.** EE$^\ast = \max_P C_{tot}(P) / P_{tot}(P)$ if, and only if, $C_{tot}(P^\ast) - EE^\ast P_{tot}(P^\ast) = \max_P C_{tot}(P) - EE^\ast P_{tot}(P) = 0$.

Then, we can rewrite the optimization problem (15) as

$$\min_P C_{tot} - EE^\ast P_{tot}, \quad (24)$$

s.t. (16), (17), (19).

To obtain $P^\ast$, we use Dinkelbach iterative method which is proved to converge to the optimal value of EE when the numerator is concave and the denominator is convex. The proposed algorithm is summarized in Table II.

To solve optimization problem (24) for a given EE, we also use Lagrangian relaxation $L_2(P, \lambda, \beta)$ to obtain the dual problem as given by

$$\min_{\lambda, \beta} \max_P L_2(P, \lambda, \beta), \quad (25)$$

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<thead>
<tr>
<th>TABLE I. GREEDY ALGORITHM FOR NON-COMP TRANSMISSIONS</th>
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<tbody>
<tr>
<td><strong>Power Allocation for Non-CoMP Transmissions</strong></td>
</tr>
<tr>
<td>Define: $f(p, k, n) = \frac{B}{N \ln(2)} + \frac{p}{\sum_{i=1}^M h_{k,i}^n w_{n,i}}$ \Delta p = \frac{p}{\sum_{i=1}^M h_{k,i}^n w_{n,i}}$</td>
</tr>
<tr>
<td>Initialization: $C_{C_{tot}(\lambda)} = 0$, $p_{k,A}^0 = 0$, $\forall n \in F_m$, $k \in S_n$</td>
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<tr>
<td>Repeat $L$ times</td>
</tr>
<tr>
<td>$\Delta c_n^k = f(p_{k,A}^n + \Delta p, k, n) - f(p_{k,A}^n, k, n)$, $\forall n \in F_m$, $k \in S_n$</td>
</tr>
<tr>
<td>$p_{k,A}^{n+1} = p_{k,A}^n + \Delta p$</td>
</tr>
<tr>
<td>$C_{C_{tot}(\lambda)} = C_{C_{tot}(\lambda)} + \Delta c_n^k$</td>
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<tr>
<td>end</td>
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<tr>
<th>TABLE II. DINKELBACH ITERATIVE ALGORITHM</th>
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<tr>
<td><strong>Resource Allocation Based on Dinkelbach Method</strong></td>
</tr>
<tr>
<td>Initialization: EE = 0, tolerance $\epsilon$, maximum iterations $I_{max}$, iteration index $i = 0$, convergence = false</td>
</tr>
<tr>
<td>while convergence = false and $i &lt; I_{max}$</td>
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<tr>
<td>solve optimization problem (24) for a given EE</td>
</tr>
<tr>
<td>if $C_{tot}(P^\ast) - EE P_{tot}(P^\ast) &lt; \epsilon$ then</td>
</tr>
<tr>
<td>convergence = true</td>
</tr>
<tr>
<td>return $P^\ast$ and EE$^\ast$ to EE</td>
</tr>
<tr>
<td>else</td>
</tr>
<tr>
<td>EE $\leftarrow C_{tot}(P^{\ast,i})$ and $i \leftarrow i + 1$</td>
</tr>
<tr>
<td>end if</td>
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<tr>
<td>end while</td>
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<th>TABLE III. SIMULATION PARAMETERS</th>
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<tr>
<td><strong>Parameter</strong></td>
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<tr>
<td>Inter-BS distance</td>
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<tr>
<td>Total bandwidth, $B$</td>
</tr>
<tr>
<td>Total number of subcarriers, $N$</td>
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<tr>
<td>Noise variance, $\sigma_n^2$</td>
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<tr>
<td>Power amplifier inefficiency constant, $\eta$</td>
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<td>Signal processing power per BS, $P_C$</td>
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<tr>
<td>Backhaul links power consumption, $P_{BH}$</td>
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<tr>
<td>Backhaul link maximum capacity, $R_{max}$</td>
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where $\lambda, \beta$ are the Lagrangian multipliers of (16) and (17), respectively. The closed-form solution for the power allocation for given $S_n$ and $W$ is given by

$$p_{k,M}^\ast = \left[ \frac{B(1-\beta_m)}{N \ln(2)} \left( \frac{\eta EE + \sum_{i=1}^M \lambda_k w_{n,i}^k}{h_{k,i}^n w_{n,i}^k} \right) - \frac{\sigma_n^2}{\sum_{i=1}^M h_{k,i}^n w_{n,i}^k} \right]^+, \quad (26)$$

Note that, (26) takes the form of multi-level water-filling in which the Lagrangian multipliers controls the power levels i.e., water levels, in order not to violate any of the constraints. In addition, EE excludes the inefficient links that have poor effective channel gains; i.e., $\sum_{k=1}^M h_{k,i}^n w_{n,i}^k$ from being allocated power by truncating their powers levels.

V. SIMULATION RESULTS

We evaluate the performance of the proposed LAC scheme via Monte Carlo simulations in terms of energy efficiency (bps/Watt), capacity (bps/Hz/BS), i.e., spectral efficiency, and fairness. The proposed scheme is compared to the conventional All-CoMP scheme in which BSs cooperate over all the sub-carriers, i.e., $\alpha = 0$. Unless otherwise stated, the system under consideration consists of $M = 3$ BSs and serves $K = 60$ users uniformly distributed over $D = [0, 1000]^2$. Each BS has $A = 3$ antennas while each user terminal has a single receive antenna. i.i.d. Rayleigh fading with unit variance along with 3GPP urban path-loss model [12] are used to simulate the channels. Table III summarizes the simulation parameters.

A. Performance of Non-CoMP Transmission

1) Average Interference Power: Fig. 2 shows the average interference power received by a generic non-CoMP user, $E[I_{2,k}]$, and the capacity of non-CoMP transmissions as a function of the total power budget for non-CoMP transmission $P_{th}$. It is observed that $P_{th}$ controls the system behavior and may lead to a noise-limited operation, i.e., $E[I_{2,k}] < \sigma_k^2$, or an interference-limited operation, i.e., $E[I_{2,k}] > \sigma_k^2$. Note that, the
resource allocation for non-CoMP transmissions is performed distributively, hence, the information about the inter-cell interference, $I_{2,k}^{th}$, from neighboring BSs is not available. That is, from the BS perspective, the foreseen capacity increases linearly with the power in the absence of $I_{2,k}^{th}$. While this is true for also the actual capacity in the noise-limited region, the actual capacity saturates in the interference-limited region and the gap between the actual capacity and the foreseen capacity increases with $P_{th}$ due to the linear increase in the interference.

2) Energy Efficiency: Fig. 3 illustrates the effect of increasing $P_{th}$ on both the foreseen energy efficiency and the actual energy efficiency of non-CoMP transmissions. Due to the unavailability of RA information at other BSs, on average, the foreseen energy efficiency is 9% higher than the actual energy efficiency. Note that, this over estimation error is sacrificed to decompose the problem and solve it in a semi-distributed manner with less complexity. In the low power budget regime, Fig. 3 shows that the system maximizes the energy efficiency in addition to increasing the capacity (Fig. 2). On the other hand, in the high power budget regime, maximizing the total capacity results in a reduced energy efficiency since the capacity gain diminishes with increasing $P_{th}$ due to interference. Therefore, $P_{th}$ is chosen to achieve maximum energy efficiency while limiting the error due to ignoring the effect of $I_{2,k}^{th}$, e.g., $P_{th} = 22 \text{ dBm}$ in this case. Note that, increasing the transmit power beyond this value does not contribute much to the non-CoMP transmissions capacity, cf. Fig. 2.

B. Overall System Performance

1) Fairness: As an indicator of fairness, Fig. 4 depicts the relation between the ratio $\alpha$ and the number of served users for both LAC and All-CoMP schemes. A user is said to be served if it is assigned at least one transmission. The figure shows the improvement gained by LAC compared to All-CoMP scheme. Since ZFBF-SUS is a greedy scheme, the number of users served by All-CoMP scheme is relatively low. As $\alpha$ increases, CoMP users who have high SINR with respect to their nearest BS are offloaded to the non-CoMP transmissions. Thus, users with less SINR have higher opportunity to be selected by ZFBF-SUS and being served by CoMP transmission; consequently, the fairness increases. Note that, after a certain value of $\alpha$, the number of served CoMP users starts to fall due to the limited number of cell-edge users. After the total number of users reaches its maximum value, increasing $\alpha$ increases the number of non-CoMP users and decreases the number of CoMP users by the same rate which maintains a constant total number of served users. Based on the results in Fig. 4, $\alpha$ is chosen such that the number of served users is maximized while the loss in the number of CoMP users is limited, e.g., $\alpha = 0.5$. Compared to All-CoMP scheme in which $16.23\%$ of the users are served, our proposed LAC scheme serves up to $78.43\%$ of the users, which represents a $383\%$ improvement in the total number of served users.

2) System Energy Efficiency: Fig. 5 shows the system energy efficiency of both LAC and All-CoMP schemes versus the total transmit power budget $P_T$. It also compares the performance of two different objective functions; namely, Energy Efficiency Maximization (EEM) and Spectral Efficiency Maximization (SEM). While EEM is the scheme described above, SEM scheme maximizes the system capacity, $C_{tot}$, subject to the same constraints (16)-(19). By comparing EEM to SEM, we can observe that SEM is a greedy scheme since its objective is to maximize the system capacity, not the energy efficiency. That is, the more the available power, the more is the consumed power regardless of the relative gain in the system capacity compared to the cost of increasing the transmit power. Therefore, the energy efficiency deteriorates in the high power budget regime. On the other hand, EEM scheme tends to approach a constant performance to maintain higher energy efficiency since the system does not consume more power after achieving the maximum energy efficiency.
10 15 20 25 30 35 40 45 50 55 0.5 1 1.5 2 2.5 3 3.5 4 4.5 x 10^5
Total transmit power budget, PT (dBm)
System energy efficiency, EE (bps/Watt)

LAC, EEM
LAC, SEM
All-CoMP, EEM
All-CoMP, SEM

3) System Capacity: The results in Fig. 6 reinforce the results in Fig. 5 and together explain the behavior of the system for both LAC and All-CoMP schemes. For instance, since the energy efficiency increases with \( P_T \) in the low power budget regime, cf. Fig. 5, the system tends to consume all the available power. On the contrary, in the high power budget regime, the system does not consume more power after achieving the maximum energy efficiency. Therefore, the system capacity increases with the power in the low power budget regime, while it approaches a constant value in the high power budget regime as shown in Fig. 6.

Figs. 4-6 altogether clearly show that LAC outperforms All-CoMP in terms of energy efficiency, capacity, and fairness. LAC scheme exploits the fact that users located within a close proximity from one of the BSs, i.e., cell-centre users, will most likely experience good SINR conditions. Although canceling the low inter-cell interference for cell-centre users via CoMP can increase the per-user performance, the system performance gain is negligible compared to the number of unserved users, system complexity, amount of used resources, and system energy efficiency loss. The proposed scheme offloads cell-centre users from CoMP service to be served by the nearest BS via a MU-MIMO transmission. Note that, the effective channel gain between a cell-centre user and her serving BS is better than that between this user and all the cooperating BSs. Furthermore, to protect non-CoMP users from excessive inter-cell interference, LAC scheme controls the transmit power of non-CoMP transmissions \( P_{th} \) to change the size of exclusion regions accordingly. The aforementioned factors explains the higher capacity (Fig. 6) and the higher energy efficiency (Fig. 5) of the proposed scheme compared to All-CoMP scheme.

VI. CONCLUSION

We have proposed a novel Location-Aware Cooperation (LAC) scheme along with a methodology to choose the system parameters. Based on the users’ SINR, the proposed scheme uses CoMP transmissions only for users with poor SINR conditions in order to reduce the system complexity (i.e., both computational and signaling complexity) and increase the energy efficiency. By serving the users with high SINR conditions through the non-CoMP (MU-MIMO) transmissions, the opportunities for users with poor SINR to be selected by ZFBF-SUS for CoMP transmissions increase. After selection of users’ mode of operation, the problem is solved in a semi-distributed manner. Compared to All-CoMP scheme, LAC scheme better utilizes the available resources to provide higher capacity and higher energy efficiency. In addition, the number of users that LAC scheme can support is much higher compared to the number of users supported by All-CoMP scheme. In this way, it increases the fairness among users.

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