

Power Allocation Algorithm for Heterogeneous Cellular Networks Based on Energy Harvesting

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Abstract. Cellular network can use renewable energy through energy harvesting technology in green communication. In this paper, power allocation for heterogeneous cellular networks (HetNets) with energy harvesting is proposed to maximize the system energy efficiency. Considering the minimal transmit rate of the users and the battery capacity of the system, a low complexity power allocation algorithm based on fractional programming is proposed to maximize the energy efficiency of the system. Simulation results demonstrate the effectiveness of the proposed algorithm.

Keywords: Energy efficiency · Energy harvesting · Power allocation · Battery capacity

1 Introduction

The heterogeneous cellular networks (HetNets), which composed of macro base stations (MBS) with small cells (SCs), is a promising technique to increase the data rate compared with the conventional MBS. However, as the number of small cell increases, energy consumption of the HetNets also increases. Energy harvesting technique has become the important technique to save the energy consumption and improving the energy efficiency in HetNets. Energy harvesting technology is a promising approach to prolong the lifetime and improve the energy efficiency of networks [1]. Energy harvesting mode of the network can generally be divided into two types according to the specific sources of the harvested energy [2]. The first one is that the base stations (BSs) and users harvest renewable energy from the environment, such as solar energy or wind energy.

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The second one is that BSs and users harvest energy from ambient radio signals. In this paper, we focus on power allocation in the HetNets with renewable energy supply.

Because the base station using energy harvesting has become increasingly prominent technology for green communication, a large number of researchers have made contributions in this field. Different energy efficient optimization algorithms [3–6] has been proposed. In [3], the authors consider a device-to-device (D2D) communication provided EH heterogeneous cellular network (D2D-EHHN), and propose an efficient and low-complex transmission mode selection strategy for the D2D-EHHN. In [4], a generalized Stackelberg game is proposed to investigate the optimal energy and resource allocation problem of an autonomous energy harvesting base station. In [5], the authors propose a user association algorithm in HetNets with BSs solely powered by renewable energy supply. In [6], energy efficiency optimization of downlink base station cooperation with energy harvesting is proposed. In [7], the authors consider a more complicated network scenarios compared to [6], and discuss the optimization of power efficiency in the two layer cellular network scenario without considering battery capacity constraints. In [8], energy efficient resource allocation algorithm is studied in an orthogonal frequency division multiple access (OFDMA) downlink network with hybrid energy harvesting base station. In [9], the authors study the effects of different energy arrival rates on the overall system rate for cellular system with energy harvesting, but the algorithm complexity is very high.

In this paper, aiming at the problem of high complexity, we consider a HetNets with energy harvesting and propose a low complexity energy efficient power allocation optimization algorithm to improve energy efficiency of the system. The remainder of this paper is organized as follows. The system model is presented in Sect. 2. Section 3 introduces the energy efficiency maximization problem. Solving algorithm, through the transformation of the problem, and finally through the two layer iteration to solve the initial optimization problem in Sect. 3, Simulation results are given in Sect. 4. Conclusions are stated in Sect. 5.

2 System Model

We focus on HetNets as shown in Fig. 1, consisting of one macrocell and multiple femtocells. Each base station of femtocell can be are powered by renewable energy harvesting unit or grid hybrid power supply. When the base station can not get enough energy to work well, it will switch to using power of the grid. In order to ensure the system coverage blind spots, stable power grid energy is used by the station of macrocell provide energy. Considering the actual deployment scenario, the system adopts centralized power control, which greatly reduces the computing power of the base station. The bandwidth of the system is B , and the frequency reuse factor is 1, that is, all the base stations use the same spectrum resource [6]. The channel model between the user and the base station is Rayleigh fading, and the channel gains of different time slots are independent and identically distributed. (i.i.d) [8].

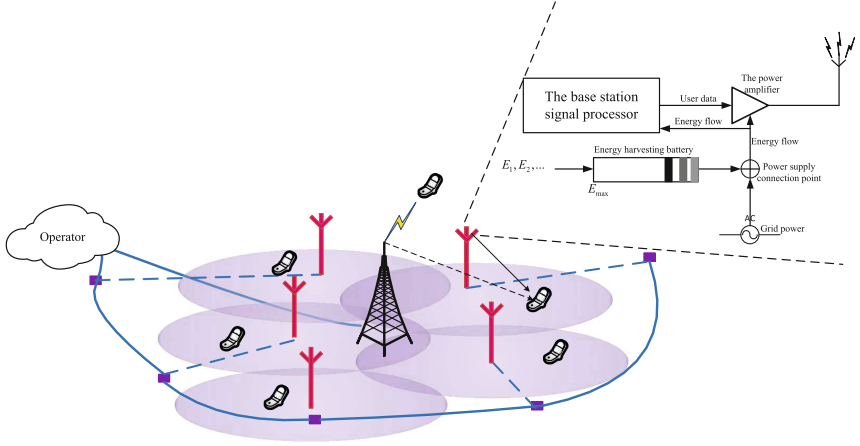


Fig. 1. System model

In renewable energy and grid hybrid power supply for the HetNets, each base stations with renewable energy harvesting devices has different energy rates. In order to provide a more general energy harvesting model for the system, we do not make specific assumption on the type of the energy collector. The arrival of energy in the energy collector is modeled as a poisson process with the arrival rata λ_E [10].

In order to facilitate the reader, the main parameters used in this paper are listed in Table 1. Assume that the energy efficiency maximization problem is considered in a fixed time interval of length T . We divide the continuous time T into K discrete time slot so as to design an power allocation.

Then, the total throughput $C(p)$ of the system and total energy consumption $P(p)$ can be expressed as follows.

$$C(p) = \sum_{n=1}^N \sum_{i=1}^K C_{i,n} \quad (1)$$

where $C_{i,n}$ is the rate of the n -th femtocell in time slot i which can be given as follows.

$$C_{i,n} = w_n \log_2 \left(1 + \frac{g_{i,n} p_{i,n}^R}{\sum_{j=1, j \neq n}^N g_{i,j} p_{i,j}^R + \sigma^2} \right) \quad (2)$$

The total power $P(p)$ consumed by the system is given by

$$P(p) = \sum_{n=1}^N \sum_{i=1}^K (p_{i,n}^R + p_{i,n}^O) \quad (3)$$

Energy efficiency maximization problem of the system is as follows.

Table 1. Summary of key notations

Nation	Description
N	The number of Femto cellular
i	The time slot i
T	time span
K	The number of time slots
\bar{L}_E	The average length of time slot
w_n	The sub channel bandwidth
$g_{i,0}$	The i time slot macro station channel gain
$p_{i,n}^R$	The i time slot the power consumption of the n base station
$p_{i,n}^O$	The i time slot the fixed power of the n base station
$C(p)$	The system throughput
$p(p)$	Total energy consumption of the system
U	The utility function
$E_{i,n}$	The i time slot n base station the remaining energy of the battery
$E_{0,n}$	The n base station initial energy in the battery
$E_{n,\max}$	The n base station the maximum capacity of the battery
$p_{i,n}^{\max}$	The i time slot the n base station maximum transmitted power
$p_{i,0}^O$	The i time slot fixed power of macro station
$p_{i,n}^R$	The i time slot radio frequency (RF) power of macro station

$$\max_p \frac{\sum_{n=1}^N \sum_{i=1}^K w_n \log_2 \left(1 + \frac{g_{i,n} p_{i,n}^R}{\sum_{j=1, j \neq n}^N g_{i,j} p_{i,j}^R + \sigma^2} \right)}{\sum_{n=1}^N \sum_{i=1}^K (p_{i,n}^R + p_{i,n}^O)} \quad (4)$$

s.t.

$$\begin{aligned} C1 : & \sum_{i=1}^j \bar{L}_E (p_{i,n}^R + p_{i,n}^O) \leq \sum_{i=0}^j E_{i,n}, \forall j, n; \\ C2 : & \sum_{i=0}^j E_{i,n} - \sum_{i=1}^j \bar{L}_E (p_{i,n}^R + p_{i,n}^O) \leq E_{\max,n}, \forall j, n; \\ C3 : & \sum_{i=1}^K \bar{L}_E C_{i,n} \geq R_{\min} \\ C4 : & p_{i,n}^R, p_{i,n}^O \geq 0, \forall i, n; \\ C5 : & p_{i,n}^R \leq p_{i,n}^{\max}, \forall i, n; \end{aligned}$$

where $C1$ and $C2$ is energy use and storage condition. The derivation process is given in appendix A. $E_{i,n}$ is the energy arrival for femtocell i in time slot n , $C3$ is the lowest transmit rate constraint for the system, $C4$ means that transmission power of the n -th femtocell is nonnegative in time slot i , and $C5$ indicate the maximum total transmit power constraint for the n -th femtocell in time slot i , respectively.

3 Power Allocation Algorithm

Because of the limitation of causality of energy arrival, we need dynamic programming to solve (3). In order to simplify the resource allocation algorithm, we assume that the resource allocation policy in each time so as to design a low complexity algorithm. Therefore, we consider the efficiency maximization problem for a fixed time $i = 1, \dots, K$ by sequential optimization method.

$$\max_p \frac{\sum_{n=1}^N w_n \log_2 \left(1 + \frac{g_{i,n} p_{i,n}^R}{\sum_{j=1, j \neq n}^N g_{i,j} p_{i,j}^R + \sigma^2} \right)}{\sum_{n=1}^N (p_{i,n}^R + p_{i,n}^O)} \quad (5)$$

s.t.

$$\begin{aligned} C'_1 &: \sum_{k=1}^i \overline{LE} (p_{k,n}^R + p_{k,n}^O) \leq \sum_{k=0}^i E_{k,n}, \forall n; \\ C'_2 &: \sum_{k=0}^i E_{k,n} - \sum_{k=1}^i \overline{LE} (p_{k,n}^R + p_{k,n}^O) \leq E_{\max,n}, \forall n; \\ C'_3 &: \overline{LE} C_{i,n} \geq \frac{R_{\min}}{K}, \forall n; \\ C'_4 &: p_{i,n}^R, p_{i,n}^O \geq 0, \forall n; \\ C'_5 &: p_{i,n}^R \leq p_{i,n}^{\max}, \forall n; \end{aligned}$$

The objective function in (5) is non-concave function, therefore problem (5) is a non-convex optimization problem. In order to solve problem (5), we transform it into an equivalent problem based on fractional programming function [11]. Let

$$C'(p) = \sum_{n=1}^N w_n \log_2 \left(1 + \frac{g_{i,n} p_{i,n}^R}{\sum_{j=1, j \neq n}^N g_{i,j} p_{i,j}^R + \sigma^2} \right), \quad P'(p) = \sum_{n=1}^N (p_{i,n}^R + p_{i,n}^O)$$

and $q = C'(p)/P'(p)$ represent the energy efficiency of the system for a given power allocation scheme, and $q^* = C'(p^*)/P'(p^*)$ represent the optimal power allocation scheme such that the energy efficiency of the system is maximized, we have following theorem [12].

Theorem 1. Consider p^* satisfies constraint $C'_1 - C'_5$ and $q^* = C'(p^*)/P'(p^*)$. Then, p^* is the solution of problem (5) if and only if

$$p^* = \arg \max_p C(p) - q^* P(p) \quad (6)$$

As a consequence of Theorem 1, solving problem (5) is equivalent to finding the unique zero of the auxiliary function $F(q)$, where $F(q)$ is given by

$$F(q) = \max_{\{p_i\}_{i=1}^N} \sum_{n=1}^N w_n C_{i,n} - q \sum_{n=1}^N (p_{i,n}^R + p_{i,n}^O) \quad (7)$$

such that q satisfies constraints $C'_1 - C'_5$.

Next, we use Lagrange dual method to solve problem (7). The Lagrange function of (7) is as follows.

$$\begin{aligned}
L(p, \gamma, \beta, \mu, v) &= \sum_{n=1}^N w_n C_{i,n} - q \sum_{n=1}^N (p_{i,n}^R + p_{i,n}^O) \\
&- \sum_{n=1}^N \gamma_n (p_{i,n}^R - p_{i,n}^{\max}) - \sum_{n=1}^N \beta_n \left(\frac{R_{\min}}{K} - \overline{L_E} C_{i,n} \right) \\
&- \sum_{n=1}^N \mu_n \left(\sum_{k=1}^i \overline{L_E} (p_{k,n}^R + p_{k,n}^O) - \sum_{k=0}^i E_{k,n} \right) \\
&- \sum_{n=1}^N v_n \left(\left[\sum_{k=0}^i E_{k,n} - \sum_{k=1}^i \left(\overline{L_E} p_{k,n}^R + \overline{L_E} p_{k,n}^O \right) \right] - E_{\max,n} \right),
\end{aligned} \tag{8}$$

where $\gamma = (\gamma_1, \gamma_2, \dots, \gamma_N)$, $\mu = (\mu_1, \mu_2, \dots, \mu_N)$ and $v = (v_1, v_2, \dots, v_N)$ are the multiplier of the constraints.

Therefore, the Lagrangian dual function can be expressed as follows:

$$\min_{\gamma, \beta, \mu, v \geq 0} \max_{p \geq 0} L(p, \gamma, \mu, v).$$

Application KKT (Karush-Kuhn-Tucker) conditions, we can get:

$$p_{i,n}^R = \frac{w}{\ln 2(q + \gamma_n)} - \frac{\sum_{j=1, j \neq n}^N g_{i,j} p_{i,j}^R + \sigma^2}{g_{i,n}} \tag{9}$$

For a given q , we can use the method of sub-gradient method to find $p_{i,n}^R$ by update the multipliers as follows [13].

$$\begin{aligned}
\gamma_n^{(t+1)} &= \gamma_n^{(t)} + \nabla_{\gamma}^{(t+1)} \times (p_{i,n}^R - p_{i,n}^{\max}) \\
\mu_n^{(t+1)} &= \mu_n^{(t)} + \nabla_{\mu}^{(t+1)} \times \left(\sum_{k=1}^i \overline{L_E} (p_{k,n}^R + p_{k,n}^O) - \sum_{k=0}^i E_{k,n} \right) \\
v_n^{(t+1)} &= v_n^{(t)} + \nabla_v^{(t+1)} \\
&\times \left(\sum_{k=0}^i E_{k,n} - \sum_{k=1}^i \left(\overline{L_E} p_{k,n}^R + \overline{L_E} p_{k,n}^O \right) - E_{\max,n} \right) \\
\beta_n^{(t+1)} &= \beta_n^{(t)} + \nabla_{\beta}^{(t+1)} \left(\frac{R_{\min}}{K} - \overline{L_E} w_n \log_2 \left(1 + \frac{g_{i,n} p_{i,n}^R}{\sum_{j=1, j \neq n}^N g_{i,j} p_{i,j}^R + \sigma^2} \right) \right)
\end{aligned} \tag{10}$$

Where $\nabla^{(t+1)} = \frac{1}{t}$ is update step size for each iteration, t is the number of iterations. Then, the optimal energy efficiency q^* can be obtained by solve equation $F(q) = 0$ by bisection method. The flow chart of the proposed algorithm is given in Fig. 2.

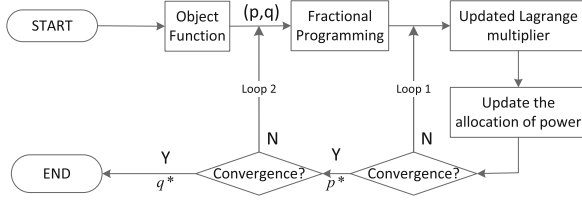


Fig. 2. Flow chart of algorithm

Table 2. Simulation parameter settings

Parameter	Value
Macro cellular/femto cellular radius	500 m/50 m
The minimum signal to noise ratio	1 dB
Femto cellular maximum transmitted power	100 mW
White noise levels	2×10^{-9} W
The channel fading model	Rayleigh
The sub channel bandwidth	5 MHz
The average time slot width	2 s
Femto cellular static power consumption	2 W

4 Simulation Results and Discussion

In the simulation conditions, we set offline optimal power allocation algorithm is the inner loop around eleven times to realize iterative convergence, outer loop around six times the iterative convergence, This shows that the algorithm complexity is low (Table 2).

Figure 3 show the average energy efficiency versus number of iterations for different number of femtocell. The proposed power allocation algorithm will be convergence in 11 times. Thus, the complexity of the proposed algorithm is low.

As shown in Fig. 4, the average energy efficiency of the system will be increased as the energy arrival rate increases. This is because the system can harvest more power for each femtocell to maximize the energy efficiency.

Figure 5 shows the relationship of battery capacity and power grid average energy efficiency under different energy arrive rate. From the figure, we can see that the maximum system efficiency is no longer affected when battery capacity exceeds a certain value.

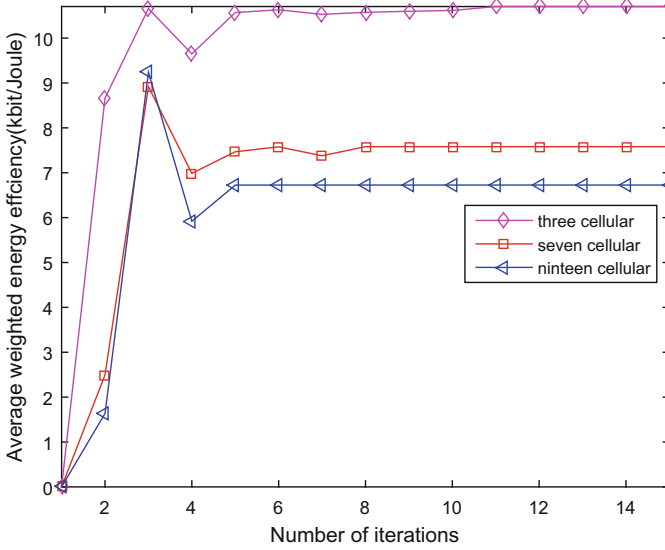


Fig. 3. Average energy efficiency versus number of iterations

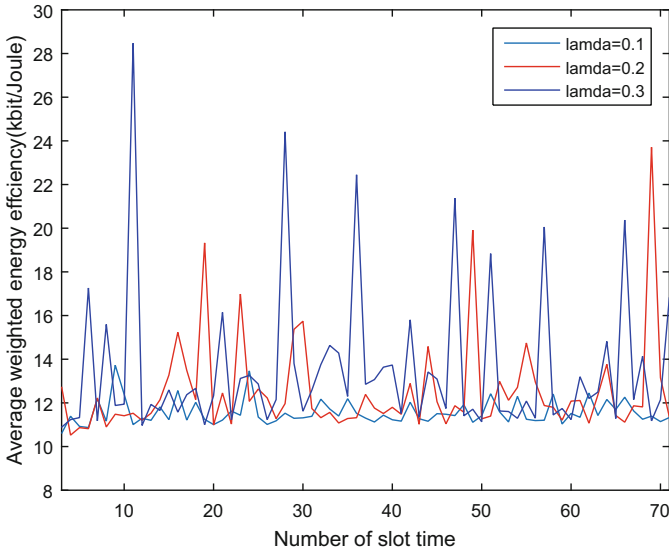


Fig. 4. Total energy efficiency versus energy arrival rate

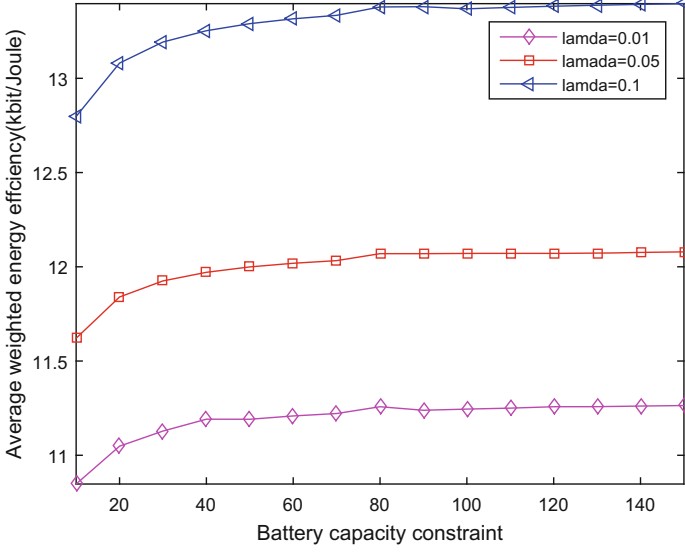


Fig. 5. Average energy efficiency versus battery capacity constraint

5 Conclusions

A low complexity energy efficient power allocation algorithm in HetNets based on energy harvesting is proposed using fractional programming. Through the simulation analysis, the algorithm can guarantee the quality of coverage and business on the basis of the lower area of the interference. The impact of energy arrival rate and battery capacity constraint on the energy efficiency of system. The next step of work is the study of hybrid energy supply, to improve the regional energy efficiency.

Appendix A

Energy use and storage conditions $C1$ and $C2$ can be derived as follows. Let $S_{i,n} = \overline{L_E} (p_{i,n}^R + p_{i,n}^O)$ be the energy used for femtocell n in time slot i . Then, for time slot 1 to K , we have following inequality constraints.

$$\begin{aligned}
 i = 1 &: \overline{L_E} (p_{1,n}^R + p_{1,n}^O) \leq E_{0,n} + E_{1,n}, \forall n \\
 i = 2 &: \overline{L_E} (p_{2,n}^R + p_{2,n}^O) \leq E_{2,n} + (E_{0,n} + E_{1,n}) - S_{1,n}, \forall n \\
 &= E_{0,n} + E_{1,n} + E_{2,n} - S_{1,n} \\
 &\vdots \\
 i = K &: \overline{L_E} (p_{K,n}^R + p_{K,n}^O) \\
 &\leq E_{K,n} + (E_{0,n} + E_{1,n} + \dots + E_{K-1,n}) - (S_{K-1,n} + \dots + S_{1,n}) \\
 &= \sum_{i=0}^K E_{i,n} - \sum_{i=1}^{K-1} S_{i,n}
 \end{aligned}$$

therefore $S_{j,n} \leq \sum_{i=0}^j E_{i,n} - \sum_{i=1}^{j-1} S_{i,n}$ is hold for $j = 1, \dots, K$, move the item $\sum_{i=1}^{j-1} S_{i,n}$ from the right side to the left side, we have

$$\sum_{i=1,n}^j S_{i,n} \leq \sum_{i=0}^j E_{i,n} \quad (11)$$

substitute $S_{i,n} = \overline{L_E} (p_{i,n}^R + p_{i,n}^O)$ into (11), we have

$$\sum_{i=1}^j \overline{L_E} (p_{i,n}^R + p_{i,n}^O) \leq \sum_{i=0}^j E_{i,n}, \forall n;$$

Therefore C1 is hold. Meanwhile, because capacity limit of the battery, the remaining battery energy in each time slot for femtocell n cannot exceed the battery capacity, more than part of the energy will be discarded:

$$\sum_{i=0}^j E_{i,n} - \sum_{i=1}^j S_i \leq E_{\max,n}$$

for each time slot $j = 1, \dots, K$, then we have

$$\sum_{i=0}^j E_{i,n} - \sum_{i=1}^j \overline{L_E} (p_{i,n}^R + p_{i,n}^O) \leq E_{\max,n}$$

Therefore C2 is hold.

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