Energy-aware Power Control in Energy-Cooperation Enabled HetNets with Hybrid Energy Supplies

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***Abstract*—This paper considers power control in energy-cooperation enabled heterogeneous networks (HetNets), where each base station (BS) is powered by hybrid energy sources consisting of the conventional power grid and renewable energy sources. Energy can be transferred between BSs with energy loss during the energy transmission process. Transmit power, grid power consumption, and transferred energy are optimized for maximizing the energy efficiency of the whole network. The considered problem is formulated as a non-linear fractional programming problem. To solve it, we propose an energy efficient algorithm, in which the optimal resource allocation policy is obtained by using the lagrangian duality method. Numerical results demonstrate that energy efficiency is substantially improved by using the proposed power control algorithm with energy cooperation, compared with the cases where either power control or energy cooperation are considered.**

I. Introduction

In 5G networks, the escalating data traffic volume and the dramatic expansion of the network infrastructure will inevitably lead to an increasing energy consumption [1], which make energy efficiency more important. One promising solution is powering base stations (BSs) by renewable energy sources, in order to supplement the energy provided by the conventional power grid. However, due to the fluctuating nature of renewable energy sources, the amount of energy harvested by BSs may not be adequate to meet their load conditions. Hence, it is necessary to develop novel resource allocation schemes for managing energy efficiently. Recent studies [2], [3] have proposed radio resource allocation algorithms involving power control and user association in renewable energy powered networks. Authors in [2] considered the joint BS assignment and power control problem in hybrid energy supply networks where BSs were powered by both the electric grid and renewable energy sources. The problem was formulated as a Markov decision problem, and the tradeoff between the energy consumption and the quality of service (QoS) was investigated. The joint user association, power control and dynamic cell activation optimization problem in two-tier heterogeneous networks (HetNets) was studied in [3] for minimizing the on-grid power consumption. The outage probability was obtained by stochastic geometry and energy consumption was analyzed using M/D/1 queue.

For conventional wireless networks with energy harvesting, when the harvested energy of the BS is insufficient, some BSs still have abundant energy and this energy may be wasted. An attractive approach to tackle this issue is referred to as energy cooperation, which allows energy to be transferred between BSs through the power grid with some energy loss during the energy transmission process. Research efforts have been made by considering energy cooperation in different networks such as two-hop relay networks [4] and multiple-access networks [5]. In [6], joint spectrum allocation and energy cooperation problem was considered, and all BSs were powered by renewable energy sources. This study showed that energy cooperation can reduce the energy consumption cost of the overall network. In [7], energy cooperation was applied in coordinated multi-point system powered by the smart grid and renewable energy sources, to maximize the sum rate of the overall network subject to power constraints.

So far, power control in the energy-cooperation enabled HetNets powered by hybrid energy sources has not been conducted. Motivated by this, this paper considers power control in energy-cooperation enabled HetNets, where all BSs are powered by both renewable energy sources and the power grid. Specifically, an optimization problem for maximizing energy efficiency is formulated as a non-linear fractional programming problem. By applying Dinkelbach's method and introducing the maximum interference temperature, we transform the problem into a concave problem, and develop a joint power control and energy cooperation algorithm based on the lagrangian duality analysis. Simulation results confirm that the proposed algorithm can greatly improve energy efficiency. Moreover, our results reveal the impacts of the energy transfer loss and the number of BSs on energy efficiency of HetNets.

The paper is organized as follows. Section II presents the system model and formulates the optimization problem. Section III gives the transformation of the problem and the proposed algorithm. Section IV and V show the simulation results and the conclusions respectively.

II. System Model and Problem Formulation

We consider a two-tier downlink HetNet consisting of one macro BS (MBS), denoted as BS_0 and M pico BS (PBSs) denoted as $BS_i, i \in \{1, 2, ..., M\}$. The overall number of user equipment (UEs) in the network is $\mathrm{UE_{num}}$. There are N_i UEs denoted as UE_j^i $(j \in \{1, 2, ..., N_i\})$ served by $BS_i, i \in \{0, 1, 2, ..., M\}$ and $\mathrm{UE_{num}} = \sum_{i=0}^{M} N_i$. Each user is associated with only one BS. In this network, all BSs

are assumed to share the same frequency band, and are powered by both renewable energy sources and the power grid. Furthermore, different BSs have different energy harvesting rates.

A. Downlink Transmission Model

When UE_j^i is connected to BS_i, its downlink data rate R_j^i is given by

$$R_j^i = \frac{W}{N_i} \log_2 \left(1 + \gamma_j^i\right), \tag{1}$$

where W is the system bandwidth, and the signal-to-interference-plus-noise ratio (SINR) γ_j^i is

$$\gamma_j^i = \frac{P_i h_j^i}{\sum\limits_{i'=0, i' \neq i}^{M} P_{i'} h_{i,j}^{i'} + \sigma^2 W}. \tag{2}$$

In (2), P_i is the transmit power of BS_i, h_j^i is the channel power gain between UE_j^i and BS_i, $h_{i,j}^{i'}$ is the interfering channel power gain between UE_j^i and $BS_{i'}$, and σ^2 is the noise power density.

B. Energy Cooperation Model

Each BS is powered by both the power grid and renewable energy sources. The energy drawn by BS_i from the grid is denoted as G_i. The energy harvested by BS_i from renewable energy sources is denoted as E_i, which is a constant in each time slot and may change from one time slot to another.

The energy transferred from BS_i to $BS_{i'}$ is denoted as $\mathcal{E}_{ii'} (\forall i, i' \in \{0, 1, 2..., M\})$, and the energy transfer efficiency factor between two BSs is denoted as $\beta_{\mathcal{E}}$. Hence $(1-\beta_{\mathcal{E}})$ specifies the energy loss during the energy transmission process. In this paper, we assume that there is no battery, and the energy cooperation problem in each time slot is independent.

The total power consumption of BS_i is modeled as

$$\mathcal{J}_i = \frac{P_i}{\rho_i} + \mathcal{J}_{i,o}, \forall i, \tag{3}$$

where ρ_i is the efficiency of the power amplifier, and $\mathcal{J}_{i,o}$ is the static power consumption.

C. Problem Formulation

Our objective is to maximize the energy efficiency via power control in energy-cooperation enabled HetNets. The energy efficiency η is defined as the ratio of the overall network throughput to the overall grid power consumption. Hence the optimization problem is formulated as

$$\begin{aligned}
\mathbf{P1}: \quad & \max_{\mathbf{P}, \mathcal{E}, \mathbf{G}} \eta = \frac{\sum\limits_{i=0}^{M} \sum\limits_{j=1}^{N_i} R_j^i}{\sum\limits_{i=0}^{M} G_i}, \\
\text{s.t.} \quad & \text{C1}: \gamma_j^i > \Gamma_j^i, \forall i, \forall j \in \{1, 2..., N_i\}, \\
& \text{C2}: \mathcal{J}_i + \sum_{i'=0, i' \neq i}^{M} \mathcal{E}_{ii'} \leq G_i + E_i + \beta_{\mathcal{E}} \sum_{i'=0, i' \neq i}^{M} \mathcal{E}_{i'i}, \forall i, \\
& \text{C3}: 0 \leq P_i \leq P_i^{\max}, \forall i, \\
& \text{C4}: G_i \geq 0, \forall i, \\
& \text{C5}: \mathcal{E}_{ii'} \geq 0, \forall i, i', i' \neq i,
\end{aligned} \tag{4}$$

where Γ_j^i denotes the minimum SINR requirement of UE_j^i and $P_i^{\max}$ is the maximum transmit power of BS_i. C1 represents the QoS constraint; C2 means that the total power supply of BS_i including the grid power, harvested energy and the transferred energy should be no less than the energy consumption of it [8]; C3 ensures that the transmit power of BS_i should be smaller than the maximum transmit power; C4 and C5 are the boundary constraints for the grid power and transferred energy, respectively.

III. Problem Transformation and Proposed Algorithm

A. Problem Transformation

The optimization problem **P1** is a non-linear fractional problem. Following [9], we reformulate the objective function of **P1** using the Dinkelbach's method. The new problem **P2** can be written as

$$\begin{aligned}
\mathbf{P2}: \max_{\mathbf{P}, \mathcal{E}, \mathbf{G}} z(\eta) = \sum_{i=0}^{M} \sum_{j=1}^{N_i} R_j^i - \eta \sum_{i=0}^{M} G_i, \\
\text{s.t.} \quad \text{C1}, \text{C2}, \text{C3}, \text{C4}.
\end{aligned} \tag{5}$$

The optimal solution set $(\mathbf{P}^*, \mathcal{E}^*, \mathbf{G}^*)$ of **P1** is the same as that of **P2** for $\eta = \eta^*$ [9], where η^* is the maximum energy efficiency given by

$$\eta^* = \frac{\sum\limits_{i=0}^{M} \sum\limits_{j=1}^{N_i} R_j^i(\mathbf{P}^*, \mathcal{E}^*, \mathbf{G}^*)}{\sum\limits_{i=0}^{M} G_i(\mathbf{P}^*, \mathcal{E}^*, \mathbf{G}^*)}. \tag{6}$$

We solve problem **P1** in an iterative manner as shown in **Algorithm 1**. First we solve the interior problem $\mathbf{P2}$ for a given η, and obtain the optimal values of $\mathbf{P}^*, \mathcal{E}^*$ and $\mathbf{G}^*$ by using **Algorithm 2**. Then, we determine the optimal η^* as (6).

The interior optimization problem **P2** is still a NP-hard problem. Inspired by [10], **P2** can be efficiently solved by introducing an additional constraint as follows.

$$\text{C6}: \sum_{i'=0, i' \neq i}^{M} P_{i'} h_{i,j}^{i'} \leq \mathcal{I}, \tag{7}$$

Algorithm 1 Dinkelbach's method to determine optimal η^*

if $t = 0$**, then**
  Intialize $\eta = 0$**.**
else
  Determine the optimal resource allocation policy $(\mathbf{P}^*, \mathcal{E}^*, \mathbf{G}^*)$ based on the η and **Algorithm 2**.
  if $\sum_{i=0}^{M}\sum_{j=1}^{N_i} R_j^i(\mathbf{P}^*, \mathcal{E}^*, \mathbf{G}^*) - \eta \sum_{i=0}^{M} G_i(\mathbf{P}^*, \mathcal{E}^*, \mathbf{G}^*) < \varepsilon$
    $\eta^* = \frac{\sum_{i=0}^{M}\sum_{j=1}^{N_i} R_j^i(\mathbf{P}^*, \mathcal{E}^*, \mathbf{G}^*)}{\sum_{i=0}^{M} G_i(\mathbf{P}^*, \mathcal{E}^*, \mathbf{G}^*)}$.
    break
  else
    Update $\eta = \frac{\sum_{i=0}^{M}\sum_{j=1}^{N_i} R_j^i(\mathbf{P}^*, \mathcal{E}^*, \mathbf{G}^*)}{\sum_{i=0}^{M} G_i(\mathbf{P}^*, \mathcal{E}^*, \mathbf{G}^*)}$.
    $t \leftarrow t + 1$.
  end if
end if

where the bound $\mathcal{I}$ is called the maximum interference temperature.[1] Then, the data rate between UE_j^i and BS_i is lower bounded as

$$\bar{R}_j^i = \frac{W}{N_i} \log_2 \left(1 + \bar{\gamma}_j^i\right), \tag{8}$$

where $\bar{\gamma}_j^i = \frac{P_i h_j^i}{\mathcal{I} + \sigma^2 W}$. By substituting (8) into **P2**, we can rewrite the problem as

$$\begin{aligned} \mathbf{P3}: \max_{\mathbf{P},\mathcal{E},\mathbf{G}} & \sum_{i=0}^{M}\sum_{j=1}^{N_i} \bar{R}_j^i - \eta \sum_{i=0}^{M} G_i, \\ \text{s.t.} \quad & \text{C1, C2, C3, C4, C5, C6.} \end{aligned} \tag{9}$$

B. Lagrangian Dual

The transformed problem $\mathbf{P3}$ is concave and the constraints of it are linear inequalities, thus the Slater's condition is satisfied and the strong duality holds. Hence the Lagrangian duality method can be adopted to solve $\mathbf{P3}$. We first present the following Lagrangian function

$$\begin{aligned} \mathcal{L}(\mathbf{P}, \mathcal{E}, \mathbf{G}, \boldsymbol{\mu}, \boldsymbol{\nu}, \boldsymbol{\theta}) &= \sum_{i=0}^{M}\sum_{j=1}^{N_i} \bar{R}_j^i - \eta \sum_{i=0}^{M} G_i \\ &- \sum_{i=0}^{M}\sum_{j=1}^{N_i} \mu_j^i \left(\Gamma_j^i - \bar{\gamma}_j^i\right) - \sum_{i=0}^{M} \nu_i \Big(\mathcal{J}_i + \sum_{i'=0, i' \neq i}^{M} \mathcal{E}_{ii'} - G_i \\ &- E_i - \beta_{\mathcal{E}} \sum_{i'=0, i' \neq i}^{M} \mathcal{E}_{i'i}\Big) - \sum_{i=0}^{M}\sum_{j=1}^{N_i} \theta_j^i \Big(\sum_{i'=0, i' \neq i}^{M} P_{i'} h_{i,j}^{i'} - \mathcal{I}\Big) \\ &= \sum_{i=0}^{M} \Big(\sum_{j=1}^{N_i} \left(\bar{R}_j^i + \mu_j^i \bar{\gamma}_j^i\right) - \nu_i \frac{P_i}{\rho_i} - P_i \sum_{i'=0, i' \neq i}^{M} \sum_{j'=1}^{N_{i'}} \theta_{j'}^{i'} h_{i',j'}^{i}\Big) \\ &+ \sum_{i=0}^{M} (\nu_i - \eta) G_i + \sum_{i=0}^{M} \sum_{i'=0, i' \neq i}^{M} \left(\beta_{\mathcal{E}} \nu_{i'} - \nu_i\right) \mathcal{E}_{ii'} \\ &- \sum_{i=0}^{M}\sum_{j=1}^{N_i} \mu_j^i \Gamma_j^i + \sum_{i=0}^{M} \nu_i \Big(E_i - \mathcal{J}_{i,o}\Big) + \sum_{i=0}^{M}\sum_{j=1}^{N_i} \theta_j^i \mathcal{I}, \end{aligned} \tag{10}$$

[1] In the considered problem, $\mathcal{I}$ is not an optimization variable but it can be properly found via simulation in an off-line manner [10].

where μ_j^i, ν_i, and θ_j^i are the non-negative Lagrange multipliers.

Based on (10), the dual function is given by

$$g(\boldsymbol{\mu}, \boldsymbol{\nu}, \boldsymbol{\theta}) = \begin{cases} \max\limits_{\mathbf{P},\mathcal{E},\mathbf{G}} \mathcal{L}(\mathbf{P}, \mathcal{E}, \mathbf{G}, \boldsymbol{\mu}, \boldsymbol{\nu}, \boldsymbol{\theta}) \\ \text{s.t. } 0 \leq P_i \leq P_i^{\max}, G_i \geq 0, \mathcal{E}_{ii'} \geq 0, \ \forall i, i'. \end{cases} \tag{11}$$

Then, the dual problem of **P3** is defined as

$$\mathbf{P3} - \mathbf{D}: \min_{\boldsymbol{\mu} \geq 0, \boldsymbol{\nu} \geq 0, \boldsymbol{\theta} \geq 0} g(\boldsymbol{\mu}, \boldsymbol{\nu}, \boldsymbol{\theta}). \tag{12}$$

To let $g(\boldsymbol{\mu}, \boldsymbol{\nu}, \boldsymbol{\theta})$ be bounded, we have the following lemma:

Lemma 1. *The dual function is bounded by satisfying*

1) $\nu_i \leq \eta, \ \forall i.$
2) $\beta_{\mathcal{E}} \nu_{i'} \leq \nu_i, \ \forall i, i', i' \neq i.$

Proof. we use contradiction to prove the lemma. First, we suppose that there exists a ν_i satisfying $\nu_i > \eta$. It can be seen that the objective value of (11) goes to infinity as $G_i \to \infty$. The dual function becomes unbounded. Hence, to ensure the bounded dual function, $\nu_i \leq \eta, \ \forall i$ must hold. Using the similar method, the second part of the **Lemma 1** can be proved. □

Given the dual variables μ_j^i, ν_i and θ_j^i, the problem in (11) can be decomposed into $(1+M)^2 + (1+M)$ subproblems by removing the constant terms of the Lagrangian function, which are as follows:

$$\max_{0 \leq P_i \leq P_i^{\max}} \sum_{j=1}^{N_i} \left(\bar{R}_j^i + \mu_j^i \bar{\gamma}_j^i\right) - \nu_i \frac{P_i}{\rho_i} - P_i \sum_{i'=0, i' \neq i}^{M} \sum_{j'=1}^{N_{i'}} \theta_{j'}^{i'} h_{i',j'}^{i}, \forall i, \tag{13}$$

$$\max_{G_i \geq 0} (\nu_i - \eta) G_i, \forall i, \tag{14}$$

$$\max_{\mathcal{E}_{ii'} \geq 0} \left(\beta_{\mathcal{E}} \nu_{i'} - \nu_i\right) \mathcal{E}_{ii'} \forall i, i', i \neq i'. \tag{15}$$

Since the subproblems in (13) are concave, some commonly-used descent methods such as Newton's method can efficiently solve it [11]. Let $f(P_i)$ be the objective function of (13), We first calculate the first-order and the second-order partial derivatives of $f(P_i)$ with respect to P_i as

$$\begin{aligned} \frac{\partial f(P_i)}{\partial P_i} = & \sum_{j=1}^{N_i} \left(\frac{W}{N_i \ln 2} \frac{\bar{\gamma}_j^i}{1 + \bar{\gamma}_j^i} \frac{1}{P_i} + \mu_j^i \frac{\bar{\gamma}_j^i}{P_i}\right) \\ & - \nu_i \frac{1}{\rho_i} - \sum_{i'=0, i' \neq i}^{M} \sum_{j'=1}^{N_{i'}} \theta_{j'}^{i'} h_{i',j'}^{i}, \end{aligned} \tag{16}$$

and

$$\frac{\partial^2 f(P_i)}{\partial P_i^2} = -\frac{W}{N_i \ln 2} \sum_{j=1}^{N_i} \left(\frac{\bar{\gamma}_j^i}{1 + \bar{\gamma}_j^i}\right)^2 \frac{1}{P_i^2}. \tag{17}$$

As such, the Newton step is $\Delta P_i = -\frac{\partial f(P_i)}{\partial P_i} / \frac{\partial^2 f(P_i)}{\partial P_i^2}$, and Newton decrement is $\Theta = \left(\frac{\partial f(P_i)}{\partial P_i}\right)^2 / \frac{\partial^2 f(P_i)}{\partial P_i^2}$, which is used as the stopping criterion [11]. Hence the optimal solution of (13) can be obtained based on Newton's method. In addition,

Algorithm Newton's method

if $t = 0$, **then**

1: Initialize $P_i(t)$, $\forall i$.

else

2: Calculate the Newton's step through

$\Delta P_i = -\frac{\partial f(P_i)}{\partial P_i} / \frac{\partial^2 f(P_i)}{\partial P_i^2}$ based on (16) and (17).

Update $P_i(t+1)$ via $P_i(t+1) = [P_i(t) + \delta(t)\,\Delta P_i]_0^{P_i^{\max}}$,

$\delta(t)$ is the step size determined by backtracking line search.

if convergence ($|\Theta|/2 \leq \epsilon$, ϵ is the tolerance)

break;

else

3: $t \leftarrow t+1$, and go to step 2.

end if

end if

with the help of **Lemma 1**, the optimal solutions of (14) and (15) are

$$G_i(\nu_i) = 0, \;\; \mathcal{E}_{ii'}(\nu_i, \nu_{i'}) = 0, \; \forall i, i'. \tag{18}$$

By using the solutions of (13), (14) and (15), we can obtain the dual function $g(\boldsymbol{\mu}, \boldsymbol{\nu}, \boldsymbol{\theta})$ in (11). To determine the optimal dual variables, we first reformulate the dual problem $\mathbf{P3-D}$. Based on **Lemma 1**, the dual problem can be equivalently rewritten as

$$\begin{aligned} \mathbf{P3-D}: \; & \min_{\boldsymbol{\mu}\geq 0, \boldsymbol{\nu}\geq 0, \boldsymbol{\theta}\geq 0} g(\boldsymbol{\mu}, \boldsymbol{\nu}, \boldsymbol{\theta}), \\ & \text{s.t.} \;\; \nu_i \leq \eta, \; \forall i, \\ & \beta_{\mathcal{E}} \nu_{i'} \leq \nu_i, \; \forall i, i', i' \neq i. \end{aligned} \tag{19}$$

The above problem is concave which can be solved by the subgradient method [12], and $\boldsymbol{\mu}$, $\boldsymbol{\nu}$, and $\boldsymbol{\theta}$ are updated such that

$$\mu_j^i(t+1) = \left[\mu_j^i(t) - \chi(t)\left(\bar{\gamma}_j^i - \Gamma_j^i\right)\right]^+, \tag{20}$$

$$\begin{aligned} \nu_i(t+1) &= \Big[\nu_i(t) - \chi(t)\Big(G_i + E_i + \beta_{\mathcal{E}} \sum_{i'=0}^{M} \mathcal{E}_{i'i}^k \\ &\quad - \mathcal{J}_i - \sum_{i'=0}^{M} \mathcal{E}_{ii'}\Big)\Big]^+ \\ &\overset{(a)}{=} \left[\nu_i(t) - \chi(t)\left(E_i - \frac{P_i^*(\boldsymbol{\mu}(t), \boldsymbol{\nu}(t), \boldsymbol{\theta}(t))}{\rho_i} - \mathcal{J}_{i,o}\right)\right]^+, \end{aligned} \tag{21}$$

$$\begin{aligned} \theta_j^i(t+1) = \Big[&\theta_j^i(t) - \chi(t)\Big(\mathcal{I} \\ &- \sum_{i'=0, i'\neq i}^{M} P_{i'}^*(\boldsymbol{\mu}(t), \boldsymbol{\nu}(t), \boldsymbol{\theta}(t)) h_{i,j}^{i'}\Big)\Big]^+, \forall i, \forall j, \end{aligned} \tag{22}$$

where $[x]^+ = \max\{x, 0\}$, t is the iteration index, and $\chi(t)$ is the step size of the iteration t.[2] In (21), step (a) is obtained by considering $\mathcal{J}_i$ given in (3) and $G_i, \mathcal{E}_{ii'}$ given in (18). Note that the updated ν_i needs to satisfy the constraints of (19).

After obtaining the optimal $\boldsymbol{\mu}^*$, $\boldsymbol{\nu}^*$, and $\boldsymbol{\theta}^*$ of $\mathbf{P3-D}$, the corresponding solution $P_i(\boldsymbol{\mu}^*, \boldsymbol{\nu}^*, \boldsymbol{\theta}^*)$ of (13) is the optimal power solution of the primal problem $\mathbf{P3}$. When the optimal BS transmit power is determined, the optimal G_i and $\mathcal{E}_{ii'}$ of $\mathbf{P3}$ can be obtained by equivalently solving the following simple linear program (LP):

$$\begin{aligned} \mathbf{P4}: \; & \min_{\mathcal{E}, \mathbf{G}} \sum_{i=0}^{M} G_i, \\ & \text{s.t.} \;\; \text{C2}, \text{C4}, \text{C5}. \end{aligned} \tag{23}$$

The problem $\mathbf{P4}$ can be efficiently solved by using CVX [13]. Then, $\mathbf{P3}$ is completely solved.

Based on the previous analysis to solve the problem **P2**, the proposed algorithm is summarized in **Algorithm 2**.

Algorithm 2 Algorithm for Solving Problem **P2**

1: **if** $t = 0$

2: Initialize $\mu_j^i(t)$, $v_i(t)$, $\theta_j^i(t)$, $\forall i, \forall j$, which are feasible for dual problem in (19). Initialize the step size $\chi(t)$ and the maximum iteration number $t_{\max}$.

3: **else**

4: Calculate $P_i(t)$ through Newton's method.

5: Update $\mu_j^i(t+1)$, $v_i(t+1)$, $\theta_j^i(t+1)$ according to (20)-(22), subject to the constraints of (19).

6: **if** convergence or exceed the maximum iteration number

7: $P_i^* = P_i(t)$.

8: **break**

9: **else**

10: $t \leftarrow t+1$.

11: **end if**

12: **end if**

13: Calculate problem $\mathbf{P4}$ through CVX, and acquire the optimal $\mathcal{E}_{ii'}^*$ and G_i^* based on P_i^*. Thus, we obtain the optimal resource allocation policy $(\mathbf{P}^*, \mathcal{E}^*, \mathbf{G}^*)$.

C. Other Scenarios

In this subsection, we give other three scenarios, namely the implementation of power control or energy cooperation solely, or neither of them is utilized in the HetNet. These scenarios are considered as baselines for the proposed algorithm, and the comparisons are shown in the simulation results of Section IV.

1) No Energy Cooperation, Power Control Solely: In this scenario, the energy transfer efficiency $\beta_{\mathcal{E}}$ is set as 0, which means that the energy cooperation is infeasible. Then, the proposed **Algorithm 1** is applied to solve this problem.

2) No Power Control, Energy Cooperation Solely: In this scenario, each BS is assumed to use the maximum transmit power for guaranteeing the QoS. Then, the new problem is as follows:

$$\begin{aligned} \mathbf{P5}: \quad & \max_{\mathcal{E}, \mathbf{G}} \frac{\sum_{i=0}^{M} \sum_{j=1}^{N_i} R_j^i}{\sum_{i=0}^{M} G_i}, \\ & \text{s.t.} \;\; \text{C2}, \text{C4}, \text{C5}. \end{aligned} \tag{24}$$

Since the numerator of the objective function is independent of $\mathcal{E}$ and $\mathbf{G}$, **P5** can be equivalently transformed as

$$\begin{aligned} \mathbf{P5-1}: & \min_{\mathcal{E}, \mathbf{G}} \sum_{i=0}^{M} G_i, \\ & \text{s.t.} \text{C2}, \text{C4}, \text{C5}. \end{aligned} \tag{25}$$

[2]There are many step size selections such as constant step size and diminishing step size. In this paper, we use the nonsummable diminishing step length, as shown in [12].

TABLE I
SIMULATION PARAMETERS

Parameter	Value
Macro cell bandwidth	20 MHz
Noise power density	-174 dBm/Hz
Cell radius	500 m
Static power consumption of MBS	780 W
Static power consumption of PBS	13.6 W
Path loss of MBS	$128.1 + 37.6\log_{10} d(\text{km})$
Path loss of PBS	$140.7 + 36.7\log_{10} d(\text{km})$
Min harvested energy of MBS	575 W
Max harvested energy of MBS	660 W
Min harvested energy of PBS	15 W
Max harvested energy of PBS	25 W
Min SINR requirement	0 dB
Max transmit power of MBS	46 dBm
Max transmit power of PBS	30 dBm
Efficiency of power amplifier	0.3 [15]

The optimization problem **P5-1** is a LP problem, which can be solved by CVX. Thus, we can obtain the optimal grid power $\mathbf{G}^*$ and optimal transferred energy $\mathcal{E}^*$ for maximizing the energy efficiency.

3) No Energy Cooperation nor Power Control: In this scenario, the transmit power of BS_i is $P_i^{\max}$, and there is no energy cooperation in the network. The optimal grid power G_i^* consumed by BS_i is directly calculated as $G_i^* = \left[\frac{P_i^{\max}}{\rho_i} + \mathcal{J}_{i,o} - E_i\right]^+$, and therefore the energy efficiency is directly calculated as $\sum_{i=0}^{M}\sum_{j=1}^{N_i} R_j^i / \sum_{i=0}^{M} G_i^*$.

IV. SIMULATION RESULTS

In this section, numerical results are presented to demonstrate the performance of the proposed power control algorithm with and without energy cooperation. In the simulations, PBSs and UEs are uniformly distributed. The energy harvesting process E_i at BS_i is modeled as a stationary stochastic process with PDF $f_i(z_i) = 1/(b_i - a_i), \forall z_i \in [a_i, b_i]$ where a_i and b_i is the minimum and maximum harvested energy of BS_i respectively [14]. For the first three figures, the ratio of the maximum interference temperature to noise $\frac{\mathcal{I}}{\sigma^2 W}$ is 25 dB, and the last figure shows the impact of the maximum interference temperature. The basic simulation parameters are shown in Table I.

Fig. 1 shows the energy efficiency versus the number of UEs UE_{num}. The number of PBSs and the energy transfer efficiency factor $\beta_{\mathcal{E}}$ are set as 5 and 0.7, respectively. We find that the proposed algorithm consisting of energy cooperation and power control achieves higher energy efficiency than the other three scenarios. The implementation of power control can significantly improve the energy efficiency, compared with the non power-control cases. In addition, by using the proposed joint power control and energy cooperation algorithm, there is a big improvement in energy efficiency when more users demand services in the network, due to the fact that the proposed algorithm is capable of exploiting the multiuser diversity (i.e., different users experience different path loss, and more users with lower path loss help enhance energy efficiency.) [16].

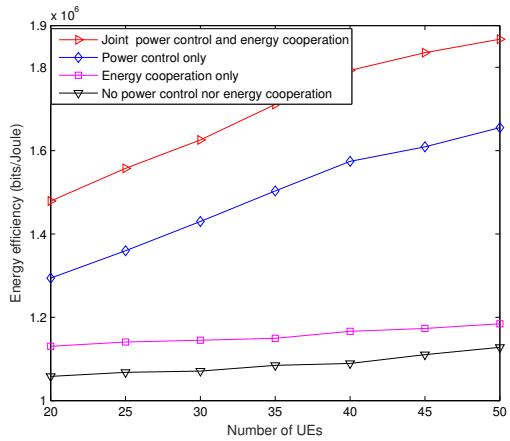

Fig. 1. Energy efficiency versus the number of UEs.

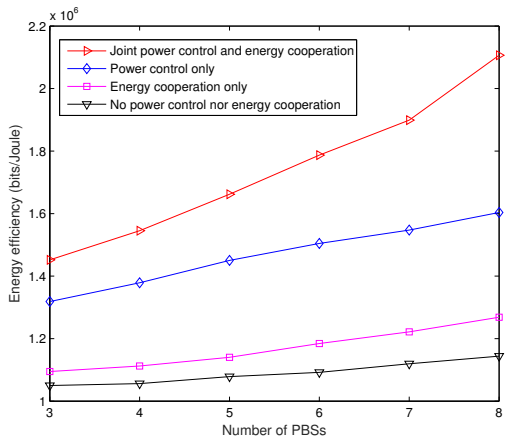

Fig. 2. Energy efficiency versus the number of PBSs.

Fig. 2 investigates the energy efficiency versus the number of PBSs. We set the energy transfer efficiency $\beta_{\mathcal{E}}$ and the number of UEs UE_{num} as 0.7 and 30, respectively. The proposed joint energy cooperation and power control algorithm outperforms the other cases. As more PBSs are deployed in the HetNet, the advantage of the proposed algorithm becomes more significant. This can be explained by the fact that more renewable energy harvested by PBSs can be transferred between BSs through energy cooperation, to reduce the consumption of grid power.

Fig. 3 depicts the energy efficiency versus the energy transfer efficiency factor $\beta_{\mathcal{E}}$. The number of PBSs is set as 5. In this figure, the non energy-cooperation scenario is considered as a baseline for comparison. It can be observed that there is a substantial increase in energy efficiency when improving the energy transfer efficiency, since the harvested renewable energy can be efficiently transferred between BSs for reducing the grid power consumption. Moreover, the performance gap

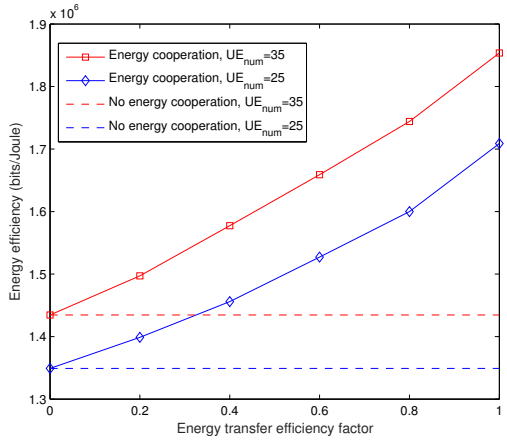

Fig. 3. Energy efficiency versus the energy transfer efficiency factor $\beta_{\mathcal{E}}$.

between the energy cooperation and non energy-cooperation expands when improving the energy transfer efficiency, which indicates that energy cooperation plays a pivotal role in improving the energy efficiency of the HetNet with hybrid energy supplies. Again, energy efficiency is enhanced by increasing the number of UEs due to the achievable multiuser diversity gain [16].

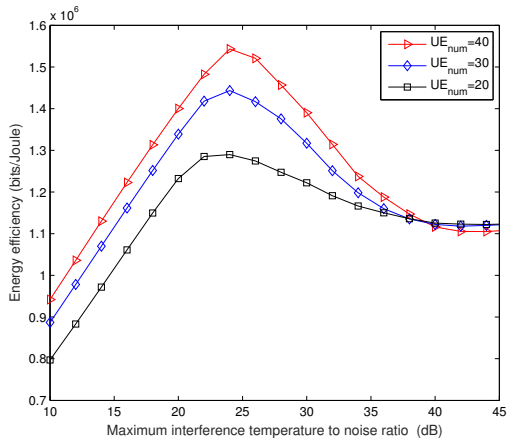

Fig. 4. Energy efficiency versus the ratio of the maximum interference temperature to noise $\mathcal{I}/\sigma^2 W$ (dB).

Fig. 4 shows the energy efficiency versus the ratio of the maximum interference temperature to noise $\frac{\mathcal{I}}{\sigma^2 W}$ (dB) for different numbers of UEs. We set the number of PBSs as 5 and the energy transfer efficiency factor as 0.7. The maximum interference temperature $\mathcal{I}$ represents the upper bound of the interference, which puts a limit on the BS's transmit power. We see that energy efficiency first increases with $\frac{\mathcal{I}}{\sigma^2 W}$. When the ratio is beyond the optimal value, it decreases with increasing $\frac{\mathcal{I}}{\sigma^2 W}$. The reason is that increasing $\frac{\mathcal{I}}{\sigma^2 W}$ allows the BS to use larger transmit power, so as to improve the lower-bound date rate in (8) and maximize the objective function of the transformed problem **P3**, however, larger BS transmit power results in more grid power consumption, which deteriorates energy efficiency, and becomes a comparably inefficient solution for **P2**. When $\frac{\mathcal{I}}{\sigma^2 W}$ is set as larger than a critical value (35 dB in this figure), the energy efficiency converges to a constant value, because of the maximum BS transmit power constraint. In practice, optimal value of $\mathcal{I}$ is found in an offline manner [10]. As suggested before, energy efficiency grows with the number of UEs.

V. Conclusions

In this paper, power control problem in energy cooperation enabled HetNets with hybrid energy supplies was took into account. An efficient power control algorithm was proposed to maximize energy efficiency of the overall network. Numerical results have demonstrated that the proposed algorithm with energy cooperation and power control achieves better performance than other cases, namely, applying energy cooperation or power control solely, or neither of them.

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