Resource Allocation Algorithm Based on Energy Cooperation in Two-way Cognitive Radio Relay Networks

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***Abstract*—We consider a two-way cognitive radio relay network where two secondary users (SUs) can simultaneously transfer energy and information to a relay. Then, a joint optimization algorithm for power allocation and energy cooperation is proposed. The algorithm proves that the formulated throughput maximization problem is a convex optimization problem. Next, we decompose the formulated problem into a power allocation problem and an energy transmission problem. Finally, the power allocation problem is solved by an iteration water-filling algorithm, and the energy transmission problem of each timeslot is solved by the derivative method. Simulation results show that energy cooperation can significantly improve system throughput.**

Keywords*—*energy harvesting (EH); energy cooperation; cognitive radio; resource allocation

I. INTRODUCTION

Energy harvesting technology has the ability to collect energy from electromagnetic waves, light and so on. So it can greatly expand the device lifecycle, reduce energy costs and improve the performance of wireless networks [1-2].

There have been many studies on the resource allocation problem of energy harvesting wireless networks. In [3], the authors consider a two-node energy harvesting network, and then a directional water-filling algorithm is proposed by the Lagrangian function and KKT conditions.

When a wireless communication system contains more than one energy harvesting node, the nodes with less energy may severely degrade the system performance. In this case, the nodes with more energy can transfer some energy through energy cooperation [4-5] to the nodes with less energy. In [6], the authors propose a two-dimensional directional water-filling algorithm by maximizing the system throughput. In [7], the authors propose a procrastinating policy in which the energy transferred in a timeslot must be used in the same timeslot, without affecting the optimal value.

However, [6-7] do not consider cognitive radio technology, which can improve spectral efficiency, whereas the problem to be solved will be more complex. In [8], assuming that the primary user (PU) and secondary user (SU) both have the energy harvesting ablity, and the PU could transmit information and energy to the SU. Then, the throughput maximization problem of the SU is decomposed into three layers, and each layer is solved by the gradient method. But [8] only takes into account a single SU, and uses the gradient method to synchronously update multiple dual variables with high computational complexity.

This paper proposes a joint optimization algorithm for power allocation and energy cooperation by maximizing the system throughput. The algorithm considers energy cooperation and cognitive radio technology, so as to improve spectral efficiency and energy efficiency simultaneously. In this paper, the two SUs can share the common spectrum of the PU [9] through a FDMA (frequency division multiple access) mode. The main contributions of this paper are as follows:

1. We prove that the formulated problem is a convex optimization problem, and there must be the procrastinating policy which is optimal for the formulated problem.

2. We decompose the joint optimization problem for power allocation and energy cooperation into a power allocation problem and an energy transmission problem of each timeslot. Then, the power allocation problem is solved by an iteration water-filling algorithm, and the energy transmission problem of each timeslot is solved by the derivative method.

3. We explain the energy backflow phenomenon, and then give a solution.

II. SYSTEM MODEL AND PROBLEM FORMULATION

This paper studies a two-way cognitive radio relay network, consisting of a PU, two SUs and a relay, as shown in Fig. 1, where the two SUs and relay all are energy harvesting nodes. The system contains N equal-length timeslots, and the duration of each timeslot is unitized to 1. Assuming that the harvested energy and transferred energy instantaneously arrive before the start of each timeslot. In addition, all channels experience Rayleigh fading. The channel fading coefficients in

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timeslot i between the PU and two SUs are denoted as $g_{1,i}$ and $g_{2,i}$, and the channel fading coefficients between the two SUs and relay are denoted as $h_{1,i}$ and $h_{2,i}$, respectively. The total bandwidth of the PU is W. We denote the harvested energy of the two SUs and relay in timeslot i as $E_{1,i}$, $E_{2,i}$ and $E_{R,i}$. At the same time, the two SUs can transfer energy with amount $\delta_{1,i}$ and $\delta_{2,i}$ to the relay in timeslot i, and the energy transfer efficiencies are set as η_1 and $\eta_2 (0 \le \eta_1, \eta_2 \le 1)$. In this paper, $\{x_i\}$ and $\mathbf{x}$ both denote the set of x_i, $1 \le i \le N$.

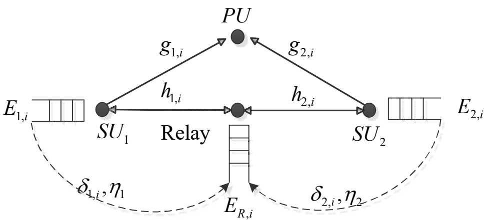

Fig. 1. Two-way cognitive radio relay network model

Assuming that the two SUs perform a bidirectional communication with each other, and each SU occupies half the bandwidth of the PU through a FDMA mode. Meanwhile, the relay uses an orthogonal carrier of the same bandwidth with the two SUs. Then, the allocated power of SU_1 in timeslot i is denoted as $p_{1,i}$, and the allocated power of SU_2 is $p_{2,i}$. The total interference of the two SUs cannot exceed the system interference threshold I [9], i.e.,

$$p_{1,i} g_{1,i} + p_{2,i} g_{2,i} \le I \tag{1}$$

The relay works in a DF full-duplex protocol, and forwards the data sent by the two SUs. Note that the relay always has one timeslot delay compared with the two SUs, as shown in Fig. 2. In timeslot i, SU_1 transfers information with power $p_{1,i}$ and energy $\delta_{1,i}$ to the relay with the energy transfer efficiency η_1. Meanwhile, SU_2 transfers information with power $p_{2,i}$ and energy $\delta_{2,i}$ to the relay with the energy transfer efficiency η_2. In timeslot $i+1$, the relay forwards the data sent in timeslot i by the two SUs with power $p_{R,i+1}$. In order to align the timeslot subscripts of the two SUs and relay, the timeslot subscripts of the relay is moved up one timeslot [6]. Assuming that the relay cannot store data, i.e., the data received in one timeslot must be forwarded in the next timeslot.

So, the energy causality constraints for the three nodes are:

$$\sum_{i=1}^{n} p_{1,i} \le \sum_{i=1}^{n} (E_{1,i} - \delta_{1,i}) \tag{2}$$

$$\sum_{i=1}^{n} p_{2,i} \le \sum_{i=1}^{n} (E_{2,i} - \delta_{2,i}) \tag{3}$$

$$\sum_{i=1}^{n} p_{R,i} \le \sum_{i=1}^{n} (E_{R,i} + \eta_1 \delta_{1,i} + \eta_2 \delta_{2,i}) \tag{4}$$

where n denotes that the energy consumed in the first n timeslots is less than or equal to the energy collected.

Since the data received by the relay in one timeslot must be forwarded in the next timeslot, we can obtain:

$$\begin{aligned} &\frac{1}{2} W \log_2 \left(1 + \frac{h_{1,i} p_{1,i}}{W N_0 / 2}\right) + \frac{1}{2} W \log_2 \left(1 + \frac{h_{2,i} p_{2,i}}{W N_0 / 2}\right) \le \\ &\frac{1}{2} W \log_2 \left(1 + \frac{\min(h_{1,i}, h_{2,i}) p_{R,i}}{W N_0 / 2}\right) \end{aligned} \tag{5}$$

where N_0 denotes the noise power spectral density of the receivers. Since $\frac{W N_0}{2}$ is a constant, let $\bar{h}_{1,i} = \frac{h_{1,i}}{W N_0 / 2}$, $\bar{h}_{2,i} = \frac{h_{2,i}}{W N_0 / 2}$ and $\bar{h}_{R,i} = \frac{\min(h_{1,i}, h_{2,i})}{W N_0 / 2}$ to simplify the derivation process.

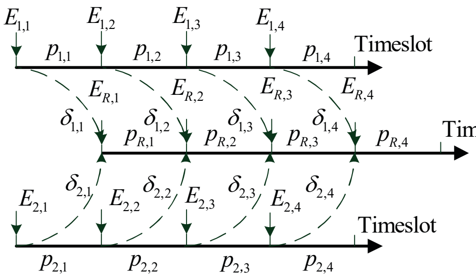

Fig. 2. Slot diagram of two-way cognitive radio relay network

We can formulate the system throughput maximization problem of N timeslots as:

$$\begin{aligned} \mathbf{P1}: \quad & \max_{\substack{\{p_{1,i}, p_{2,i}, \\ p_{R,i}, \delta_{1,i}, \delta_{2,i}\}}} \sum_{i=1}^{N} \log_2(1 + \bar{h}_{1,i} p_{1,i}) + \log_2(1 + \bar{h}_{2,i} p_{2,i}) \\ s.t. \quad & p_{1,i} g_{1,i} + p_{2,i} g_{2,i} \le I \\ & \sum_{i=1}^{n} p_{1,i} \le \sum_{i=1}^{n} (E_{1,i} - \delta_{1,i}) \\ & \sum_{i=1}^{n} p_{2,i} \le \sum_{i=1}^{n} (E_{2,i} - \delta_{2,i}) \\ & \sum_{i=1}^{n} p_{R,i} \le \sum_{i=1}^{n} (E_{R,i} + \eta_1 \delta_{1,i} + \eta_2 \delta_{2,i}) \\ & \log_2(1 + \bar{h}_{1,i} p_{1,i}) + \log_2(1 + \bar{h}_{2,i} p_{2,i}) \le \log_2(1 + \bar{h}_{R,i} p_{R,i}) \\ & 0 \le p_{1,i},\ 0 \le p_{2,i},\ 0 \le p_{R,i},\ 0 \le \delta_{1,i},\ 0 \le \delta_{2,i} \end{aligned} \tag{6}$$

where $\frac{1}{2} W$ is omitted temporarily in the objective function for convenience, and we will add it in **Algorithm 1**.

Next, we prove that **P1** is a convex optimization problem.

Proof: Let $r_{1,i}=\log_2(1+\bar{h}_{1,i}p_{1,i})$, $r_{2,i}=\log_2(1+\bar{h}_{2,i}p_{2,i})$ and $r_{R,i}=\log_2(1+\bar{h}_{R,i}p_{R,i})$ for $1\le i\le N$, and then **P1** is equivalent to:

$$\begin{aligned}
&\max_{\substack{\{r_{1,i},r_{2,i},\\ r_{R,i},\delta_{1,i},\delta_{2,i}\}}} \sum_{i=1}^{N} r_{1,i}+r_{2,i} \\
&s.t.\quad \frac{2^{r_{1,i}}-1}{\bar{h}_{1,i}}g_{1,i}+\frac{2^{r_{2,i}}-1}{\bar{h}_{2,i}}g_{2,i}\le I \\
&\qquad \sum_{i=1}^{n}\frac{2^{r_{1,i}}-1}{\bar{h}_{1,i}}\le\sum_{i=1}^{n}(E_{1,i}-\delta_{1,i}) \\
&\qquad \sum_{i=1}^{n}\frac{2^{r_{2,i}}-1}{\bar{h}_{2,i}}\le\sum_{i=1}^{n}(E_{2,i}-\delta_{2,i}) \\
&\qquad \sum_{i=1}^{n}\frac{2^{r_{R,i}}-1}{\bar{h}_{R,i}}\le\sum_{i=1}^{n}(E_{R,i}+\eta_1\delta_{1,i}+\eta_2\delta_{2,i}) \\
&\qquad r_{1,i}+r_{2,i}\le r_{R,i} \\
&\qquad 0\le r_{1,i},\ 0\le r_{2,i},\ 0\le r_{R,i},\ 0\le\delta_{1,i},\ 0\le\delta_{2,i}
\end{aligned}\tag{7}$$

Assuming that there are two feasible strategies $(\mathbf{r_1^1},\mathbf{r_2^1},\mathbf{r_R^1},\boldsymbol{\delta}_1^1,\boldsymbol{\delta}_2^1)$ and $(\mathbf{r_1^2},\mathbf{r_2^2},\mathbf{r_R^2},\boldsymbol{\delta}_1^2,\boldsymbol{\delta}_2^2)$. And another strategy $(\mathbf{r_1^3},\mathbf{r_2^3},\mathbf{r_R^3},\boldsymbol{\delta}_1^3,\boldsymbol{\delta}_2^3)=\lambda(\mathbf{r_1^1},\mathbf{r_2^1},\mathbf{r_R^1},\boldsymbol{\delta}_1^1,\boldsymbol{\delta}_2^1)$+(1-$\lambda$)$(\mathbf{r_1^2},\mathbf{r_2^2},\mathbf{r_R^2},\boldsymbol{\delta}_1^2,\boldsymbol{\delta}_2^2)$ is given, where $0<\lambda<1$. First, we prove that the strategy $(\mathbf{r_1^3},\mathbf{r_2^3},\mathbf{r_R^3},\boldsymbol{\delta}_1^3,\boldsymbol{\delta}_2^3)$ is a feasible strategy, that is, the constraint set of (7) is a convex set for the strategy $(\mathbf{r_1},\mathbf{r_2},\mathbf{r_R},\boldsymbol{\delta}_1,\boldsymbol{\delta}_2)$. For the first constraint,

$$\begin{aligned}
&\frac{2^{r_{1,i}^3}-1}{\bar{h}_{1,i}}g_{1,i}+\frac{2^{r_{2,i}^3}-1}{\bar{h}_{2,i}}g_{2,i} \\
&=\frac{2^{\lambda r_{1,i}^1+(1-\lambda)r_{1,i}^2}-1}{\bar{h}_{1,i}}g_{1,i}+\frac{2^{\lambda r_{2,i}^1+(1-\lambda)r_{2,i}^2}-1}{\bar{h}_{2,i}}g_{2,i} \\
&\overset{(a)}{\le}\frac{\lambda 2^{r_{1,i}^1}+(1-\lambda)2^{r_{1,i}^2}-1}{\bar{h}_{1,i}}g_{1,i}+\frac{\lambda 2^{r_{2,i}^1}+(1-\lambda)2^{r_{2,i}^2}-1}{\bar{h}_{2,i}}g_{2,i} \\
&\le\lambda I+(1-\lambda)I=I
\end{aligned}\tag{8}$$

where the reason of (a) is that the exponential function is a convex function.

For the second constraint,

$$\begin{aligned}
&\sum_{i=1}^{n}\frac{2^{r_{1,i}^3}-1}{\bar{h}_{1,i}}=\sum_{i=1}^{n}\frac{2^{\lambda r_{1,i}^1+(1-\lambda)r_{1,i}^2}-1}{\bar{h}_{1,i}} \\
&\le\sum_{i=1}^{n}\frac{\lambda(2^{r_{1,i}^1}-1)+(1-\lambda)(2^{r_{1,i}^2}-1)}{\bar{h}_{1,i}} \\
&\le\lambda\sum_{i=1}^{n}(E_{1,i}-\delta_{1,i}^1)+(1-\lambda)\sum_{i=1}^{n}(E_{1,i}-\delta_{1,i}^2)=\sum_{i=1}^{n}(E_{1,i}-\delta_{1,i}^3)
\end{aligned}\tag{9}$$

The feasibility proofs for $\mathbf{r_2^3}$, $\mathbf{r_R^3}$ are similar to (9) and will not be repeated. The other constraints all are linear and must be feasible. As a result, the constraint set of (7) is a convex set. Meanwhile, since the objective function of (7) is a linear function, which must a convex function. In summary, equation (7) is a convex optimization problem [10].

III. Optimal Power Allocation Algorithm

In the optimal power allocation strategy, we could obtain $\log_2(1+\bar{h}_{1,i}p_{1,i})+\log_2(1+\bar{h}_{2,i}p_{2,i})=\log_2(1+\bar{h}_{R,i}p_{R,i})$ for $1\le i\le N$, without affecting the optimal value of (6). If $\log_2(1+\bar{h}_{1,i}p_{1,i})+\log_2(1+\bar{h}_{2,i}p_{2,i})<\log_2(1+\bar{h}_{R,i}p_{R,i})$, the energy of the relay is wasted. In this case, let $p_{R,i}=\frac{2^{\log_2(1+\bar{h}_{1,i}p_{1,i})+\log_2(1+\bar{h}_{2,i}p_{2,i})}-1}{\bar{h}_{R,i}}$, and then the optimal value of (6) is unchanged.

Proposition 1: There must be the procrastinating policy $p_{R,i}\ge\eta_1\delta_{1,i}+\eta_2\delta_{2,i}$, for $1\le i\le N$ [7], which is an optimal solution of **P1**, i.e., the energy transferred to the relay in a timeslot must be used out in the same timeslot.

Proof: Assuming that $\{p_{1,i}^*,p_{2,i}^*,p_{R,i}^*,\delta_{1,i}^*,\delta_{2,i}^*\}$ is an optimal solution of **P1** , and it does not satisfy the procrastinating policy $p_{R,i}\ge\eta_1\delta_{1,i}+\eta_2\delta_{2,i}$, $1\le i\le N$. Then, there is at least one timeslot n , $1\le n\le N$, where $p_{R,n}^*<\eta_1\delta_{1,n}^*+\eta_2\delta_{2,n}^*$ is satisfied. We assume that the allocated power $p_{R,n}^*$ consists of $\varepsilon_{1,n}$ from SU_1 , $\varepsilon_{2,n}$ from SU_2 and $\varepsilon_{R,n}$ from the relay itself, that is, $p_{R,n}^*=\eta_1\varepsilon_{1,n}+\eta_2\varepsilon_{2,n}+\varepsilon_{R,n}$. When $n<N$, let $\delta_{1,n+1}^*=\delta_{1,n+1}^*+\delta_{1,n}^*-\varepsilon_{1,n}$, $\delta_{2,n+1}^*=\delta_{2,n+1}^*+\delta_{2,n}^*-\varepsilon_{2,n}$, $\delta_{1,n}^*=\varepsilon_{1,n}$ and $\delta_{2,n}^*=\varepsilon_{2,n}$. When $n=N$, just let $\delta_{1,n}^*=\varepsilon_{1,n}$, $\delta_{2,n}^*=\varepsilon_{2,n}$. Now the procrastinating policy is satisfied. Since $\{p_{1,i}^*,p_{2,i}^*,p_{R,i}^*\}$ will not be changed, the optimal value obtained by **P1** is not changed. Meanwhile, since we only delay the energy transmitted in timeslot n to timeslot $n+1$, it is easy to verify that all the constraints are not violated.

By **Proposition 1**, let $\bar{p}_{1,i}=p_{1,i}+\delta_{1,i}$ denote the actual consumed power of SU_1 , $\bar{p}_{2,i}=p_{2,i}+\delta_{2,i}$ for SU_2 and $\bar{p}_{R,i}=p_{R,i}-\eta_1\delta_{1,i}-\eta_2\delta_{2,i}$ for the relay. Then, **P1** is transformed into:

$$\begin{aligned}
&\textbf{P2:}\max_{\substack{\{\bar{p}_{1,i},\bar{p}_{2,i},\\ \bar{p}_{R,i},\delta_{1,i},\delta_{2,i}\}}}\sum_{i=1}^{N}\log_2(1+\bar{h}_{1,i}(\bar{p}_{1,i}-\delta_{1,i}))+\log_2(1+\bar{h}_{2,i}(\bar{p}_{2,i}-\delta_{2,i})) \\
&s.t.\quad \bar{p}_{1,i}g_{1,i}+\bar{p}_{2,i}g_{2,i}-g_{1,i}\delta_{1,i}-g_{2,i}\delta_{2,i}\le I \\
&\qquad \sum_{i=1}^{n}\bar{p}_{1,i}\le\sum_{i=1}^{n}E_{1,i} \\
&\qquad \sum_{i=1}^{n}\bar{p}_{2,i}\le\sum_{i=1}^{n}E_{2,i} \\
&\qquad \sum_{i=1}^{n}\bar{p}_{R,i}\le\sum_{i=1}^{n}E_{R,i} \\
&\qquad \log_2(1+\bar{h}_{1,i}(\bar{p}_{1,i}-\delta_{1,i}))+\log_2(1+\bar{h}_{2,i}(\bar{p}_{2,i}-\delta_{2,i}))= \\
&\qquad\qquad \log_2(1+\bar{h}_{R,i}(\bar{p}_{R,i}+\eta_1\delta_{1,i}+\eta_2\delta_{2,i})) \\
&\qquad \delta_{1,i}\le\bar{p}_{1,i},\ 0\le\delta_{1,i} \\
&\qquad \delta_{2,i}\le\bar{p}_{2,i},\ 0\le\delta_{2,i} \\
&\qquad 0\le\bar{p}_{R,i}
\end{aligned}\tag{10}$$

Since the system capacity of the i-th timeslot

$\log_2(1+\bar{h}_{1,i}(\bar{p}_{1,i}-\delta_{1,i}))+\log_2(1+\bar{h}_{2,i}(\bar{p}_{2,i}-\delta_{2,i}))$ is only related to the index i in the objective function of **P2**, we can define:

$$
\begin{aligned}
& f(\bar{p}_{1,i},\bar{p}_{2,i},\bar{p}_{R,i})= \\
& \max_{\{\delta_{1,i},\delta_{2,i}\}} \quad \log_2(1+\bar{h}_{1,i}(\bar{p}_{1,i}-\delta_{1,i}))+\log_2(1+\bar{h}_{2,i}(\bar{p}_{2,i}-\delta_{2,i})) \\
& s.t. \quad -g_{1,i}\delta_{1,i}-g_{2,i}\delta_{2,i}\le I-\bar{p}_{1,i}g_{1,i}-\bar{p}_{2,i}g_{2,i} \\
& \qquad \log_2(1+\bar{h}_{1,i}(\bar{p}_{1,i}-\delta_{1,i}))+\log_2(1+\bar{h}_{2,i}(\bar{p}_{2,i}-\delta_{2,i}))= \\
& \qquad \log_2(1+\bar{h}_{R,i}(\bar{p}_{R,i}+\eta_1\delta_{1,i}+\eta_2\delta_{2,i})) \\
& \qquad \delta_{1,i}\le \bar{p}_{1,i},\ 0\le\delta_{1,i} \\
& \qquad \delta_{2,i}\le \bar{p}_{2,i},\ 0\le\delta_{2,i}
\end{aligned} \tag{11}
$$

where $f(\bar{p}_{1,i},\bar{p}_{2,i},\bar{p}_{R,i})$ denotes the maximum system throughput of (11) by optimizing $\delta_{1,i}$ and $\delta_{2,i}$ in the case where $\bar{p}_{1,i}$, $\bar{p}_{2,i}$ and $\bar{p}_{R,i}$ are determined. Then, we can prove $f(\bar{p}_{1,i},\bar{p}_{2,i},\bar{p}_{R,i})$ is a joint convex function of $\bar{p}_{1,i}$, $\bar{p}_{2,i}$ and $\bar{p}_{R,i}$ in a similar way to the proof of **P1**.

At the same time, **P2** is equivalent to:

$$
\begin{aligned}
\textbf{P3:}\quad & \max_{\{\bar{p}_{1,i},\bar{p}_{2,i},\bar{p}_{R,i}\}} \sum_{i=1}^{N}\left\{f(\bar{p}_{1,i},\bar{p}_{2,i},\bar{p}_{R,i})\right\} \\
s.t. \quad & \bar{p}_{1,i}g_{1,i}+\bar{p}_{2,i}g_{2,i}\le I \\
& \sum_{i=1}^{n}\bar{p}_{1,i}\le\sum_{i=1}^{n}E_{1,i} \\
& \sum_{i=1}^{n}\bar{p}_{2,i}\le\sum_{i=1}^{n}E_{2,i} \\
& \sum_{i=1}^{n}\bar{p}_{R,i}\le\sum_{i=1}^{n}E_{R,i} \\
& 0\le\bar{p}_{1,i},0\le\bar{p}_{2,i},0\le\bar{p}_{R,i}
\end{aligned} \tag{12}
$$

where $\sum_{i=1}^{N}\left\{f(\bar{p}_{1,i},\bar{p}_{2,i},\bar{p}_{R,i})\right\}$ is a joint convex function of $\left\{\bar{p}_{1,i},\bar{p}_{2,i},\bar{p}_{R,i}\right\}$, because the sum of several convex functions is still convex [10]. Meanwhile, since all constraints of **P3** are linear for $\left\{\bar{p}_{1,i},\bar{p}_{2,i},\bar{p}_{R,i}\right\}$, the constraint set is convex. So **P3** is a convex optimization problem.

To facilitate solving **P3**, we initialize $\delta_{1,i}=0$, $\delta_{2,i}=0$, for $1\le i\le N$. Meanwhile, let $E_{1,i}=E_{1,i}-\delta_{1,i}$, $E_{2,i}=E_{2,i}-\delta_{2,i}$ and $E_{R,i}=E_{R,i}+\eta_1\delta_{1,i}+\eta_2\delta_{2,i}$, for $1\le i\le N$ to denote the actual energy harvested by each node after energy transfer. Then we can solve **P3** by the iterative water-filling algorithm [11] to obtain $\left\{\bar{p}_{1,i},\bar{p}_{2,i},\bar{p}_{R,i}\right\}$ due to $\delta_{1,i}=0$, $\delta_{2,i}=0$, for $1\le i\le N$, where $\left\{\bar{p}_{R,i}\right\}$ is obtained by the criterion of $p_{R,i}=\frac{2^{\log_2(1+\bar{h}_{1,i}p_{1,i})+\log_2(1+\bar{h}_{2,i}p_{2,i})}-1}{\bar{h}_{R,i}}$. Note that $\bar{p}_{1,i}=p_{1,i}$, $\bar{p}_{2,i}=p_{2,i}$, $\bar{p}_{R,i}=p_{R,i}$ due to $\delta_{1,i}=0$, $\delta_{2,i}=0$, for $1\le i\le N$.

First, let $p_{R,i}=E_{R,i}$. When $p_{R,i}>\frac{2^{\log_2(1+\bar{h}_{1,i}p_{1,i})+\log_2(1+\bar{h}_{2,i}p_{2,i})}-1}{\bar{h}_{R,i}}$, the energy of the relay is wasted because of the requirement of $\delta_{1,i}\ge 0$, $\delta_{2,i}\ge 0$, so let

$$
\begin{aligned}
p_{R,i+1} &= p_{R,i+1}+p_{R,i}-\frac{2^{\log_2(1+\bar{h}_{1,i}p_{1,i})+\log_2(1+\bar{h}_{2,i}p_{2,i})}-1}{\bar{h}_{R,i}} \\
p_{R,i} &= \frac{2^{\log_2(1+\bar{h}_{1,i}p_{1,i})+\log_2(1+\bar{h}_{2,i}p_{2,i})}-1}{\bar{h}_{R,i}}
\end{aligned} \tag{13}
$$

where just let $p_{R,N}=\frac{2^{\log_2(1+\bar{h}_{1,N}p_{1,i})+\log_2(1+\bar{h}_{2,N}p_{2,i})}-1}{\bar{h}_{R,N}}$ if $i=N$.

When $p_{R,i}<\frac{2^{\log_2(1+\bar{h}_{1,i}p_{1,i})+\log_2(1+\bar{h}_{2,i}p_{2,i})}-1}{\bar{h}_{R,i}}$, the two SUs need to transfer energy to the relay. We substitute $\bar{p}_{1,i}$, $\bar{p}_{2,i}$ and $\bar{p}_{R,i}$ into (11), and then compute the optimal $\delta^*_{1,i}$ and $\delta^*_{2,i}$ in timeslot i. The specific steps are given as follows:

1. First, from the equality constraint of (11), we can obtain:

$$
\delta_{2,i}=\frac{a_i-b_i\delta_{1,i}}{c_i-\bar{h}_{1,i}\bar{h}_{2,i}\delta_{1,i}} \tag{14}
$$

where

$$
\begin{aligned}
a_i &= (1+\bar{h}_{1,i}\bar{p}_{1,i})(1+\bar{h}_{2,i}\bar{p}_{2,i})-1-\bar{h}_{R,i}\bar{p}_{R,i} \\
b_i &= \bar{h}_{1,i}(1+\bar{h}_{2,i}\bar{p}_{2,i})+\eta_1\bar{h}_{R,i} \\
c_i &= \bar{h}_{2,i}(1+\bar{h}_{1,i}\bar{p}_{1,i})+\eta_2\bar{h}_{R,i}
\end{aligned} \tag{15}
$$

2. Equation (14) is substituted into (11) to obtain:

$$
\begin{aligned}
\max_{\delta_{1,i}} \quad & \log_2\left(1+\bar{h}_{R,i}\left(\bar{p}_{R,i}+\eta_1\delta_{1,i}+\eta_2\frac{a_i-b_i\delta_{1,i}}{c_i-\bar{h}_{1,i}\bar{h}_{2,i}\delta_{1,i}}\right)\right) \\
s.t. \quad & \left[a_i-c_i\bar{p}_{2,i}+(\bar{h}_{1,i}\bar{h}_{2,i}\bar{p}_{2,i}-b_i)\delta_{1,i}\right](c_i-\bar{h}_{1,i}\bar{h}_{2,i}\delta_{1,i})\le 0 \\
& 0\le(a_i-b_i\delta_{1,i})(c_i-\bar{h}_{1,i}\bar{h}_{2,i}\delta_{1,i}) \\
& \delta_{1,i}\le\bar{p}_{1,i},\ 0\le\delta_{1,i}
\end{aligned} \tag{16}
$$

where $-g_{1,i}\delta_{1,i}-g_{2,i}\delta_{2,i}\le I-\bar{p}_{1,i}g_{1,i}-\bar{p}_{2,i}g_{2,i}$ is omitted since $I-\bar{p}_{1,i}g_{1,i}-\bar{p}_{2,i}g_{2,i}\ge 0$ and $-g_{1,i}\delta_{1,i}-g_{2,i}\delta_{2,i}\le 0$ always hold.

3. The optimal $\delta^*_{1,i}$ must be at the points which are the boundary points of feasible region or satisfy that the first derivative of the objective function is zero. From the latter, we get:

$$
\begin{aligned}
& \eta_1(\bar{h}_{1,i}\bar{h}_{2,i})^2(\delta_{1,i})^2-2\eta_1\bar{h}_{1,i}\bar{h}_{2,i}c_i\delta_{1,i}+\eta_1(c_i)^2+ \\
& \eta_2(\bar{h}_{1,i}\bar{h}_{2,i}a_i-b_ic_i)=0
\end{aligned} \tag{17}
$$

Equation (17) is a quadratic function whose discriminant is:

$$
\begin{aligned}
\Delta&=(2\eta_1\overline{h}_{1,i}\overline{h}_{2,i}c_i)^2-4\eta_1(\overline{h}_{1,i}\overline{h}_{2,i})^2\left[\eta_1(c_i)^2+\eta_2(\overline{h}_{1,i}\overline{h}_{2,i}a_i-b_ic_i)\right]\\
&=4\eta_1\eta_2(\overline{h}_{1,i}\overline{h}_{2,i})^2(b_ic_i-\overline{h}_{1,i}\overline{h}_{2,i}a_i)\\
&=4\eta_1\eta_2(\overline{h}_{1,i}\overline{h}_{2,i})^2\left\{\overline{h}_{1,i}\overline{h}_{2,i}+\overline{h}_{R,i}\left[\begin{array}{c}\overline{h}_{1,i}\overline{h}_{2,i}\overline{p}_{R,i}+\eta_2\overline{h}_{1,i}(1+\overline{h}_{2,i}\overline{p}_{2,i})+\\ \eta_1\overline{h}_{2,i}(1+\overline{h}_{1,i}\overline{p}_{1,i})+\eta_1\eta_2\overline{h}_{R,i}\end{array}\right]\right\}\\
&>0
\end{aligned}
\tag{18}
$$

The two solutions of (17) are:

$$
\begin{aligned}
x_{1,i}&=\frac{2\eta_1\overline{h}_{1,i}\overline{h}_{2,i}c_i+\sqrt{\Delta}}{2\eta_1(\overline{h}_{1,i}\overline{h}_{2,i})^2}\\
x_{2,i}&=\frac{2\eta_1\overline{h}_{1,i}\overline{h}_{2,i}c_i-\sqrt{\Delta}}{2\eta_1(\overline{h}_{1,i}\overline{h}_{2,i})^2}
\end{aligned}
\tag{19}
$$

4. The possible boundary points of feasible region are $\left\{0,\frac{a_i}{b_i},\frac{c_i}{\overline{h}_{1,i}\overline{h}_{2,i}},\frac{c_i\overline{p}_{2,i}-a_i}{\overline{h}_{1,i}\overline{h}_{2,i}\overline{p}_{2,i}-b_i},\overline{p}_{1,i}\right\}$. So we verify $\{x_{1,i},x_{2,i}\}$ and $\left\{0,\frac{a_i}{b_i},\frac{c_i}{\overline{h}_{1,i}\overline{h}_{2,i}},\frac{c_i\overline{p}_{2,i}-a_i}{\overline{h}_{1,i}\overline{h}_{2,i}\overline{p}_{2,i}-b_i},\overline{p}_{1,i}\right\}$ to find the optimal points which satisfy all the constraints of (16). Finally, all the possible optimal points are substituted into the objective function of (16) to find the optimal $\delta_{1,i}^*$, which can obtain the maximum objective function over the other possible optimal points, and $\delta_{2,i}^*$ is calculated by (14).

However, in some adjacent timeslots, there may be an energy backflow phenomenon, as shown in Fig. 3. We explain it in timeslots i and $i+1$. In the process of solving **P3** by the iterative water-filling algorithm, firstly, the directional water-filling [3] of the two SUs in the horizontal direction will be carried out respectively, where $\overline{E}_{1,i}=\frac{E_{1,i}+1/\overline{h}_{1,i}+E_{1,i+1}+1/\overline{h}_{1,i+1}}{2}-\frac{1}{\overline{h}_{1,i}}$, and $\overline{E}_{1,i+1}=\frac{E_{1,i}+1/\overline{h}_{1,i}+E_{1,i+1}+1/\overline{h}_{1,i+1}}{2}-\frac{1}{\overline{h}_{2,i}}$. Meanwhile, the relay allocates $p_{R,i}=E_{R,i}$, $p_{R,i+1}=E_{R,i+1}$, as shown in Fig. 3(a)-(b). Assuming that the maximum total throughputs of the two SUs in timeslot i and $i+1$ both are more than the maximum throughputs of the relay, as shown in Fig. 3(c). Obviously, the two SUs should transfer energy to the relay. Since $E_{R,i}<E_{R,i+1}$, we can obtain $\delta_{1,i}^*>\delta_{1,i+1}^*$, which will lead to the energy level $(\overline{E}_{1,i}-\delta_{1,i}^*)<(\overline{E}_{1,i+1}-\delta_{1,i+1}^*)$. On the other hand, it violates the directional water-filling in the horizontal direction, so the energy of SU_1 in timeslot $i+1$ should flow back. Meanwhile, since the energy flows back in the horizontal direction, the maximum total throughput of the two SUs in timeslot $i+1$ will less than the maximum throughput of the relay, and the relay should flow energy back to the two SUs and so on. This process will be repeated until the energy levels of the two SUs satisfy the directional water-filling in the horizontal direction, and the maximum total throughputs of the two SUs in timeslot i and $i+1$ both are equal the maximum throughputs of the relay. Note that Fig. 3 is only to illustrate the energy backflow phenomenon, so the peak power constraint of each SU is not marked.

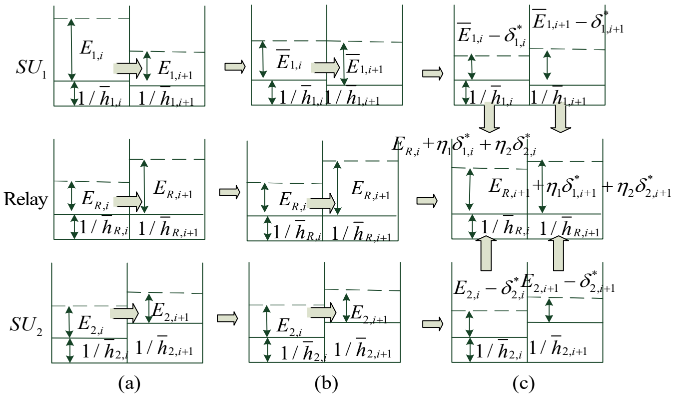

Fig. 3. Schematic diagram of the energy backflow phenomenon

For the energy backflow in the horizontal direction, we solve it by reusing the iterative water-filling algorithm. For the energy backflow in the vertical direction, we use the method of defining the metric taps [6]. The detailed steps are as follows:

1. First, we initialize the system throughput initial value $C^0=0$, and transferred energy $\delta_{1,i}^0=0$, $\delta_{2,i}^0=0$ for $1\le i\le N$, where the superscript n represents the n-th iteration. Meanwhile, let $E_{1,i}^0{=}E_{1,i}$, $E_{2,i}^0{=}E_{2,i}$, $E_{R,i}^0{=}E_{R,i}$, for $1\le i\le N$. Then, we define the metric taps $tap_{1,i}$ and $tap_{2,i}$ in the vertical direction to record the energy transferred from the two SUs to the relay in each timeslot, where the initial values are $tap_{1,i}=0$, $tap_{2,i}=0$ for $1\le i\le N$, and the positive direction is specified from the two SUs to the relay.

2. Let $n=1$ to represent the 1-th iteration. The actual energy harvested by each node after energy transfer will be $E_{1,i}^1{=}E_{1,i}^0-\delta_{1,i}^0$, $E_{2,i}^1{=}E_{2,i}^0-\delta_{2,i}^0$, $E_{R,i}^1{=}E_{R,i}^0+\eta_1\delta_{1,i}^0+\eta_2\delta_{2,i}^0$, $1\le i\le N$.

3. Let $\delta_{1,i}=0$, $\delta_{2,i}=0$, $1\le i\le N$. Note that we have consider the transferred energy in step 2, and the initialization of this step is just to give an initial value to solve **P3** and get $\{\overline{p}_{1,i},\overline{p}_{2,i},\overline{p}_{R,i}\}$. Next, we solve **P3** by the iterative water-filling algorithm to obtain $\{\overline{p}_{1,i}^1,\overline{p}_{2,i}^1\}$, where the directional water-filling in the horizontal direction is done and the energy backflow in the horizontal direction is solved.

4. Let $\{\overline{p}_{R,i}^1=E_{R,i}^1\}$. If $\log_2(1+\overline{h}_{1,i}\overline{p}_{1,i}^1)+\log_2(1+\overline{h}_{2,i}\overline{p}_{2,i}^1)<\log_2(1+\overline{h}_{R,i}\overline{p}_{R,i}^1)$, we update $\overline{p}_{R,i}^1$ by (13). Otherwise, $(\delta_{1,i}^1,\delta_{2,i}^1)$ is calculated by the

above method of (14)-(19), and let $\overline{p}_{1,i}^{1} = \overline{p}_{1,i}^{1} - \delta_{1,i}^{1}$, $\overline{p}_{2,i}^{1} = \overline{p}_{2,i}^{1} - \delta_{2,i}^{1}$, $\overline{p}_{R,i}^{1} = \overline{p}_{R,i}^{1} + \eta_1 \delta_{1,i}^{1} + \eta_2 \delta_{2,i}^{1}$. Meanwhile, the metric taps are updated as $tap_{1,i} = tap_{1,i} + \delta_{1,i}^{1}$, $tap_{2,i} = tap_{2,i} + \delta_{2,i}^{1}$.

5. The system throughput $C^1 = \sum_{i=1}^{N} \frac{W}{2} \log_2(1 + \overline{h}_{R,i} \overline{p}_{R,i}^{1})$ is obtained. Let $u = C^1 - C^0$ to represent the gain obtained by this iteration over the system throughput calculated by last time iteration. If $u > 0$, we repeat the steps 2-5 until the system throughput converges to a fixed value.

Note that when $n \geq 2$, if the maximum total throughput of the two SUs in timeslot i is less than the maximum throughput of the relay, we cannot directly update $\overline{p}_{R,i}^{n}$ by (13). Because although the relay cannot transfer energy to the two SUs, there is the energy backflow in the vertical direction. The method of energy backflow is as follows:

If $\log_2(1 + \overline{h}_{1,i} \overline{p}_{1,i}^{n}) + \log_2(1 + \overline{h}_{2,i} \overline{p}_{2,i}^{n}) < \log_2(1 + \overline{h}_{R,i} \overline{p}_{R,i}^{n})$, $tap_{1,i} > 0$ and $tap_{2,i} > 0$, the ratio of the energy backflow is determined according to (14), otherwise only the energy of the SU whose metric tap is more than zero is flowed back. This process will be carried out until $\log_2(1 + \overline{h}_{1,i} \overline{p}_{1,i}^{n}) + \log_2(1 + \overline{h}_{2,i} \overline{p}_{2,i}^{n}) = \log_2(1 + \overline{h}_{R,i} \overline{p}_{R,i}^{n})$ or the metric taps of the two SUs both equal zero. The energy of backflow is recorded as $\{y_{1,i}^{n}, y_{2,i}^{n}\}$. In this process, the two SUs will not transfer energy to the relay. Then, let $\overline{p}_{1,i}^{n} = \overline{p}_{1,i}^{n} + y_{1,i}^{n}$, $\overline{p}_{2,i}^{n} = \overline{p}_{2,i}^{n} + y_{2,i}^{n}$, $\overline{p}_{R,i}^{n} = \overline{p}_{R,i}^{n} - \eta_1 y_{1,i}^{n} - \eta_2 y_{2,i}^{n}$. If $\log_2(1 + \overline{h}_{1,i} \overline{p}_{1,i}^{n}) + \log_2(1 + \overline{h}_{2,i} \overline{p}_{2,i}^{n}) < \log_2(1 + \overline{h}_{R,i} \overline{p}_{R,i}^{n})$ is still satisfied, $\overline{p}_{R,i}^{n}$ can be simply updated by (13).

Unless the system throughput achieves the optimal value, each iteration will monotonically increase the system throughput. Meanwhile, **P3** is a convex optimization problem with a unique optimal value. If we repeat iterations many times, the convergence of the original problem is guaranteed. The detailed process can be seen in **Algorithm 1**.

Algorithm 1: Optimal Power Allocation

1. Initialize $n = 0$, $E_{1,i}^{0} = E_{1,i}$, $E_{2,i}^{0} = E_{2,i}$, $E_{R,i}^{0} = E_{R,i}$, the metric taps $tap_{1,i} = 0$, $tap_{2,i} = 0$, transferred energy $\delta_{1,i}^{0} = 0$, $\delta_{2,i}^{0} = 0$, energy of backflow $y_{1,i}^{0} = 0$, $y_{2,i}^{0} = 0$, $1 \leq i \leq N$, $C^0 = 0$, $u = 1$;
2. **while** u>0 **do**
3. $n = n + 1$;
4. Let $E_{1,i}^{n} = E_{1,i}^{n-1} - \delta_{1,i}^{n-1} + y_{1,i}^{n-1}$, $E_{2,i}^{n} = E_{2,i}^{n-1} - \delta_{2,i}^{n-1} + y_{2,i}^{n-1}$, $E_{R,i}^{n} = E_{R,i}^{n-1} + \eta_1(\delta_{1,i}^{n-1} - y_{1,i}^{n-1}) + \eta_2(\delta_{2,i}^{n-1} - y_{2,i}^{n-1})$, $1 \leq i \leq N$;
5. Initialize $\delta_{1,i} = 0$, $\delta_{2,i} = 0$, $1 \leq i \leq N$, obtain $\{\overline{p}_{1,i}^{n}, \overline{p}_{2,i}^{n}\}$ by the iterative water-filling algorithm, and let $\{\overline{p}_{R,i}^{n} = E_{R,i}^{n}\}$;
6. **for** $i = 1:N$ **do**
7. **if** $\log_2(1 + \overline{h}_{1,i} \overline{p}_{1,i}^{n}) + \log_2(1 + \overline{h}_{2,i} \overline{p}_{2,i}^{n}) < \log_2(1 + \overline{h}_{R,i} \overline{p}_{R,i}^{n})$ **do**
8. Compute $y_{1,i}^{n}$, $y_{2,i}^{n}$ by the above method of energy backflow and let $\delta_{1,i}^{n} = 0$, $\delta_{2,i}^{n} = 0$, $\overline{p}_{1,i}^{n} = \overline{p}_{1,i}^{n} + y_{1,i}^{n}$, $\overline{p}_{2,i}^{n} = \overline{p}_{2,i}^{n} + y_{2,i}^{n}$, $\overline{p}_{R,i}^{n} = \overline{p}_{R,i}^{n} - \eta_1 y_{1,i}^{n} - \eta_2 y_{2,i}^{n}$; If $\log_2(1 + \overline{h}_{1,i} \overline{p}_{1,i}^{n}) + \log_2(1 + \overline{h}_{2,i} \overline{p}_{2,i}^{n}) < \log_2(1 + \overline{h}_{R,i} \overline{p}_{R,i}^{n})$ is still satisfied, update $\overline{p}_{R,i}^{n}$ by (13);
9. **else**
10. Compute $\delta_{1,i}^{n}$, $\delta_{2,i}^{n}$ by the above method of energy transfer and let $y_{1,i}^{n} = 0$, $y_{2,i}^{n} = 0$, $\overline{p}_{1,i}^{n} = \overline{p}_{1,i}^{n} - \delta_{1,i}^{n}$, $\overline{p}_{2,i}^{n} = \overline{p}_{2,i}^{n} - \delta_{2,i}^{n}$, $\overline{p}_{R,i}^{n} = \overline{p}_{R,i}^{n} + \eta_1 \delta_{1,i}^{n} + \eta_2 \delta_{2,i}^{n}$;
11. **end if**
12. Update $tap_{1,i} = tap_{1,i} + \delta_{1,i}^{n} - y_{1,i}^{n}$, $tap_{2,i} = tap_{2,i} + \delta_{2,i}^{n} - y_{2,i}^{n}$;
13. **end for**
14. Compute $C^n = \sum_{i=1}^{N} \frac{W}{2} \log_2(1 + \overline{h}_{R,i} \overline{p}_{R,i}^{n})$;
15. $u = C^n - C^{n-1}$;
16. **end while**

IV. SIMULATION RESULTS AND ANALYSIS

The simulation parameters are set according to [7]. Assuming that the number of timeslots is $N = 20$, and the total bandwidth of the PU is $W = 2\,\text{MHz}$. The noise power spectral density of the receivers is $N_0 = 10^{-19}\,\text{W/Hz}$. At the same time, the channel fading coefficients $h_{1,i}$, $h_{2,i}$ are modeled as Rayleigh fading with mean $-110\,\text{dB}$, and $g_{1,i}$, $g_{2,i}$ with mean $-100\,\text{dB}$. Assuming that the harvested energy of the two SUs and relay in each timeslot is uniformly distributed between $[0, E_1^{\max}]$, $[0, E_2^{\max}]$ and $[0, E_R^{\max}]$.

We compare the system throughputs of the two-way energy cooperation by using **Algorithm 1**, the one-way energy cooperation where only one-way energy transfer from SU_1 to relay is allowed and the no-energy cooperation where energy transfer is not allowed.

Fig. 4 shows the system throughput comparison under different E_R^{max}, where $E_1^{max}=E_2^{max}=10\,\text{mJ}$, $I=0.4\times10^{-9}$ mW, $\eta_1=\eta_2=0.5$. When E_R^{max} is small, the gain of energy cooperation is large. With the increase of E_R^{max}, the gain of energy cooperation gradually decreases. Finally, the throughputs of different algorithms will converge to the same optimal value. In fact, when E_R^{max} is sufficiently large, the two SUs do not need to transfer energy to the relay.

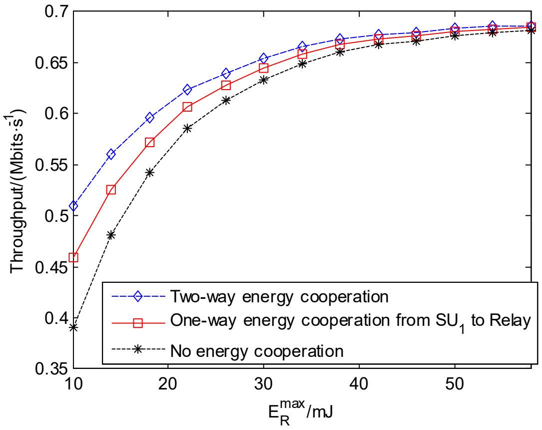

Fig. 4. System throughput comparison under different E_R^{max}

Fig. 5 shows the system throughput comparison under different interference threshold I, where $\eta_1=\eta_2=0.5$, $E_1^{max}=E_2^{max}=E_R^{max}=10\,\text{mJ}$. With the increase of I, the system throughputs of three algorithms all gradually increase. On the other hand, when I is sufficiently large, the system throughputs of three algorithms will converge to different values, because the system throughputs will be limited by the harvested energy of the two SUs and relay.

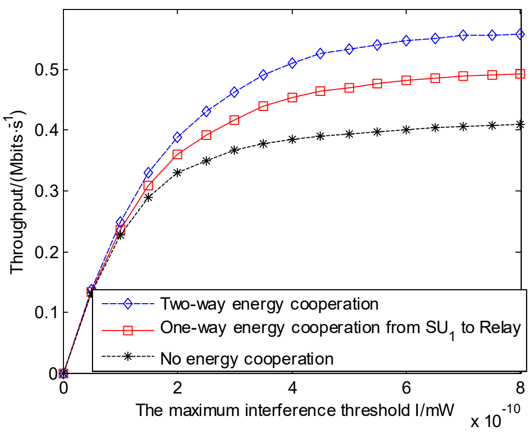

Fig. 5. System throughput comparison under different I

V. CONCLUSIONS

In this paper, a joint optimization algorithm for power allocation and energy cooperation is proposed by maximizing the system throughput. The proposed algorithm considers energy cooperation and cognitive radio technology. Firstly, we formulate the throughput maximization problem, and then decompose it into a power allocation problem and an energy transmission problem of each timeslot. For the energy backflow phenomenon in some timeslots, this paper gives the water-filling interpretation. The simulation results verify that energy cooperation can significantly improve the system throughput, especially for some energy-constrained nodes.

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