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# Sparse Beamforming for Real-time Energy Trading in CoMP-SWIPT Networks

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**Abstract**—In this paper, we propose a coordinated base-station energy management (CoBEM) technique in which the BSs in a coordinated multipoint (CoMP) with rate-limited backhaul links collaborate to keep the demand and supply balanced using local renewable energies. We formulate two sparse beamforming techniques as  $\ell_0$ -norm optimisation problems and apply a method that can replace  $\ell_0$ -norm with  $\ell_1$ -norm and iteratively updated the weight factors to obtain a sufficient sparsity solution called *reweighted  $\ell_1$ -norm minimisation*. For *user-centric clustering* technique, each user terminal selects a cluster of BSs, whereas, for *BS-centric clustering* technique, the BSs with a shortage of power budget are authorised to select an optimal number of user terminals based on their available energy budget. In both techniques, we investigate the optimal tradeoff between the BS-receiver cooperation links, the overall energy consumption by the BSs and the energy purchased by the retailer from the real-time market, whilst accounting for the quality-of-service (QoS) requirements for simultaneous wireless information and power transfer (SWIPT). Extensive simulation results confirm that the proposed sparse beamforming techniques significantly improve the infeasibility of a full cooperation in CoMP-SWIPT networks and reveal that the *BS-centric clustering* is more profitable than the *user-centric clustering* in real-time energy balancing.

## I. INTRODUCTION

Coordinated multipoint (CoMP) transmission that allows neighbouring base stations (BSs) to collaborate with each other for simultaneous wireless information and power transfer (SWIPT), has been extensively scrutinised as a promised solution for intercell interference mitigation [1], [2]. It has been proven that the total transmit power in a CoMP is reduced when a full cooperation is enabled [3]. However, if all the BSs in a CoMP network cooperate to transfer energy to all energy receiving terminals (ETs) and share the information of all information receiving terminals (ITs), huge backhaul capacity is needed [4]–[8]. In practice, all the BSs in a CoMP are connected with a cloud computing centralized unit (CU) via rate-limited backhaul links. Therefore, full cooperation may be infeasible.

All these have sparked interest among telecommunication researchers to investigate multi-cell cooperation transmission with restricted backhaul capacity [4]–[6], [8]–[11] motivated by the remarkable performance of *reweighted  $\ell_1$ -norm minimisation algorithm* in compressing sensing introduced in [12]. These studies proposed an iterative sparse beamforming algorithm to lessen the load of the backhaul links and used  $\ell_1$ -norm of the beamforming vector to approximate the cluster size. Interestingly, [6] adopted a new weight factor updating rule and achieved a better tradeoff between the total power transmit from all BSs and the sum backhaul capacity. However,

most of the sparse beamforming literature cited above does not consider the existence of energy harvesting devices and renewable energy productions for the green network. In [2], the resource allocation algorithm design for a CoMP-SWIPT network is proposed by optimising the transmit beamforming vectors at the CU and energy sharing between the CU and remote radio heads (RRH). This architecture however, does not consider renewable energy resources that can be further extended for energy cooperation and energy trading in the CoMP-SWIPT network.

To the best of our knowledge, this paper is the first to consider sparse beamforming for real-time energy trading and power balancing using local renewable energies in CoMP-SWIPT networks with restricted backhaul capacity links, called as a coordinated base-station energy management (CoBEM). To further reduce the overall cost in CoMP-SWIPT networks, we propose new approaches in sparse beamforming designs and energy transfer to the ETs. In the first sparse beamforming design, we adopt *user-centric clustering* technique where the serving BSs are not determined by the supply site but by the receiving terminals, where these terminals are allowed to choose a group of BSs. Contrastively, in the second design, permission is given by the CU to the BSs with a shortage of power budget in order to select an optimal number of receiving terminals based on their renewable energy resources. The non-zero entries in a sparse beamforming vector are consistent with the number of a serving BSs in the former design and a group of receiving terminals in the latter design. We formulate two optimisation problems to find the optimal tradeoff between the BS to receiver cooperation links, the sum transmit power by transmitting terminals, and the energy purchased by the retailer from the real-time market, whilst accounting for the quality-of-service (QoS) requirements for CoMP-SWIPT system. We also propose an iterative algorithm based on fixed-priority preemptive scheduling (FPPS) system, in which, the CU ensures that at any given time, the highest-priority ET is granted to harvest energy from the nearest BS.

*Notations:* Throughout the paper,  $w$ ,  $\mathbf{w}$ ,  $\mathbf{W}$ ,  $(\cdot)^H$  and  $\text{tr}(\cdot)$ , respectively, represent a scalar  $w$ , a vector  $\mathbf{w}$ , a matrix  $\mathbf{W}$ , the complex conjugate transpose operators and the trace operators.  $\mathbf{W} \succeq 0$  denotes that  $\mathbf{W}$  is a positive semidefinite matrix and  $\mathbb{C}^{n \times m}$  indicates the sets of  $n$ -by- $m$  dimensional complex matrices.  $\mathbb{CN}(\mu, \Gamma)$  represents the circularly symmetric complex normal distribution with mean  $\mu$  and variance  $\Gamma$ .  $\|\cdot\|_p$  is used to denote the  $\ell_p$ -norm of a vector and  $\|\cdot\|_0$  indicates the number of non-zero entries in the vector. In this paper, we normalized the unit of energy, i.e.,  $J_s^{-1}$ , therefore, 'power' and 'energy' terms are mutually convertible.

## II. SYSTEM MODEL AND PROBLEM FORMULATION

We consider simultaneous energy and information transmission in a CoMP multiuser downlink communication network. The system consists of a CU,  $N$  BSs, each equipped with  $M$  antennas,  $K_e$  prioritized single antenna energy-receiving terminals (ETs) and  $K_i$  single antenna information-receiving terminals (ITs). Let  $\mathcal{L}_b = \{1, \dots, N\}$ ,  $\mathcal{L}_e = \{1, \dots, K_e\}$  and  $\mathcal{L}_i = \{1, \dots, K_i\}$ , respectively, indicate the set of indexes of the BSs, the prioritized ETs and the ITs in the CoMP system. So, the set of index of the active receiving terminals,  $\mathcal{L}_a$  can be defined as  $\mathcal{L}_a = \{1, \dots, U\}$  where  $U = K_e + K_i$ . Furthermore, we define  $\mathcal{L}_e^{\text{[idle]}} = \{1, \dots, K_e^{\text{[idle]}}\}$  is the set of index of the idle ETs. The CU, which is connected to the grid via the retailer is the core unit and is where it accomplishes all the statistical computations and decisions.

### A. Resource Management and Energy Trading model

At the supply-side, we assume that each BS $_n$ ,  $n \in \mathcal{L}_b$ , is equipped with renewable energy devices, e.g., solar panel and/or wind turbine that produce energy  $E_n$ . Each BS is also installed with a smart meter to enable it to trade energy with the grid via the retailer. Let  $B_n^{\text{[ahead]}}$ ,  $B_n^{\text{[real]}}$ ,  $S_n$  denote a bulk of energy that has already been purchased from the grid in the day-ahead market, an amount of energy purchased from the grid in the real-time market, and an amount of energy sold to the grid by the retailer, respectively, by the BS $_n$ . Then, the total power consumption at BS $_n$ ,

$$P_n^{\text{[total]}} = P_n^{\text{[Tx]}} + P_n^{\text{[circuit]}} \leq E_n + B_n^{\text{[ahead]}} + B_n^{\text{[real]}} - S_n. \quad (1)$$

where  $P_n^{\text{[Tx]}}$  and  $P_n^{\text{[circuit]}}$  indicate the total transmit power at the BS $_n$  and the processing power consumed by the BS $_n$  to maintain its routine. Let  $\pi^{\text{[ahead]}}$  and  $\pi^{\text{[sell]}}$  be the agreed price per unit energy for purchasing  $B_n^{\text{[ahead]}}$  and selling off  $S_n$  excessive energy to the grid by the retailer. To maintain a target profit margin at the grid, we assume  $\pi^{\text{[ahead]}} \geq \pi^{\text{[sell]}}$ . If the energy is inadequate for the need of any BS, the retailer is obliged to purchase  $B_n^{\text{[real]}}$  with the price of  $\pi^{\text{[real]}}$  per unit energy. In practice, the grid may demand a higher price in the real-time market than the price in the day-ahead market, i.e.,  $\pi^{\text{[real]}} \geq \pi^{\text{[ahead]}} \geq \pi^{\text{[sell]}}$ . So, from the supply-side management perspective, it is desirable to coordinate the BSs and the user terminals to reduce the energy cost. Consequently, the users' billing charges can be reduced.

### B. Downlink Transmission Model

Let  $\mathbf{w}_{np} \in \mathbb{C}^{M \times 1}$  be the beamforming vector formed by the  $n$ -th BS towards the  $p$ -th user terminal,  $p \in \mathcal{L}_a$ . We view all  $N$  BSs of the CoMP as a single virtual BS and formulate the problem from the perspective of sparse optimisation. The antennas of the virtual BS can be partitioned into  $N$  groups, each corresponding to an individual BS. Let  $\mathbf{w}_p = [\mathbf{w}_{1p}^H, \dots, \mathbf{w}_{Np}^H]^H \in \mathbb{C}^{MN \times 1}$  indicate the beamforming vector formed by the virtual BS towards the  $p$ -th user terminal. Let  $\mathbf{w}_n = [\mathbf{w}_{n1}^H, \dots, \mathbf{w}_{nU}^H]^H \in \mathbb{C}^{MN \times 1}$  denote the beamforming vector formed by the  $n$ -th BS towards the all of the  $U$  users in the system. The requirement that some BSs may not participate in transmission towards a user terminal  $p$ , due to some energy restrictions, translates to the group

sparse structure of the virtual beamformer  $\mathbf{w}_p$ . That is, if  $\mathbf{w}_{np} = \mathbf{0}$ , then the  $n$ -th BS is not participating in serving the user terminal  $p$ . Similarly, inserting  $\mathbf{w}_{np} = \mathbf{0}$  in  $\mathbf{w}_n$  means that the user  $p$  is not served by the BS  $n$ , due to shortage of energy budget at the  $n$ -th BS. Let  $\mathbf{h}_{np} \in \mathbb{C}^{M \times 1}$  denote the channel vector between the  $n$ -th BS and the  $p$ -th user terminal. The received signals at the  $p$ -th user terminal,  $p \in \mathcal{L}_a$  in a CoMP downlink network, i.e.,  $\mathbf{y}_p \in \mathbb{C}$  can be expressed as

$$\mathbf{y}_p = \mathbf{h}_p^H \mathbf{w}_p s_p + \sum_{j=\mathcal{L}_a, j \neq p} \mathbf{h}_p^H \mathbf{w}_j s_j + n_p, \quad (2)$$

where  $\mathbf{h}_p = [\mathbf{h}_{1p}^H, \dots, \mathbf{h}_{Np}^H]^H \in \mathbb{C}^{MN \times 1}$  denotes the overall channel vector from the virtual BS to the  $p$ -th user terminal,  $s_p \sim \mathcal{CN}(0, 1)$  is the intended symbol for the  $p$ -th user terminal and  $n_p \sim \mathcal{CN}(0, \sigma_p^2)$  is the zero-mean circularly symmetric complex Gaussian noise. Note that we assume the noise variance,  $\sigma_p^2$  is identical at all user terminals. Then, the signal-to-interference-plus-noise ratio (SINR) at the  $i$ -th IT,  $i \in \mathcal{L}_i$ , can be defined as

$$\text{SINR}_i^{\text{[IT]}} = \frac{|\mathbf{h}_i^H \mathbf{w}_i|^2}{\sum_{j=\mathcal{L}_a, j \neq i} |\mathbf{h}_i^H \mathbf{w}_j|^2 + \sigma_i^2}. \quad (3)$$

Furthermore, we define  $\|\|\mathbf{w}_{ni}\|_2\|_0$  as an indicator function that illustrates the scheduling choices of the individual ITs, i.e.,

$$\|\|\mathbf{w}_{ni}\|_2\|_0 = \begin{cases} 0, & \text{if } \|\mathbf{w}_{ni}\|_2 = 0, \\ 1, & \text{if } \|\mathbf{w}_{ni}\|_2 \neq 0, \end{cases} \quad (4)$$

and the backhaul capacity consumption for the BS $_n$  can be defined as  $C_n^{\text{[backhaul]}} = \sum_{i \in \mathcal{L}_i} \|\|\mathbf{w}_{ni}\|_2\|_0 R_i$ ,  $\forall n \in \mathcal{L}_b$ , where

$R_i = \log_2(1 + \text{SINR}_i^{\text{[IT]}})$  is the the achievable data rate (bit/s/Hz) for the  $i$ -th IT. Note that  $\|\mathbf{w}_{ni}\|_2 = 0$  indicates partial cooperation in the view of the fact that the  $n$ -th BS is not participating in the joint transmission to the  $i$ -th IT.

### C. Coordinated Base-station Energy Management (CoBEM)

By using the *user-centric clustering* strategy, each user terminal is able to select a cluster of BSs from the total number of  $N$  BSs, which is modeled by inserting zeros for the group of elements corresponding to the non-serving BSs in the beamforming vector of  $\mathbf{w}_p$ ,  $\forall p \in \mathcal{L}_a$ , of the virtual BS. The number of active BSs serving user  $p$  can be formulated using the  $\ell_0$ -norm as  $\|\|\mathbf{w}_{1p}\|_2, \dots, \|\mathbf{w}_{Np}\|_2\|_0$ , where  $\|\cdot\|_0$  denotes the  $\ell_0$ -norm and represents the number of non-zero elements in the respective vector. Whereas, by using the *BS-centric clustering* strategy, the BSs with a shortage of power choose a group of user terminals based on their available renewable energy budget. This is modeled by inserting zeros in the beamforming vector of  $\mathbf{w}_n$ ,  $\forall n \in \mathcal{L}_b$  for the group of elements corresponding to the group of users who are not served by the  $n$ -th BS. The number of active users chosen by the  $n$ -th BS can be formulated using the  $\ell_0$ -norm as  $\|\|\mathbf{w}_{n1}\|_2, \dots, \|\mathbf{w}_{nU}\|_2\|_0$ . Let  $P_n^{\text{[budget]}}$  define the energy budget of the BS $_n$ ,  $n \in \mathcal{L}_b$ . We say that the  $n$ -th BS has shortage of power budget if

$$P_n^{\text{[budget]}} \leq \sum_{n=\mathcal{L}_b} \left( \frac{E_n + B_n^{\text{[ahead]}} - P_n^{\text{[circuit]}}}{N} \right). \quad (5)$$

Let  $\mathcal{L}_s = \{1, \dots, Z\}$ ,  $\mathcal{L}_s \subset \mathcal{L}_b$  indicate the set of indexes of the BSs with shortage of power budget in the CoMP system. These BSs can only serve a limited number of user terminals whose number can be expressed in terms of  $\ell_0$ -norm as  $\|[\|\mathbf{w}_{s1}^*\|_2, \dots, \|\mathbf{w}_{sU}^*\|_2]\|_0$ , for any  $s$ -th BS,  $s \in \mathcal{L}_s$ .

In a SWIPT network, unbalanced conditions resulting from an increasing number of ETs may lead to further degradation of the power quality and other problems. The system should properly be reinforced to balance the supply and demand in the CoMP system. Inspired by the FPPS system commonly used in real-time system, we propose an iterative algorithm to ensure that at any given time, the CU serves the highest priority ET of all those ETs that are currently ready to be served. The total energy harvested by the  $e$ -th prioritised ET,  $e \in \mathcal{L}_e$ , is

$$\mathcal{G}_e^{[ET]} = \eta \left( |\mathbf{g}_e^H \mathbf{w}_e|^2 + \sum_{j \in \mathcal{L}_a, j \neq e} |\mathbf{g}_j^H \mathbf{w}_j|^2 \right), \quad (6)$$

where the constant  $0 \leq \eta \leq 1$  indicates the conversion efficiency from the harvested RF energy to the electrical energy and it is assumed to be identical for all ETs;  $\mathbf{g}_e = [\mathbf{g}_{1e}^H, \dots, \mathbf{g}_{Ne}^H]^H \in \mathbb{C}^{MN \times 1}$  represents the overall channel vector from the virtual BS to the  $e$ -th prioritised ET. In Algorithm 1, we assume that the CU having the ability to define the higher-priority ETs, decides the maximum amount of energy that can be allocated to them,  $P_{max}^{[ET]}$  and only authorize the nearest BS denoted by  $BS_x$ ,  $x \in N$  to serve the  $e$ -th prioritised ET, whereas all the beamforming vector from other BSs to the  $e$ -th ET are set to be zero,  $\|[\|\mathbf{w}_{xe}\|_2]\|_0 = 1$  and  $\|[\|\mathbf{w}_{me}\|_2]\|_0 = 0$ ,  $m \in \mathcal{L}_b$ ,  $m \neq x$ . If the  $j$ -th ET,  $j \in \mathcal{L}_e^{[idle]}$  has been set as an idle ET, it can only harvest an amount of energy from the surrounding and can be calculated as  $\mathcal{G}_j^{[ET:idle]} = \eta \left( \sum_{p \in \mathcal{L}_a} |\mathbf{f}_j^H \mathbf{w}_p|^2 \right)$ , where  $\mathbf{f}_j = [\mathbf{f}_{1j}^H, \dots, \mathbf{f}_{Nj}^H]^H \in \mathbb{C}^{MN \times 1}$  denotes the overall channel vector from all the BSs to the  $j$ -th idle ET.

**Algorithm 1** A Fixed-priority pre-emptive scheduling for ETs

- 1: **Initialize:** CU frequently defines the priority of all ETs in descending order  $\mathcal{R} = \{\mathcal{R}_1, \mathcal{R}_2, \dots, \mathcal{R}_{K_e + K_e^{[idle]}}\}$  with  $\mathcal{R}_1 > \mathcal{R}_2 > \dots > \mathcal{R}_{K_e + K_e^{[idle]}}$ . Initial the accumulated total power transmit to the higher priority ETs  $P_{acc}^{[ET]}(0) = \sum_{t=1}^p P(\mathcal{R}_0) = 0$ , ET count  $p = 0$ .
- 2: **while**  $\sum_{t=1}^p P(\mathcal{R}_t) \neq P_{max}^{[ET]}$  and  $p \neq K_e + K_e^{[idle]}$  **do**
- 3: Increment the number of higher-priority ET  $p = p + 1$ .
- 4: CU calculates the amount of power that should be transmitted from the nearest  $BS_x$  to the  $p$ -th higher-priority ET to satisfy its minimum request,  $P_p^{[min]}$ .
- 5: **If**  $\sum_{t=1}^p P(\mathcal{R}_t) < P_{max}^{[ET]}$
- 6: CU serves energy request from the  $p$ -th higher-priority ET and set as a prioritised ET,  $p \in \mathcal{L}_e$ .
- 7: **else** CU discard the  $p$ -th higher-priority ET and set as an idle ET  $p \in \mathcal{L}_e^{[idle]}$ .
- 8: **end while**
- 9: CU update the accumulated total power transmit,  $P_{acc}^{[ET]}(p)$ .

### III. SPARSE BEAMFORMING OPTIMISATION PROBLEMS

In this section, we introduce two sparse beamforming optimisation problems, namely, *user-centric-clustering* and *BS-centric clustering*.

#### A. User-centric clustering

*User-centric clustering* technique is formulated as the tradeoff between the BS cluster over all user terminals, the total network transmit power, and the energy purchased by the retailer from the real-time market whilst providing QoS for multiuser SWIPT within the CoMP system, as follows

$$\begin{aligned} \min_{\mathbf{w}_p^n, B_p^n} \quad & \beta \sum_{p \in \mathcal{L}_a} \|[\|\mathbf{w}_{1p}\|_2, \dots, \|\mathbf{w}_{Np}\|_2]\|_0 \quad (7) \\ & + \zeta \sum_{p \in \mathcal{L}_a} \sum_{n \in \mathcal{L}_b} \|\mathbf{w}_{np}\|_2^2 + \sum_{n \in \mathcal{L}_b} B_n^{[real]}, \\ \text{s.t.} \quad & \text{C1: } \text{SINR}_i^{[IT]} \geq \gamma_i, \quad \forall i \in \mathcal{L}_i, \\ & \text{C2: } \mathcal{G}_e^{[ET]} \geq P_e^{[min]}, \quad \forall e \in \mathcal{L}_e, \\ & \text{C3: } P_{acc}^{[ET]} \leq P_{max}^{[ET]}, \\ & \text{C4: } P_n^{[Tx]} + P_n^{[circuit]} \leq E_n + B_n^{[ahead]} \\ & \quad \quad \quad + B_n^{[real]} - S_n, \quad \forall n \in \mathcal{L}_b \\ & \text{C5: } C_n^{[backhaul]} \leq C_n^{[b-limit]}, \quad \forall n \in \mathcal{L}_b, \\ & \text{C6: } B_n^{[real]} \geq 0, \quad \text{C7: } S_n \geq 0, \quad \forall n \in \mathcal{L}_b \end{aligned}$$

where  $\beta \geq 0$  and  $\zeta \geq 0$  in the objective function are, respectively, the preference for the BS cluster over all user terminals and the total power consumption in a network. The required  $\gamma_i$  represents the minimum SINR requirement of the  $i$ -th IT,  $i \in \mathcal{L}_i$  in C1.  $P_e^{[min]}$  in C2 is the minimum energy requested by the  $e$ -th higher-priority ET to extend its lifetime, while  $P_{max}^{[ET]}$  in C3 is the maximum energy that can be allocated to all the higher-priority ETs in a CoMP network. The constraint set in C4 represents the total transmit power by the  $BS_n$ ,  $n \in \mathcal{L}_b$  which is limited by its power budget. C5 denotes the individual backhaul link capacity limitation. In C6 and C7, the optimisation variables are set to be positive value constraints.

#### B. BS-centric clustering

For *BS-centric clustering* approach, we investigate the optimal tradeoff between the number of active users chosen by the BSs with a shortage of power budget, the total network transmit power, and the energy purchased from the real-time market whilst providing QoS for multiuser SWIPT, as follows

$$\begin{aligned} \min_{\mathbf{w}_p^t, B_p^t} \quad & \beta \left( \sum_{p \in \mathcal{L}_a} \|[\|\mathbf{w}_{1p}^*\|_2]\|_0 + \dots + \sum_{p \in \mathcal{L}_a} \|[\|\mathbf{w}_{Zp}^*\|_2]\|_0 \right) \\ & + \zeta \sum_{p \in \mathcal{L}_a} \sum_{n \in \mathcal{L}_b} \|\mathbf{w}_{np}\|_2^2 + \sum_{n \in \mathcal{L}_b} B_n^{[real]}, \quad (8) \\ \text{s.t.} \quad & \text{C1} - \text{C7 in (7)}. \end{aligned}$$

Note that the optimisation problems in (7) and (8) are non-convex due to the non-convexity of the C1-C5 constraints and  $\ell_0$ -norm representation of the BS-receiver cooperation links in the both objective problems. First, we propose to

solve objective problems heuristically by iteratively relaxing the  $\ell_0$ -norm as a weighted  $\ell_1$ -norm, initially designed in the compressive sensing [12].

### C. Iterative Algorithm with Reweighted $\ell_1$ -norm and SDP

The number of BSs serving  $p$ -th user terminal,  $p \in \mathcal{L}_a$  in  $\|[\|\mathbf{w}_{1p}\|_2, \dots, \|\mathbf{w}_{Np}\|_2]\|_0$  and the number of active users chosen by the  $s$ -th BS,  $s \in \mathcal{L}_s$  in  $\|[\|\mathbf{w}_{s1}^*\|_2, \dots, \|\mathbf{w}_{sN}^*\|_2]\|_0$  do not change if the  $\ell_2$ -norm is replaced by  $\ell_2$ -norm square and the  $\ell_0$ -norm can be approximated by  $\ell_1$ -norm [6]. So, both can be approximated as  $\|[\|\xi_p^1 \mathbf{w}_{1p}\|_2^2, \dots, \|\xi_p^N \mathbf{w}_{Np}\|_2^2]\|_1 = \sum_{n=\mathcal{L}_b} \xi_p^n \|\mathbf{w}_{np}\|_2^2$  and  $\|[\|\xi_p^1 \mathbf{w}_{s1}^*\|_2^2, \dots, \|\xi_p^N \mathbf{w}_{sN}^*\|_2^2]\|_1 = \sum_{p=\mathcal{L}_a} \xi_p^s \|\mathbf{w}_{sp}^*\|_2^2$ , respectively, where  $\xi_p^n$  and  $\xi_p^s$  are the weight associated with BS $_n$  and BS $_s$  to the  $p$ -th user terminal, respectively and can be used to attain solution sparsity. We make an observation that if  $\xi_p^n$  and  $\xi_p^s$  are fixed, the solution does not necessarily provide sparsity. As a result, the approximation adopted in (9) and (10) may not be tight. Nevertheless, if we apply a technique called *Reweighted  $\ell_1$ -norm method* as shown in Algorithm 2, we ultimately get a sparse beamforming vector for each BS cluster. The entries relating to the receiving terminals outside of the optimal serving cluster fall to zero in the limit. We adopt the following reweighting function modified from [6] to repeatedly update the weight factor as per step 4 in Algorithm 2, where  $x$  is a positive exponent and  $\Pi$  is a small positive value. Here, we make an adjustment to the second term of denominator in order to provide stability in our proposed problems and to ensure that a zero valued component in  $\mathbf{w}_{np}(t)$ ,  $\forall n \in \mathcal{L}_b$ ,  $\forall p \in \mathcal{L}_a$  does not strictly prohibit a nonzero approximate at the next iteration [12]. By defining  $\mathbf{H}_i = \mathbf{h}_i \mathbf{h}_i^H$ ,  $\mathbf{G}_e = \mathbf{g}_e \mathbf{g}_e^H$  and the rank-one semidefinite matrix  $\mathbf{W}_p = \mathbf{w}_p \mathbf{w}_p^H$ , we reformulate the problem in (7) as a semidefinite programming (SDP) and can be relaxed as

$$\begin{aligned} \min_{\mathbf{W}_p^*, B_n^*} \quad & \beta \sum_{p=\mathcal{L}_a} \left( \sum_{n=\mathcal{L}_b} \xi_{np} \text{tr}(\mathbf{W}_p \mathbf{D}_n) \right) \\ & + \zeta \sum_{p=\mathcal{L}_a} \sum_{n=\mathcal{L}_b} \text{tr}(\mathbf{W}_p \mathbf{D}_n) + \sum_{n=\mathcal{L}_b} B_n^{[real]}, \quad (9) \\ \text{s.t.} \quad & \text{C1: } \frac{\text{tr}(\mathbf{H}_i \mathbf{W}_i)}{\gamma_i} \geq \sum_{j \in \mathcal{L}_a, j \neq i} \text{tr}(\mathbf{H}_i \mathbf{W}_j) + \sigma_i^2, \\ & \quad \quad \quad \forall i \in \mathcal{L}_i, \\ & \text{C2: } \frac{\text{tr}(\mathbf{G}_e \mathbf{W}_e)}{\eta} + \sum_{j \in \mathcal{L}_a, j \neq e} \frac{\text{tr}(\mathbf{G}_e \mathbf{W}_j)}{\eta} \geq P_e^{[\min]}, \\ & \quad \quad \quad \forall e \in \mathcal{L}_e, \\ & \text{C3: } \sum_{e=\mathcal{L}_e} \text{tr}(\mathbf{W}_e \mathbf{D}_x) \leq P_{max}^{[ET]}, \quad x \in \mathcal{N}, \\ & \text{C4: } \sum_{p \in \mathcal{L}_a} \text{tr}(\mathbf{W}_p \mathbf{D}_n) + \leq [E_n + B_n^{[ahead]} + B_n^{[real]} \\ & \quad \quad \quad - S_n - P_n^{[circuit]}], \quad \forall n \in \mathcal{L}_b, \\ & \text{C5: } \sum_{i \in \mathcal{L}_i} \xi_{ni} \text{tr}(\mathbf{W}_i \mathbf{D}_n) \hat{R}_i \leq C_n^{[b-limit]}, \quad \forall n \in \mathcal{L}_b, \\ & \text{C6 - C7 in (7),} \\ & \text{C8: } \mathbf{W}_i \succeq 0, \forall i \in \mathcal{L}_i, \quad \text{C9: } \mathbf{W}_e \succeq 0, \forall e \in \mathcal{L}_e, \end{aligned}$$

and the non-convex problem in (8) can be transformed as

$$\begin{aligned} \min_{\mathbf{W}_p^*, B_n^*} \quad & \beta \left( \sum_{p=\mathcal{L}_a} \xi_{1p} \text{tr}(\mathbf{W}_{1p}^*) + \dots + \sum_{p=\mathcal{L}_a} \xi_{Zp} \text{tr}(\mathbf{W}_{Zp}^*) \right) \\ & + \zeta \sum_{p=\mathcal{L}_a} \sum_{n=\mathcal{L}_b} \text{tr}(\mathbf{W}_p \mathbf{D}_n) + \sum_{n=\mathcal{L}_b} B_n^{[real]}, \quad (10) \\ \text{s.t.} \quad & \text{C1 - C9 in (9),} \end{aligned}$$

where,  $\mathbf{D}_n \succeq 0$  is a block diagonal matrix is given by

$$\mathbf{D}_n \triangleq \text{diag}(\underbrace{0, \dots, 0}_{(n-1)M}, \underbrace{1, \dots, 1}_M, \underbrace{0, \dots, 0}_{(N-n)M}), \forall n \in \mathcal{L}_b.$$

### Algorithm 2 Reweighted $\ell_1$ -norm method.

- 1: **Initialize:** constant  $x > 0$ , constant  $\Pi \rightarrow 0$ , iteration count  $t = 0$ , weight factor  $\xi_{np}(0) = 1$ , maximum number of iterations  $t_{max}$ ,  $\hat{R}_i(0) = \log_2(1 + \gamma_i)$ .
- 2: **while**  $\xi_{ni}$  is not converged or  $t \neq t_{max}$  **do**
- 3: Find the optimal beamformers  $\mathbf{W}_p(t)$  by solving (9).
- 4: Update the weight factor  $\xi_{np}(t+1)$  as follows,
 
$$\xi_{np}(t+1) = \frac{1}{(\text{tr}(\mathbf{W}_p(t) \mathbf{D}_n))^x + \sqrt{\max(\text{tr}(\mathbf{W}_p(t) \mathbf{D}_n), \Pi)^x}},$$

$$\forall n \in \mathcal{L}_b, \forall p \in \mathcal{L}_a.$$
- 5: Calculate the achievable rate  $R_i(t)$  as follows,

$$R_i(t) = \log_2 \left( 1 + \frac{\text{tr}(\mathbf{H}_i \mathbf{W}_i(t))}{\sum_{j \in \mathcal{L}_a, j \neq i} \text{tr}(\mathbf{H}_i \mathbf{W}_j(t)) + \sigma_i^2} \right);$$

- 6: Update  $\hat{R}_i(t+1) = R_i(t)$ ;
- 7: Increment the iteration number  $t = t + 1$ ;
- 8: **end while**

The optimal solutions to the problems (9) and (10) satisfy  $\text{rank}(\mathbf{W}_p^*) = 1$  with probability one via SDR approach and can be solved efficiently by numerical CVX solvers [13] such as SDPT3 and SeDuMi.

## IV. SIMULATION RESULTS AND DISCUSSION

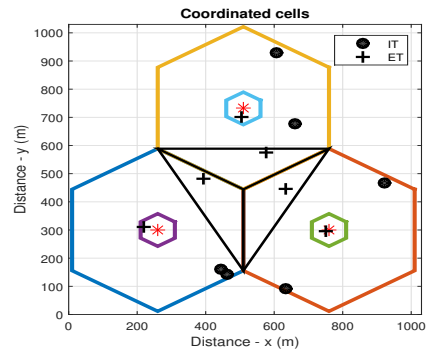


Fig. 1. A Downlink CoMP with SWIPT Simulation Topology

The effectiveness of the proposed sparse beamforming designs and algorithms are verified through simulations based on 3 neighbouring 8-antennae BSs located 500m away from each other. Based on Fig. 1, 6 ITs and 6 ETs are randomly generated over 300 channel realisations satisfying

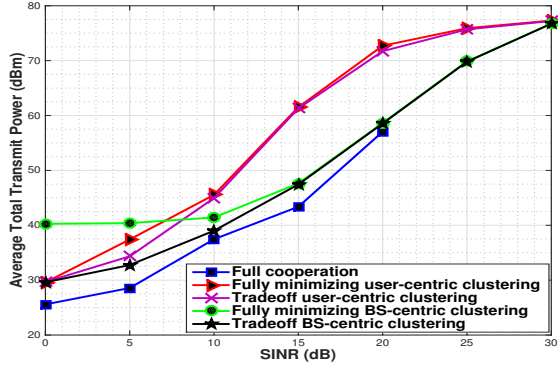
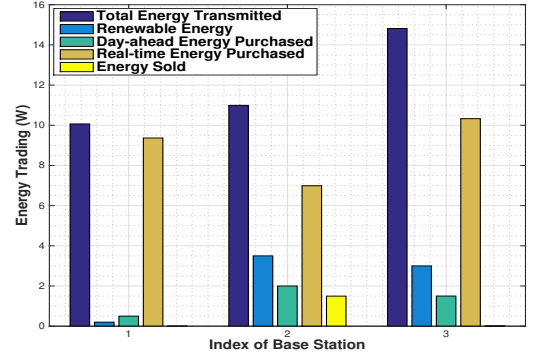


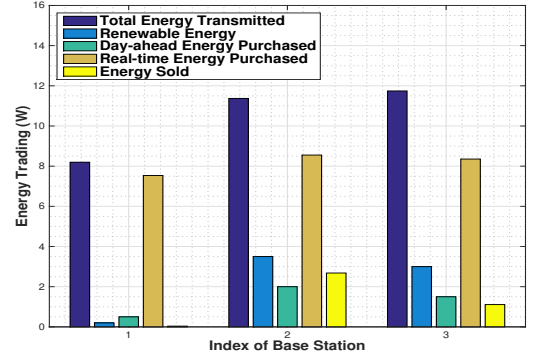
Fig. 2. Total Transmit Power (dBm) versus SINR (dB) for different schemes

all the constraints until feasible solutions are achieved. In algorithms, we set  $P^{[\min]} = 1$  uW,  $P_{max}^{[ET]} = 1.01$  mW, constant  $\Pi = 10^{-6}$  and positive exponent  $x = 2$ . The channel vectors  $\mathbf{h}_i$ ,  $\mathbf{g}_e$  and  $\mathbf{f}_z$  are assumed to be independently distributed and a correlated channel model  $\mathbf{h}_{ni} = \mathbf{h}_w \mathbf{R}^{1/2}$  is adopted [14], where  $\mathbf{h}_w \in \mathbb{C}^{M \times 1}$  are ZMCSCG random variables with unit variance,  $\mathbf{R} \in \mathbb{C}^{M \times M}$  is the spatial covariance matrix and its  $(m, n)$ -th element is given by  $G_a L_p \sigma_F^2 e^{-0.5 \left( \frac{\sigma_s \ln 10}{100} \right)^2} e^{j \frac{2\pi \delta}{\lambda} [(n-m) \sin \theta]} e^{-2 \left[ \frac{\pi \delta \sigma}{\lambda} (n-m) \cos \theta \right]^2}$ , where  $G_a = 15$  dBi is antenna gain,  $L_p(\text{dB}) = 125.2 + 36.3 \log_{10}(d)$  is the path loss model over a distance of  $d$  km [15],  $\sigma_F^2$  is the variance of the complex Gaussian fading coefficient,  $\sigma_s = 8$  dB is the log-normal shadowing standard deviation,  $\delta = \lambda/2$  is the antenna spacing,  $\sigma = 2^\circ$  is the angular offset standard deviation and  $\theta$  is the estimated angle of departure. The channel bandwidth, noise figure at receiving terminals and noise power spectral density are set to be 20 MHz, 5 dB and  $-174$  dBm/Hz, respectively. For the purpose of study, renewable energy productions at BSs are,  $E_1 = 0.2$  W,  $E_2 = 3.5$  W and  $E_3 = 3.0$  W and  $C_n^{[b\text{-limit}]} = 1200$  bits/s/Hz. The retailer also purchased  $B_1^{[\text{ahead}]} = 0.5$  W,  $B_2^{[\text{ahead}]} = 2$  W and  $B_3^{[\text{ahead}]} = 1.5$  W with price  $\pi^{[\text{ahead}]} = \pounds 0.05/\text{W}$ . If the resources are insufficient, the retailer buys the energy from the real-time market with a higher price,  $\pi^{[\text{real}]} = \pounds 0.1/\text{W}$  and sells back the extra energy with an agreed price,  $\pi^{[\text{sell}]} = \pounds 0.03/\text{W}$ . For simplicity, we set  $P_n^{[\text{circuit}]} = 0$ ,  $\forall n \in L_b$  and the efficiency ratio,  $\eta = 0.5$ .

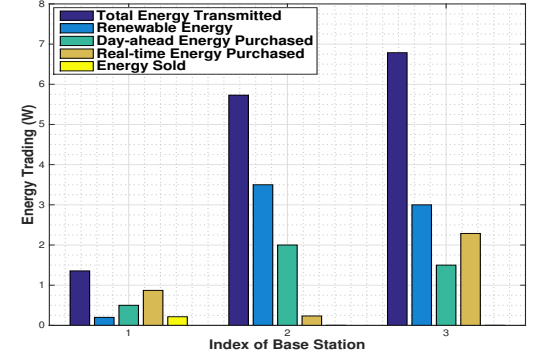
In this study, we divided our CoBEM investigation into 5 schemes which are; full cooperation scheme is obtained by setting  $\beta = 0, \zeta = 1$  in (9), fully minimizing *user-centric clustering* scheme by setting  $\beta = 1, \zeta = 0$ , tradeoff *user-centric clustering* scheme by setting  $\beta = 1, \zeta = 1$ , fully minimizing *BS-centric clustering* scheme by setting  $\beta = 1, \zeta = 0$ , and tradeoff *BS-centric clustering* scheme by setting  $\beta = 1, \zeta = 1$ , respectively. In Fig. 2, we study the average total transmit power versus SINR for different CoBEM schemes. Overall, the total power transmit increases monotonically with increasing SINR requirement. It is expected that when full cooperation is possible in rate-limited backhaul links, a significant system performance gain is achieved as intercell interference is diminished but become infeasible at SINR requirement when it is higher than 20 dB. As observed, at higher SINR requirement, both *user-centric clustering* schemes consume higher transmit



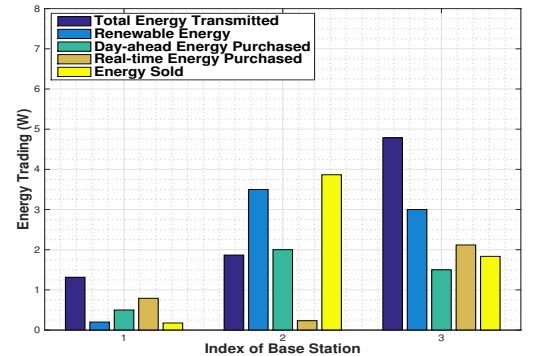
(a) Fully minimizing *user-centric clustering*



(b) Tradeoff *user-centric clustering*



(c) Fully minimizing *BS-centric clustering*



(d) Tradeoff *BS-centric clustering*

Fig. 3. Optimal energy trading for proposed schemes at  $\gamma = 10$  dB

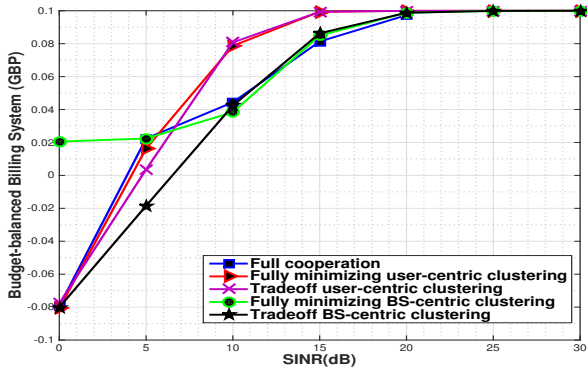


Fig. 4. Budget-balanced billing per unit energy for different schemes.

powers as compared to both *BS-centric clustering* schemes. This is because all of the active receiving terminals are permitted to choose a set of BSs, whereas, in the *BS-centric clustering* schemes, the BSs with shortage of power budget are only authorised to select a number of active receiving terminals depending on their local renewable energy resources. In Fig. 3, we illustrate in details the energy trading between the retailer and the grid for each BS to satisfy 10 dB of SINR target. It can be observed that, the tradeoff clustering schemes are able to reduce the total transmit power by the BSs in real-time power balancing by jointly minimising BS-receiver cooperation links and total power consumption as compared to fully minimizing schemes. Another interesting aspect is shown in Fig. 4. We have plotted the minimum billing per unit energy to be charged to the user terminals by the retailer using different schemes. The billing system used is budget-balanced [16], where the retailer may charge the user terminals equal to the total cost of the retailer using different schemes in real-time power balancing. The minimum charges per unit energy using the  $S$ -th scheme,  $\mathcal{B}^{[S]}$  can be calculated as

$$\mathcal{B}^{[S]} = \left( \frac{\sum_{n=\mathcal{L}_b} \left( \pi^{[\text{ahead}]} B_n^{[\text{ahead}]} + \pi^{[\text{real}]} B_n^{[\text{real}]} - \pi^{[\text{sell}]} S_n \right)}{\sum_{p=\mathcal{L}_a} \sum_{n=\mathcal{L}_b} \text{tr}(\mathbf{W}_p \mathbf{D}_n)} \right)^{[S]} \quad (11)$$

If the retailer wants to make a profit, the retailer should charge the users with the higher price than the results illustrated in Fig. 4. Catching the attention, at very low SINR target, the ITs and ETs are able to get free data access or energies, respectively. Overall, we can conclude that *BS-centric clustering* schemes are more profitable than the *user-centric clustering* schemes.

## V. CONCLUSION

In this paper, we introduced optimal CoBEM schemes for multiuser CoMP-SWIPT network by adopting a compressive sensing technique. Two sparse beamforming strategies have been proposed using reweighted  $\ell_1$ -norm method to estimate the  $\ell_0$ -norm. The *user-centric clustering* approach is able to obtain a sparse beamforming vector of the virtual BS where the non-zero entries correspond to serving BSs. For *BS-centric clustering*, the BSs with a shortage of power budget can effectively minimize the number of cooperation links with user terminals, thus reducing the overall cost in real time

power balancing. In terms of the total cost of the retailer, it is revealed that the latter design is better to be implemented in the real time power balancing scenario where the renewable energy productions and energy demands at each BS are not consistent. Furthermore, fixed-priority pre-emptive scheduling system that has been proposed in Algorithm 1 can contribute to energy efficiency and provide practical implementation in CoMP-SWIPT network where there are a limited number of higher-priority ETs that are granted to harvest energy from the nearest BS at a given time.

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