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 $BS_i, i \in \{1,2,\ldots,M\}$. The overall number of user equipment (UEs) in the network is $UE_{\text{total}}$. There are $N_j$ UEs denoted as $UE_j^i$ ($j \in \{1,2,\ldots,N_j\}$) served by $BS_i, i \in \{0,1,2,\ldots,M\}$ and $UE_{\text{total}} = \sum_{i=0}^{M} N_i$. 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

$$R^j_i = \frac{W}{N_i} \log_2 (1 + \gamma^j_i),$$  

(1)

where $W$ is the system bandwidth, and the signal-to-interference-plus-noise ratio (SINR) $\gamma^j_i$ is

$$\gamma^j_i = \frac{P_i h^j_i}{\sum_{i'=0,i'\neq i}^M P_{i'} h_{i',j}^i + \sigma^2 W}.$$  

(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$^i_{i'}$, and $\sigma^2$ 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$^i_{i'}$ is denoted as $\mathcal{E}_{i,i'}(\forall i,j \in \{0, 1, 2, \ldots, M\})$, and the energy transfer efficiency factor between two BSs is denoted as $\beta_{i,j}$. Hence $(1-\beta_{i,j})$ 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

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

(3)

where $\rho_i$ 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 $\eta$ is defined as the ratio of the overall network throughput to the overall grid power consumption. Hence the optimization problem is formulated as

$$\begin{align*}
P_1 : & \max_{P_i, G} \eta = \frac{\sum_{i=0}^M \sum_{j=1}^N R^j_i}{\sum_{i=0}^M G_i}, \\
\text{s.t.} & C1 : \gamma^j_i \geq \Gamma^j_i, \forall i, \forall j \in \{1, 2, \ldots, N_i\}, \\
& C2 : \mathcal{J}_i + \sum_{i'=0, i' \neq i}^M \mathcal{E}_{i,i'}, \Gamma^j_i + G_i \leq \beta^j_i, \forall i, \\
& C3 : 0 \leq P_i \leq P_{i,max}, \forall i, \\
& C4 : G_i \geq 0, \forall i, \\
& C5 : \mathcal{E}_{i,i'} \geq 0, \forall i, \forall i', i' \neq i,
\end{align*}$$  

(4)

where $\Gamma^j_i$ 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

$$\begin{align*}
P_2 : & \max_{P_i, G} z(\eta) = \sum_{i=0}^M \sum_{j=1}^N R^j_i - \eta \sum_{i=0}^M G_i, \\
\text{s.t.} & C1, C2, C3, C4.
\end{align*}$$  

(5)

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

$$\eta^* = \frac{\sum_{i=0}^M \sum_{j=1}^N R^j_i (P^*, \mathcal{E}^*, G^*)}{\sum_{i=0}^M G_i (P^*, \mathcal{E}^*, G^*)}.$$  

(6)

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

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

(7)
Algorithm 1: Dinkelbach’s method to determine optimal $\eta^*$

1. if $t = 0$, then
2. Initialize $\eta = 0$.
3. else
4. Determine the optimal resource allocation policy $(P^*, E^*, G^*)$ based on the $\eta$ and Algorithm 2.
5. if $\sum_{i=0}^{M} \sum_{j=1}^{N_i} R^j_i (P^*, E^*, G^*) - \eta \sum_{i=0}^{M} G_i (P^*, E^*, G^*) < \varepsilon$
6. $\eta^* = \frac{\sum_{i=0}^{M} \sum_{j=1}^{N_i} R^j_i (P^*, E^*, G^*)}{\sum_{i=0}^{M} G_i (P^*, E^*, G^*)}$.
7. break
8. else
9. Update $\eta = \frac{\sum_{i=0}^{M} \sum_{j=1}^{N_i} R^j_i (P^*, E^*, G^*)}{\sum_{i=0}^{M} G_i (P^*, E^*, G^*)}$.
10. $t \leftarrow t + 1$.
11. end
12. end if

where the bound $I$ is called the maximum interference temperature. Then, the data rate between $UE^j$ and $BS_i$ is lower bounded as

$$R^j_i = \frac{W}{N_i} \log_2 \left( 1 + \frac{\gamma^j_i}{1 + \gamma^j_i} \right),$$

where $\gamma^j_i = \frac{P_h^j}{P_h^i} \mu_i$. By substituting (8) into P2, we can rewrite the problem as

$$P3: \max_{P, E, G, \mu, \nu, \theta} \sum_{i=0}^{M} \sum_{j=1}^{N_i} R^j_i - \eta \sum_{i=0}^{M} G_i,$$

s.t. $C1, C2, C3, C4, C5, C6$. (9)

B. Lagrangian Dual

The transformed problem 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 P3. We first present the following Lagrangian function

$$\mathcal{L}(P, E, G, \mu, \nu, \theta) = \sum_{i=0}^{M} \sum_{j=1}^{N_i} R^j_i - \eta \sum_{i=0}^{M} G_i - \nu \sum_{i=0}^{M} \sum_{j=1}^{N_i} G^j_i (1 - \mu_i) - \sum_{i=0}^{M} \sum_{j=1}^{N_i} E^j_i G_i - E_i - \beta \sum_{i=0}^{M} \sum_{j=1}^{N_i} \sum_{i' \neq i} P_{i, i', j} h_{i', j} - I_i = \sum_{i=0}^{M} \sum_{j=1}^{N_i} R^j_i + \sum_{i=0}^{M} \sum_{j=1}^{N_i} (\theta_i^j - \nu) E_i^j + M \sum_{i=0}^{M} \sum_{j=1}^{N_i} \sum_{j' < j} \theta_i^j h_{i', j'},$$

where $\mu_i, \nu_i, \theta_i$ are the non-negative Lagrange multipliers.

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

$$g(\mu, \nu, \theta) = \max_{P, E, G} \mathcal{L}(P, E, G, \mu, \nu, \theta)$$

s.t. $0 \leq P_i \leq P_i^{\max}, G_i \geq 0, E_i^j \geq 0, \forall i, j \neq i'$.

Then, the dual problem of P3 is defined as

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

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

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

1. $\nu_i \leq \eta, \forall i$.
2. $\beta \nu_i \leq \nu_i, \forall i, i', i' \neq i$.

Proof. We use contradiction to prove the lemma. First, we suppose that there exists a $\nu_i$ satisfying $\nu_i > \eta$. It can be seen that the objective value of (11) goes to infinity as $G_i \rightarrow \infty$. 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 $\mu_i^j, \nu_i, \theta_i^j$, 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:

$$\max_{\nu, \theta} \sum_{i=0}^{M} \sum_{j=1}^{N_i} \left( R^j_i + \mu_i^j \gamma^j_i \right) - \nu \sum_{i=0}^{M} P_i / \mu_i - P_i \sum_{j=1}^{N_i} \sum_{j' < j} \theta_i^j h_{i', j'}, \forall i,\nu_i \geq 0.$$

(13)

$$\max_{\nu, \theta} \sum_{i=0}^{M} \sum_{j=1}^{N_i} \left( \beta \nu_i \gamma^j_i - \nu_i \right) E_i^j, \forall i, i', i' \neq i.$$

(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

$$\frac{\partial f(P_i)}{\partial P_i} = \frac{W}{N_i \ln 2} \left( \frac{\gamma^j_i}{1 + \gamma^j_i} P_i + \mu_i^j \gamma^j_i \right) - \nu \frac{P_i}{\mu_i} - \sum_{i' \neq i} \sum_{j' < j} \theta_i^j h_{i', j'},$$

(16)

and

$$\frac{\partial^2 f(P_i)}{\partial P_i^2} = -\frac{W}{N_i \ln 2} \left( \frac{\gamma^j_i}{1 + \gamma^j_i} \right)^2 \frac{1}{P_i^2}. \quad \text{(17)}$$

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 $\Theta = \left( \frac{\partial f(P_i)}{\partial P_i} / \frac{\partial^2 f(P_i)}{\partial P_i^2} \right)$, which is used as the stopping criterion [11]. Hence the optimal solution of (13) can be obtained based on Newton’s method. In addition,
with the help of Lemma 1, the optimal solutions of (14) and (15) are

\[ G_i (\nu_t) = 0, \quad E_{i,t}^+ (\nu_t, \nu_t') = 0, \forall i, i'. \quad (18) \]

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

\[ \text{P3 - D}: \min_{\mu \geq 0, \nu \geq 0, \theta \geq 0} g(\mu, \nu, \theta), \]

s.t. \( \nu_t \leq \eta_i, \forall i, \beta \nu_{t'} \leq \nu_i, \forall i, i', i' \neq i. \]

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

\[ \mu_i^j (t + 1) = \left[ \mu_i^j (t) - \chi (t) \left( \eta_i^j - G_i^j \right) \right]^+, \]

\[ \nu_i (t + 1) = \left[ \nu_i (t) - \chi (t) \left( G_i + E_i + \beta E_\nu \sum_{i'} E_{i',j}^0 \right) - J_i - \sum_{i'=0}^M E_{i',j}^i \right]^+, \]

\[ (\theta) \left[ \nu_i (t) - \chi (t) \left( E_i - \frac{P^*_i (\mu(t), \nu(t), \theta(t))}{\rho_i} - J_i, \nu \right) \right]^+, \]

\[ \theta_j^i (t + 1) = \left[ \theta_j^i (t) - \chi (t) \left( I - \sum_{i'=0,i' \neq i} P^*_i (\mu(t), \nu(t), \theta(t)) h^i_{j,i'} \right) \right]^+, \forall i, \forall j. \]

where \( [x]^+ = \max \{x, 0\} \), \( t \) is the iteration index, and \( \chi (t) \) is the step size of the iteration \( t. \) In (21), (22) is obtained by considering \( J_i \) given in (3) and \( G_i, E_{i,t} \) given in (18). Note that the updated \( \nu_t \) needs to satisfy the constraints of (19).

After obtaining the optimal \( \mu^*, \nu^*, \) and \( \theta^* \) of P3 - D, the corresponding solution \( P_t (\mu^*, \nu^*, \theta^*) \) of (13) is the optimal power solution of the primal problem P3. When the optimal BS transmit power is determined, the optimal \( G_i \) and \( E_{i,t} \) of P3 can be obtained by equivalently solving the following simple linear program (LP):

\[ \text{P4}: \min_{\epsilon, \theta_i} \sum_{i=0}^M G_i, \]

s.t. C2, C4, C5.

The problem P4 can be efficiently solved by using CVX [13]. Then, 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 \( \mu_t^i (t), \nu_t (t), \theta_t^i (t), \forall i, j \), which are feasible for dual problem in (19). Initialize the step size \( \chi (t) \) and the maximum iteration number \( t_{\text{max}}. \)
3: else
4: Calculate \( P_t (t) \) through Newton’s method.
5: Update \( \mu_t^i (t + 1), \nu_t (t + 1), \theta_t^i (t + 1) \) according to (20)-(22), subject to the constraints of (19).
6: if convergence or exceed the maximum iteration number
7: \( P_t^* = P_t (t) \).
8: break
9: end if
10: \( t \leftarrow t + 1 \).
11: end if
12: end if
13: Calculate problem P4 through CVX, and acquire the optimal \( E_{i,t} \) and \( G_i^* \) based on \( P_t^* \). Thus, we obtain the optimal resource allocation policy \( (\mu^*, \nu^*, \theta^*) \).

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 \( \beta \) 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:

\[ \text{P5}: \max_{\epsilon, \theta_i} \frac{\sum_{i=0}^M \sum_{j=1}^{N_i} R_{i,j}^i}{\sum_{i=0}^M G_i}, \]

s.t. C2, C4, C5.

Since the numerator of the objective function is independent of \( \epsilon \) and \( G \), P5 can be equivalently transformed as

\[ \text{P5} - 1: \min_{\epsilon, \theta_i} \sum_{i=0}^M G_i^i, \]

s.t. C2, C4, C5.
The optimization problem $P5-1$ is a LP problem, which can be solved by CVX. Thus, we can obtain the optimal grid power $G^*$ and optimal transferred energy $E^*$ for maximizing the energy efficiency.

3) No Energy Cooperation nor Power Control: In this scenario, the transmit power of $BS_i$ is $P_{t,max}$, and there is no energy cooperation in the network. The optimal grid power $G^*_i$ consumed by $BS_i$ is directly calculated as $G^*_i = P_{t,max} + J_{i,o} - E_{i}$, and therefore the energy efficiency is directly calculated as $\sum_{i=0}^{M} \sum_{j=1}^{N_i} R_j / \sum_{i=0}^{M} G^*_i$.

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 $T/R$ 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 $E_{UE_{num}}$. The number of PBSs and the energy transfer efficiency factor $\beta_E$ 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.](image)

![Fig. 2. Energy efficiency versus the number of PBSs.](image)

Fig. 2 investigates the energy efficiency versus the number of PBSs. We set the energy transfer efficiency $\beta_E$ and the number of UEs $E_{UE_{num}}$ 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 $\beta_E$. 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

<table>
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<tr>
<th>Parameter</th>
<th>Value</th>
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<tr>
<td>Macro-cell bandwidth</td>
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<td>Noise power density</td>
<td>-174 dBm/Hz</td>
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<tr>
<td>Cell radius</td>
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<td>Static power consumption of MBS</td>
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<tr>
<td>Static power consumption of PBS</td>
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</tr>
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<td>Path loss of MBS</td>
<td>$125.1 + 3.6605 \log(d_{km})$</td>
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<tr>
<td>Path loss of PBS</td>
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<tr>
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<td>Max transmit power of PBS</td>
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<tr>
<td>Efficiency of power amplifier</td>
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</table>

![Table I. Simulation Parameters](image)
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. 3 shows the energy efficiency versus the ratio of the maximum interference temperature to noise $\frac{I}{\sigma^2W}$ (dB).

Fig. 4 shows the energy efficiency versus the ratio of the maximum interference temperature to noise $\frac{I}{\sigma^2W}$ (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 $I$ 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 $\frac{I}{\sigma^2W}$. When the ratio is beyond the optimal value, it decreases with increasing $\frac{I}{\sigma^2W}$. The reason is that increasing $\frac{I}{\sigma^2W}$ 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 $\frac{I}{\sigma^2W}$ 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 $I$ 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 taken 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.

References