Energy Efficiency Based Resource Allocation Scheme for Cooperative Cognitive Radio Networks

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Abstract—**Cooperative communication in cognitive radio networks has been introduced as an important and efficient technique to improve the transmission performance of PUs or SUs. In this paper, we consider a cooperative cognitive radio network (CCRN) consisting of multiple primary users (PUs) and multiple secondary users (SUs), where each PU can choose one SU as its relay node. To encourage the forwarding behavior of the SUs, PUs lease a fraction of their allocated spectrum to the corresponding relay SUs, so that the SUs are capable of transmitting their own data packets. A centralized resource management architecture is introduced and an energy efficiency based relay selection and power allocation scheme is proposed for the PUs and SUs. The optimization problem is formulated and solved based on a modified Kuhn-Munkres bipartite matching algorithm. Simulation results demonstrate the effectiveness of the proposed scheme.**

I. INTRODUCTION

In the past ten years, wireless networks have had an exponential growth and various wireless network services have been witnessed. In addition to that, current static spectrum policy results in the almost exhaustion of the licensed spectrum, while a lot of licensed spectrum bands are extremely under-utilized. Cognitive radio networks (CRNs) have attracted considerable attention in recent years due to a basic idea that if a spectrum is not used by primary users (PUs), secondary users (SUs) may use it based on cognitive radio technologies [1], [2]. In addition, cooperative transmissions have been proposed as an important technique to provide better transmission performance by increasing spatial diversity. There are three types of possible cooperation in CRNs: 1) cooperation between PU peers, 2) cooperation between SU peers and 3) cooperation between PUs and SUs.

Many previous papers have discussed the possibility of using cooperative communications in CRNs in order to improve the performance of PUs or SUs. In [3], a CRN consisting of multiple source-destination pairs and relays is considered. A joint optimal channel allocation and relay assignment scheme is proposed which maximizes the minimum transmission rate among the source-destination pairs. The power allocation problem for downlink transmission in cooperative CRNs (C-CRNS) is investigated in [4] and an optimal scheme with the objective to maximize the energy efficiency of the SUs in the network is proposed.

In [5], Qiong *et al.* propose a CCRN framework in which PUs assist the transmissions of SUs and in return they receive payments from SUs. The authors in [6] investigate joint relay selection and power allocation problem in a CRN in which some relay SUs are selected to forward information for the source SUs. A two-step optimization scheme is proposed to maximize the system throughput of the SUs with minimum data rate guarantees. In [7], the authors consider a CCRN in which SUs are used as cooperative relays for the corresponding PUs, in return SUs have the opportunity to use the spare channels of the PUs to transmit their own data. A coalitional game is formulated which jointly maximize the utility of PUs and SUs.

In the works [3-6], the authors mainly focus on the performance optimization of the SUs without considering performance enhancement of the PUs. In [7], it is assumed both PUs and SUs use fixed transmit power, no optimal power allocation is considered. In this paper, we consider a CCRN consisting of multiple PUs and multiple SUs, where each PU can use one SU as its relay node, and as a reward, PUs should lease a fraction of the spectrum to the corresponding SUs so that the SUs can transmit their own information. To stress the optimal relay selection and power allocation for PUs and SUs, a centralized resource management architecture is introduced and an energy efficiency maximization based algorithm is proposed.

The rest of the paper is organized as follows. In Section II, the system model considered in this paper is described. In Section III, we describe the centralized resource management architecture. In Section IV, the energy efficiency optimization problem is formulated. The problem solving procedure is discussed in section V. Simulation results are presented in Section VI. Finally, we conclude this paper in Section VII.

II. SYSTEM MODEL

In this paper, we consider a CCRN consisting of multiple PUs, multiple SUs, one primary base station (PBS) and one secondary BS (SBS). Assume PUs are allocated non-overlapping spectrum, hence are allowed to transmit to the PBS simultaneously in a frequency division multiple access (FDMA) manner. Further, assume that PUs may transmit to the PBS in direct transmission mode or in one-hop relay transmission mode, while the relay SUs may also transmit their own data packets to the SBS. Fig. 1 shows the system model considered in this paper.

To encourage SUs to forward data packets for the PUs, we propose a spectrum leasing scheme in this paper. More specifically, the PUs lease a part of their allocated spectrum to their corresponding relay SUs so that the relay SUs can transmit their own data packets to the SBS on the part of the spectrum. In order to forward data packets for PUs and to transmit their own information, the transmit power of the SUs is divided into two portions correspondingly.

Let M and K denote the number of PUs and the number of SUs, respectively, B_m denote the allocated bandwidth of the mth PU, ρ_m denote the spectrum fraction of the mth PU for transmitting the data packets of the PU in the relay transmission mode, and as a consequence $1-\rho_m$ is the remaining spectrum available for the relay SU to transmit its own data to the SBS, $0 \leq \rho_m \leq 1$, $1 \leq m \leq M$. To support relay transmission, the transmission time slot T is divided into two equal periods. For the first $\frac{T}{2}$ time period, the PUs transmit their data packets to the corresponding relay SUs, then the SUs forward the received data packets to the PBS during the second $\frac{T}{2}$ time period. The bandwidth allocated for both transmission is $\rho_m B$. Meanwhile, the SUs transmit their own data packets to the SBS on the bandwidth $(1-\rho_m)B$ for the total T time period. Fig. 2 shows the time and spectrum division mode for relay transmission of the mth PU.

As each PU may choose direct transmission mode or relay transmission mode. In the case of multiple relay SUs being available, the optimal relay selection scheme should be designed. Furthermore, for each PU-SU pair, the transmit power of the PU and the transmit power of the relay SU should be designed in an optimal manner in order to achieve the performance optimization of the network. The detail algorithm will be discussed in follow sections.

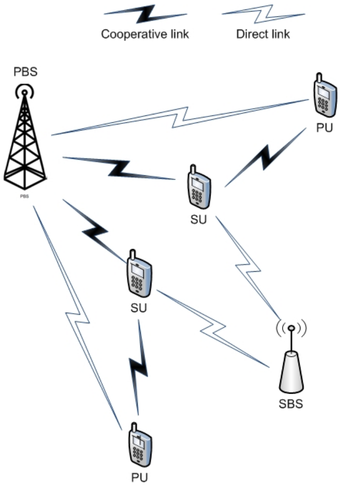

Fig. 1. System model

III. Proposed Architecture for CCRN

In CCRN, one of the goals is to use the available spectrum resources in an efficient and coordinated way to guarantee a satisfied level of QoS for all users and achieve performance enhancement of the whole network. To this end, in this section, we propose a centralized resource management network architecture consisting of a number of user resource management entities (URMEs), local resource management entities (LRMEs), and one global resource management entities (GRME), as shown in Fig. 3. The main functions of UMREs, LRMEs and GRME are described as follows.

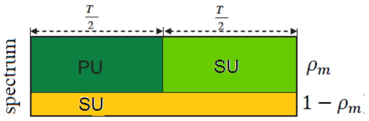

Fig. 2. Bandwidth allocation for PU and SU

URME: functional module embedded in each PU and SU, used to store channel state information, device characteristics and service requirements, etc. Through contacting associated LRMEs, URMEs send the collected information to the network and receive the resource allocation strategy accordingly.

LRME: deployed in each PBS or SBS, being responsible for managing local resource status through interacting with the associated URMEs and the GRME. More specifically, receiving the network and service information from URMEs and then forwarding to the GRME, and receiving the resource management strategy from the GRME and forwarding to the URMEs.

GRME: deployed over the considered network. Through interacting with the LRME, the GMRE receives the network status, channel state information and user service requirement information, conducts the proposed resource allocation and relay selection algorithm to obtain the optimal strategy, and send back sent to the associated LRMEs.

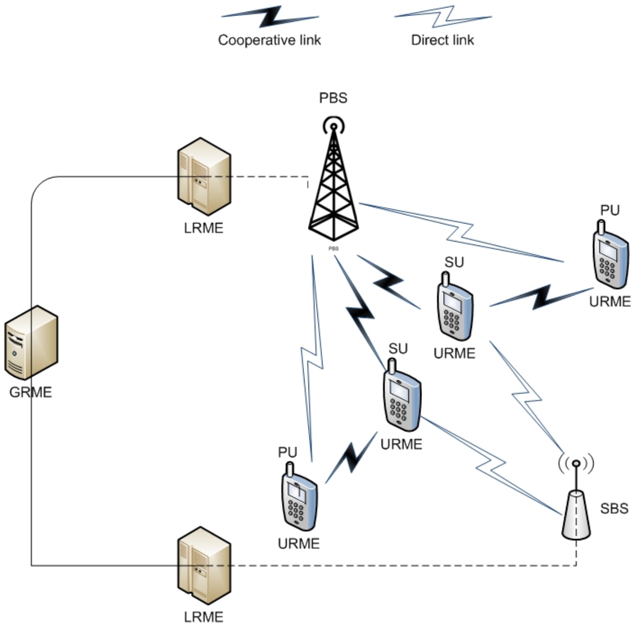

Fig. 3. Proposed architecture

IV. PROPOSED JOINT RESOURCE ALLOCATION AND RELAY SELECTION SCHEME

In this section, we present the expression of the total energy efficiency of the PUs and SUs, and the constraints of power allocation and relay selection, then formulate the energy efficiency maximization problem as an optimization problem.

The total energy efficiency of the PUs and the SUs can be formulated as:

$$\eta = \eta^{(\mathrm{p})} + \eta^{(\mathrm{s})}, \tag{1}$$

where $\eta^{(\mathrm{p})}$ and $\eta^{(\mathrm{s})}$ denote respectively the energy efficiency of the PUs and SUs, which will be expressed in the following subsections.

A. Energy Efficiency of PUs

The energy efficiency of all the PUs can be expressed as:

$$\eta^{(\mathrm{p})} = \sum_{m=1}^{M} \eta_m^{(\mathrm{p})}, \tag{2}$$

where $\eta_m^{(\mathrm{p})}$ denotes the energy efficiency of the mth PU. As PUs may choose direct transmission or cooperative transmission through a relay SU for information transmission to the PBS, the energy efficiency of the mth PU can be calculated as:

$$\eta_m^{(\mathrm{p})} = \beta_m^{(\mathrm{d})} \eta_m^{(\mathrm{p,d})} + \sum_{k=1}^{K} \beta_{m,k}^{(\mathrm{c})} \eta_{m,k}^{(\mathrm{p,c})}, \tag{3}$$

where $\eta_m^{(\mathrm{p,d})}$ denotes the energy efficiency of the mth PU when using direct mode, $\beta_m^{(\mathrm{d})}$ denotes the transmission variable of the mth PU for the direct mode. More specifically, if $\beta_m^{(\mathrm{d})} = 1$, the mth PU uses direct transmission mode, $\beta_m^{(\mathrm{d})} = 0$, otherwise, $\eta_{m,k}^{(\mathrm{p,c})}$ denotes the energy efficiency of the mth PU when using the kth SU as relay node for cooperative transmission mode, and $\beta_{m,k}^{(\mathrm{c})}$ denotes the corresponding transmission and relay selection variable, i.e., $\beta_{m,k}^{(\mathrm{c})} = 1$ represents that the mth PU uses the kth SU as relay node for cooperative transmission, $\beta_{m,k}^{(\mathrm{c})} = 0$, otherwise. In the following subsections, we will discuss the expression of $\eta_m^{(\mathrm{p,d})}$ and $\eta_{m,k}^{(\mathrm{p,c})}$, respectively.

1) Direct Mode:

1) Direct Mode: The energy efficiency of the mth PU in direct mode, i.e., $\eta_m^{(\mathrm{p,d})}$ can be calculated as:

$$\eta_m^{(\mathrm{p,d})} = \frac{R_m^{(\mathrm{p,d})}}{P_m^{(\mathrm{p,d})} + P_{\mathrm{c}}^{(\mathrm{p})}}, \tag{4}$$

where $P_m^{(\mathrm{p,d})}$ denotes the power consumed by the mth PU when transmitting in direct mode, $P_{\mathrm{c}}^{(\mathrm{p})}$ denotes the circuit power of the mth PU, which is assumed to be a constant for all the PUs in this paper, and $R_m^{(\mathrm{p,d})}$ denotes the data rate achieved by the mth PU in direct mode, which can be expressed as:

$$R_m^{(\mathrm{p,d})} = B \log_2 \left(1 + \frac{P_m^{(\mathrm{p,d})} h_m^{(\mathrm{p,d})}}{\sigma^2} \right), \tag{5}$$

where B denotes the bandwidth of the mth PU, $h_m^{(\mathrm{p,d})}$ denotes the channel gain of the link between the mth PU and the PBS, and σ^2 denotes the noise power of the link between the mth PU and the PBS. For convenience, the noise power of all the transmission links are assumed to be the same in this paper.

2) Relay Mode: The energy efficiency of the mth PU when using the kth SU as relay node for cooperative transmission, denoted by $\eta_{m,k}^{(\mathrm{p,c})}$, can be expressed as:

$$\eta_{m,k}^{(\mathrm{p,c})} = \frac{R_{m,k}^{(\mathrm{p,c})}}{P_{m,k}^{(\mathrm{p,c})}}, \tag{6}$$

where $R_{m,k}^{(\mathrm{p,c})}$ and $P_{m,k}^{(\mathrm{p,c})}$ denote respectively the data rate and power consumption of the mth PU when using the kth SU as relay node for cooperative transmission. In this paper, we assume that decode-and-forward (DF) scheme is applied at each relay node, $R_{m,k}^{(\mathrm{p,c})}$ can be expressed as:

$$R_{m,k}^{(\mathrm{p,c})} = \min(R_{m,k}^{(\mathrm{p,s})}, R_{m,k}^{(\mathrm{p,r})}), \tag{7}$$

where $R_{m,k}^{(\mathrm{p,s})}$ and $R_{m,k}^{(\mathrm{p,r})}$ denote the data rate of the link from the mth PU to the kth SU and that from the kth SU to the PBS when the kth SU is chosen as the relay node of the mth PU. $R_{m,k}^{(\mathrm{p,s})}$ in (7) can be calculated as:

$$R_{m,k}^{(\mathrm{p,s})} = \frac{1}{2} \rho_m B \log_2 \left(1 + \frac{P_{m,k}^{(\mathrm{p,s})} h_{m,k}^{(\mathrm{p,s})}}{\sigma^2} \right), \tag{8}$$

where $P_{m,k}^{(\mathrm{p,s})}$ denotes the transmit power of the mth PU when transmitting to the kth SU in cooperative mode, $h_{m,k}^{(\mathrm{p,s})}$ denotes the transmission gain of the link between the mth PU and the kth SU. $R_{m,k}^{(\mathrm{p,r})}$ in (7) can be expressed as:

$$R_{m,k}^{(\mathrm{p,r})} = \frac{1}{2} \rho_m B \log_2 \left(1 + \frac{P_{m,k}^{(\mathrm{p,r})} h_{m,k}^{(\mathrm{p,r})}}{\sigma^2} \right), \tag{9}$$

where $P_{m,k}^{(\mathrm{p,r})}$ denotes the transmit power of the kth SU when forwarding data packets for the mth PU, and $h_{m,k}^{(\mathrm{p,r})}$ denotes the channel gain of the link between the kth SU and the PBS.

$P_{m,k}^{(\mathrm{p,c})}$ in (6) can be calculated as:

$$P_{m,k}^{(\mathrm{p,c})} = P_{m,k}^{(\mathrm{p,s})} + P_{m,k}^{(\mathrm{p,r})} + P_{\mathrm{c}}^{(\mathrm{p})} + P_{\mathrm{c}}^{(\mathrm{s})}, \tag{10}$$

where $P_{\mathrm{c}}^{(\mathrm{s})}$ denotes the circuit power consumption of the SU which is assumed to be a constant for all the SUs.

B. Energy Efficiency of SUs

The energy efficiency of all the SUs in the CCRN, denoted by $\eta^{(\mathrm{s})}$ in (1), can be calculated as:

$$\eta^{(\mathrm{s})} = \sum_{m=1}^{M} \sum_{k=1}^{K} \beta_{m,k}^{(\mathrm{c})} \eta_{m,k}^{(\mathrm{s})}, \tag{11}$$

where $\eta_{m,k}^{(\mathrm{s})}$ denotes the energy efficiency of the kth SU when transmitting its own data on the subchannel leased by the mth PU, which can be calculated as:

$$\eta_{m,k}^{(\mathrm{s})} = \frac{R_{m,k}^{(\mathrm{s})}}{P_{m,k}^{(\mathrm{s})} + P_{\mathrm{c}}^{(\mathrm{s})}}, \tag{12}$$

where $R^{(\mathrm{s})}_{m,k}$ and $P^{(\mathrm{s})}_{m,k}$ denote the data rate and the transmit power of the kth SU when transmitting its own data on the subchannel leased by the mth PU. $R^{(\mathrm{s})}_{m,k}$ can be expressed as:

$$R^{(\mathrm{s})}_{m,k} = (1-\rho_m) B \log_2 \left(1 + \frac{P^{(\mathrm{s})}_{m,k} h^{(\mathrm{s})}_{m,k}}{\sigma^2} \right), \tag{13}$$

where $h^{(\mathrm{s})}_{m,k}$ denotes the channel gain between the kth SU and its destination.

C. Optimization Constraints

1) Transmission Variables Constraint: It is assumed in this paper that every PU can only choose direct transmission mode or cooperative transmission mode. For cooperative transmission, each PU can only select one SU as its relay node, and each SU can only forward data packets for one PU, hence, we can obtain the constraints on the transmission and relay selection variables:

$$\beta^{(d)}_m + \sum_{k=1}^{K} \beta^{(c)}_{m,k} \le 1, \tag{14}$$

$$\sum_{m=1}^{M} \beta^{(c)}_{m,k} \le 1. \tag{15}$$

2) Maximum Power Constraint: The transmit power of both PUs and SUs should meet their maximum power constraint. Denoting $P^{(\mathrm{p,max})}_m$ and $P^{(\mathrm{s,max})}_k$ as the maximum transmit power of the mth PU and the kth SU, respectively, we can obtain following constraints:

$$P^{(\mathrm{p,d})}_m \le P^{(\mathrm{p,max})}_m, \tag{16}$$

$$P^{(\mathrm{p,s})}_{m,k} \le P^{(\mathrm{p,max})}_m, \tag{17}$$

$$P^{(\mathrm{p,r})}_{m,k} + P^{(\mathrm{s})}_{m,k} \le P^{(\mathrm{s,max})}_k. \tag{18}$$

3) Data Rate Constraint: The data transmission of each PU and SU may subject to certain data rate constraint. Denoting $R^{(p,\mathrm{min})}_m$ and $R^{(s,\mathrm{min})}_k$ as the minimum data rate of the mth PU and the kth SU, respectively, we can obtain following optimization constraints: In order for the cooperation to be possible a certain data rate requirement should be met. In case of PU transmission assisted by a relaying SU, data rates of both links of the transmission have to meet the data rate requirement. Denoting $R^{(p,min)}_m$ the minimum data rate requirement for every PU, we can formulate the data rate constraint as:

$$R^{(\mathrm{p,d})}_m \ge R^{(\mathrm{p,min})}_m, \quad \text{if} \quad \beta^{(\mathrm{d})}_m = 1, \tag{19}$$

$$R^{(\mathrm{p,s})}_{m,k} \ge R^{(\mathrm{p,min})}_m, \quad \text{if} \quad \beta^{(\mathrm{c})}_{m,k} = 1, \tag{20}$$

$$R^{(\mathrm{p,r})}_{m,k} \ge R^{(\mathrm{p,min})}_m, \quad \text{if} \quad \beta^{(\mathrm{c})}_{m,k} = 1, \tag{21}$$

$$R^{(\mathrm{s})}_{m,k} \ge R^{(\mathrm{s,min})}_{m,k}, \quad \text{if} \quad \beta^{(\mathrm{c})}_{m,k} = 1. \tag{22}$$

D. Optimization Problem Formulation

The energy efficiency based resource allocation and relay selection scheme can be formulated as the following optimization problem:

$$\begin{aligned} &\max_{\beta^{(\mathrm{d})}_m, \beta^{(\mathrm{c})}_{m,k}, P^{(\mathrm{p,d})}_m, P^{(\mathrm{p,s})}_{m,k}, P^{(\mathrm{p,r})}_{m,k}, P^{(\mathrm{s})}_{m,k}} \eta \\ \text{s. t.}\ \ &\mathrm{C1}: \ \beta^{(d)}_m + \sum_{k=1}^{K} \beta^{(c)}_{m,k} \le 1, \quad m = 1, 2 ..., M \\ &\mathrm{C2}: \ \sum_{m=1}^{M} \beta^{(c)}_{m,k} \le 1, \\ &\mathrm{C3}: \ P^{(\mathrm{p,d})}_m \le P^{(\mathrm{p,max})}_m, \\ &\mathrm{C4}: \ P^{(\mathrm{p,s})}_{m,k} \le P^{(\mathrm{p,max})}_m, \\ &\mathrm{C5}: \ P^{(\mathrm{p,r})}_{m,k} + P^{(\mathrm{s})}_{m,k} \le P^{(\mathrm{s,max})}_k, \\ &\mathrm{C6}: \ R^{(\mathrm{p,d})}_m \ge R^{(\mathrm{p,min})}_m, \quad \text{if} \quad \beta^{(\mathrm{d})}_m = 1, \\ &\mathrm{C7}: \ R^{(\mathrm{p,s})}_{m,k} \ge R^{(\mathrm{p,min})}_m, \quad \text{if} \quad \beta^{(\mathrm{c})}_{m,k} = 1, \\ &\mathrm{C8}: \ R^{(\mathrm{p,r})}_{m,k} \ge R^{(\mathrm{p,min})}_m, \quad \text{if} \quad \beta^{(\mathrm{c})}_{m,k} = 1, \\ &\mathrm{C9}: \ R^{(\mathrm{s})}_{m,k} \ge R^{(\mathrm{s,min})}_{m,k}, \quad \text{if} \quad \beta^{(\mathrm{c})}_{m,k} = 1. \end{aligned} \tag{23}$$

V. SOLUTION OF THE OPTIMIZATION PROBLEM

The optimization problem formulated in (23) is a nonlinear binary fractional problem, which cannot be solved conveniently using traditional optimization methods. From the optimization optimization constraints given in (23), it can be proved that the optimization problem (23) can be transformed equivalently into two subproblems, i.e., power allocation subproblem, and transmission mode and relay selection subproblem.

A. Power Allocation Subproblem

Assuming that the mth PU selects direct transmission mode, i.e., $\beta^{(\mathrm{d})}_m = 1$, the energy efficient optimal power allocation problem can be formulated as:

$$\begin{aligned} &\max_{P^{(\mathrm{p,d})}_m} \eta^{(\mathrm{p,d})}_m \\ \text{s. t.}\ \ &\mathrm{C1}: \ P^{(\mathrm{p,d})}_m \le P^{(\mathrm{p,max})}_m, \\ &\mathrm{C2}: \ R^{(\mathrm{p,d})}_m \ge R^{(\mathrm{p,min})}_m. \end{aligned} \tag{24}$$

For a given range of $P^{(\mathrm{p,d})}_m$, i.e. $0 < P^{(\mathrm{p,d})}_m \le P^{(\mathrm{p,max})}_m$, the optimal power of the mth PU can be obtained through solving above problem via optimization techniques or numerical methods [8]. The corresponding optimal energy efficiency of the mth PU when using direct mode can then be obtained, which is denoted as $\eta^{*}_m, \ 1 \le m \le M$.

For the cooperative transmission mode, we assume that the mth PU selects the kth SU as its relay node, i.e., $\beta^{(\mathrm{c})}_{m,k} = 1$, the energy efficiency of the pair of PU-SU can be expressed as

$$\eta^{(\mathrm{p,c})}_{m,k} + \eta^{(\mathrm{s})}_{m,k}. \tag{25}$$

The energy efficient optimal power allocation problem for the mth PU and the kth SU can be formulated as:

$$\max_{P_{m,k}^{(\mathrm{p,s})},P_{m,k}^{(\mathrm{p,r})},P_{m,k}^{(\mathrm{s})}} \eta_{m,k}^{(\mathrm{p,c})}+\eta_{m,k}^{(\mathrm{s})} \tag{26}$$

$$\begin{aligned} \text{s. t.}\;\; &\mathrm{C1}: \; P_{m,k}^{(\mathrm{p,s})} \le P_{m}^{(\mathrm{p,max})}, \\ &\mathrm{C2}: \; P_{m,k}^{(\mathrm{p,r})}+P_{m,k}^{(\mathrm{s})} \le P_{k}^{(\mathrm{s,max})}, \\ &\mathrm{C3}: \; R_{m,k}^{(\mathrm{p,s})} \ge R_{m}^{(\mathrm{p,min})}, \\ &\mathrm{C4}: \; R_{m,k}^{(\mathrm{p,r})} \ge R_{m}^{(\mathrm{p,min})}, \\ &\mathrm{C5}: \; R_{m,k}^{(\mathrm{s})} \ge R_{m,k}^{(\mathrm{s,min})}. \end{aligned}$$

Following similar optimization method as in direct transmission mode, above optimization problem can be solved to obtain the optimal power of the PU-SU pairs and the corresponding energy efficiency. For convenience, we denote $\eta_{m,k}^{*}$ as the optimal energy efficiency of the mth PU and the kth SU pair, $1 \le m \le M$, $1 \le k \le K$.

B. Transmission Mode and Relay Selection Subproblem

1) Subproblem Formulation: Given the optimal transmit power of the PUs and the SUs, the total energy efficiency of the network can be calculated as:

$$\eta^{*}=\sum_{m=1}^{M}\sum_{k=1}^{K}(\beta_{m}^{(\mathrm{d})}\eta_{m}^{*}+\beta_{m,k}^{(\mathrm{c})}\eta_{m,k}^{*}) \tag{27}$$

The transmission mode and relay selection subproblem can be formulated as:

$$\max_{\beta_{m}^{(\mathrm{d})},\beta_{m,k}^{(\mathrm{c})}} \eta^{*} \tag{28}$$

$$\begin{aligned} \text{s. t.}\;\; &\mathrm{C1}: \; \beta_{m}^{(d)}+\sum_{k=1}^{K}\beta_{m,k}^{(c)} \le 1, \\ &\mathrm{C2}: \; \sum_{m=1}^{M}\beta_{m,k}^{(c)} \le 1. \end{aligned}$$

The optimization formulated in (28) is a linear binary optimization problem, which can be solved using graph-based optimization method. To illustrate above optimization problem, we construct the following optimal energy efficiency table, in which the direct mode column denotes the maximum energy efficiency obtained when the mth PU chooses direct transmission mode, the other columns represent the optimal energy efficiency obtained when the mth PU chooses the kth SU as relay node for cooperation transmission mode.

It can be seen that to obtain the optimal transmission mode and relay selection solution of (28) is equivalent to finding the maximum sum of the energy efficiency elements which are chosen from various rows and columns, except for the direct mode. From (28), we can see that in the case that the energy efficiency of the mth PU obtained in direct mode is larger than all of the energy efficiency of the PU obtained in cooperative mode, the PU should choose the direct mode. Hence, to solve the optimization problem formulated in (28), for the mth row, $1 \le m \le M$, we first compare the element in direct mode with the other elements in the same row, if the energy efficiency of the PU obtained in direct mode is the largest, then we set $\beta_{m}^{(\mathrm{d})}=1$, $\beta_{m,k}^{(\mathrm{c})}=0$, and delete the corresponding row in Table I. For the remaining table, we can temporarily ignore the direct mode column, solve the optimal relay selection subproblem for cooperation transmission mode.

Given the constraints on both PUs and SUs, the optimal relay selection subproblem can be described as a bipartite graph and the problem of finding the optimal relay can be regarded as an optimal matching algorithm in the bipartite graph and can be solved based on the typical algorithm such as modified Kuhn-Munkres (K-M) algorithm.

TABLE I
FINAL MATRIX

	Direct mode	Cooperation with SU$_1$	Cooperation with SU$_2$	$\cdots$	Cooperation with SU$_K$
PU$_1$	η_1^*	$\eta_{1,1}^*$	$\eta_{1,2}^*$	$\cdots$	$\eta_{1,K}^*$
PU$_2$	η_2^*	$\eta_{2,1}^*$	$\eta_{2,2}^*$	$\cdots$	$\eta_{2,K}^*$
$\cdots$		$\cdots$			$\cdots$
PU$_M$	η_M^*	$\eta_{M,1}^*$	$\eta_{M,2}^*$	$\cdots$	$\eta_{M,K}^*$

TABLE II
COOPERATIVE MODE MATRIX

	Cooperation with SU$_1$	Cooperation with SU$_2$	$\cdots$	Cooperation with SU$_K$
PU$_1$	$\eta_{1,1}^*$	$\eta_{1,2}^*$	$\cdots$	$\eta_{1,K}^*$
PU$_2$	$\eta_{2,1}^*$	$\eta_{2,2}^*$	$\cdots$	$\eta_{2,K}^*$
$\cdots$	$\cdots$			$\cdots$
PU$_M$	$\eta_{M,1}^*$	$\eta_{M,2}^*$	$\cdots$	$\eta_{M,K}^*$

2) Introduction to K-M Algorithm: In the following, we briefly introduce some definitions and a theorem regarding the K-M algorithm before we apply it.

Bipartite: A bipartite graph is a graph whose vertices can be divided into two disjoint sets U and V, such that every edge connects a vertex in U to one in V. It can be represented as: $G=(U,V,E)$ with E denoting the edges of the graph.

Weighted bipartite: A weighted bipartite is a bipartite in which each edge (u,v) has a weight factor $w(u,v)$.

Matching: A matching in a graph is a subset $H \subseteq E$. If H and G share the same vertex set, then H is called a complete matching. The size of a matching is denoted as $|H|$ which equals to the number of edges in H.

Feasible vertex labeling: A feasible vertex labeling in G is a real-valued function l on $U \cup V$ such that for $u \in U$ and $v \in V$,

$$l(u)+l(v) \ge w(u,v) \tag{29}$$

Equality subgraph: If l is a feasible labeling, we denote a subgraph of G as G_l which contains a number of edges and the endpoints of these edges. If the edges of G_l meet the condition $l(u)+l(v) \ge w(u,v)$, then G_l is called the equality subgraph for l.

Theorem: If l is a feasible vertex labeling for G, and H is a complete matching of U to V with $H \subseteq G_l$, then H is an optimal assignment of U to V.

3) Solving Optimal Relay Selection Problem Based on K-M Algorithm: Applying K-M algorithm to solve the optimal relay selection problem of the PUs, a weighted bipartite graph G with a bipartite division $G^0 = (U, V, E)$ is constructed, where the set of vertices U represents the set of PUs, i.e., $U = [\mathrm{PU}_1, \mathrm{PU}_2, ..., \mathrm{PU}_M]$ and the set of vertices V represents the set of SUs, $V = [\mathrm{SU}_1, \mathrm{SU}_2, ..., \mathrm{SU}_K]$. The weight of the edge $(\mathrm{PU}_m, \mathrm{SU}_k)$ in the weighted bipartite graph can be defined as the joint energy efficiency of the mth PU and the kth SU, i.e., $\eta_{m,k}^{(\mathrm{p,c})} + \eta_{m,k}^{(\mathrm{s})}$, $m = 1, 2..., M$ and $k = 1, 2..., K$.

The steps of solving the optimal relay selection problem based on K-M algorithm can be described as follows:

1) Find initial feasible vertex labeling and determine G_l^0. A distribution of H is selected in G_l^0.
2) If H is perfect, then the optimization problem is solved. Otherwise, the label having not being allotted by the distribution H is selected in G_l^0. Set $S = U$, and T=Φ.
3) $N_{G_l^0}(S)$ denotes the collection of points which connect with S in G_l^0. If $N_{G_l^0}(S) \neq T$, go to step 2). Otherwise, $N_{G_l^0}(S) = T$. Find

$$\Delta = \min(l(u) + l(v) \geq w(u, v) | u \in S, v \in V - T) \tag{30}$$

and replace existing labeling l with l' by

$$l'(u) = \begin{cases} l(u) - \Delta, & u \in S \\ l(u) + \Delta, & u \in T \\ l(u), & \text{others} \end{cases}$$

Note that $\Delta > 0$ and $N_{G_l^0}(S) \neq T$. Replacing l by l', and G_l^0 with $G_{l'}^0$.

The process continues until an equal subgraph consisting complete match is obtained.

Based on the optimal relay selection results, we obtain the corresponding energy efficiency for cooperation mode, which is compared with that obtained from direct mode for each PU, if the latter is larger, we set the transmission mode of the corresponding PU as direct mode and re-conduct K-M algorithm, until the optimal energy efficiency obtained for cooperative mode is larger than that from direct mode for all the PUs. In Table II, we present a brief description of the main algorithm.

VI. NUMERICAL RESULTS

In this section, we evaluate the performance of the proposed algorithm via numerical simulations based on Matlab. In the simulation, we consider an area 100m x 100m with 10 PUs and 10 SUs randomly located, and one PBS and one SBS being deployed at fixed position. The bandwidth B is set to be 1.5MHz and the power of noise is $\sigma^2 = 10^{-10}$. In addition, we set $\rho_m = 0.66$, $1 \leq m \leq M$, because in this way we will have the same fraction of bandwidth for every transmission link, i.e., from the source PUs to relay SUs, from the relay SUs to the PBS and from the SUs to the SBS. The circuit power for PUs is set to be 0.4W and the one for SUs is set at 0.5W.

TABLE III
OPTIMAL MATCHING ALGORITHM

```
Algorithm 1 Optimal Transmission Model
            and Relay Selection Algorithm
Solving optimal power allocation subproblem
to obtain $\eta_m^*$ and $\eta_{m,k}^*$, construct Table I
for the $m$th PUs
    if $\eta_m^* > \eta_{m,k}^*, \forall\ 1 \leq k \leq K$
        then
            set $\beta_m^{(\mathrm{p,d})} = 1$
            delete the $m$th row in Table I
        end
    end
Obtain Table II through removing direct mode
column of Table I
repeat
Apply K-M algorithm on Table II to find
optimal relay node
obtaining $\beta_{m,k}^{(c)}$
if
$\beta_{m,k}^{(c)}\eta_{m,k}^* < \eta_m^*,\ 1 \leq m \leq M$
        set $\beta_m^{(p,d)} = 1$
        set $\beta_{m,k}^{(c)} = 0$
Update Table II through removing the $m$th row
        end
        until $\beta_{m,k}^{(c)}\eta_{m,k}^* > \eta_m^*, \forall$ PU$_m$ in Table II.
```

In Fig. 4 and Fig. 5, we examine the total energy efficiency of the network through summing up the energy efficiency of all the 10 PUs and 10 SUs. The results are averaged over 1000 random generations of the positions of the PUs and SUs. Fig. 4 shows the total energy efficiency of the network versus the maximum power of PUs and SUs. For a given maximum transmit power of all the PUs and SUs, we calculate the total energy efficiency obtained from our proposed algorithm. We also consider the case that only direct transmission mode is applied at every PU. It can be seen from the figure that the proposed algorithm outperforms the direct transmission case, this is because being able to choose between cooperative mode and direct mode improves the performance of the network in a considerable amount.

Fig. 5 shows the energy efficiency of the network versus the number of PUs. To plot both curves, we apply power optimization for all the PUs and SUs. To examine the performance of relay selection, we plot the results obtained from our proposed optimal relay selection method based on K-M algorithm, and those obtained from random choice algorithm in which the cooperative relays are selected randomly. It can be seen that the proposed algorithm offers a better performance in comparison with the random choice algorithm.

In Fig. 6 and Fig. 7, we focus on one pair of PU and SU and examine the impacts of power optimization on energy efficiency. The results are averaged over 1000 random

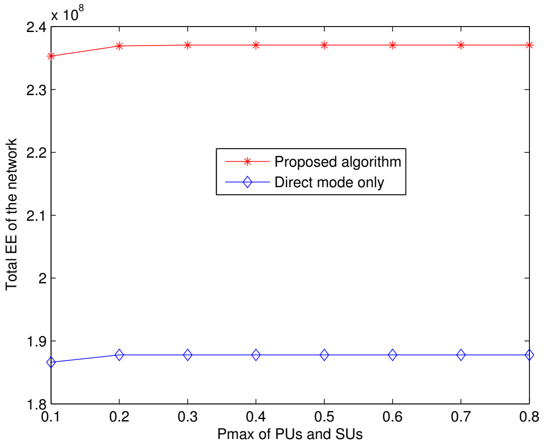

Fig. 4. Energy efficiency versus the maximum power of PUs and SUs

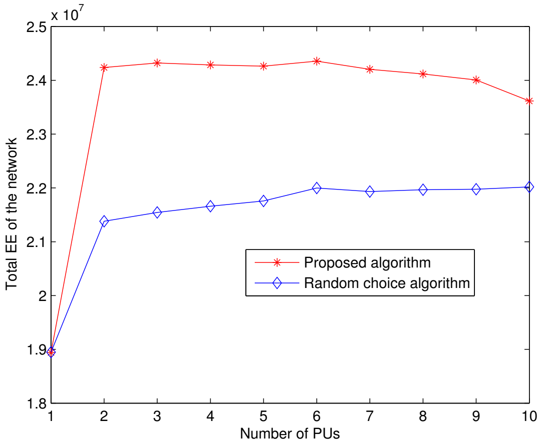

Fig. 5. Energy efficiency versus the number of PUs

generations of the position of the PU-SU pair. Fig. 6 plots the energy efficiency of the PU-SU pair versus the maximum power of the SU We consider the case that the transmit power of the PU is kept at the optimal level and that the transmit power of the PUs is fixed as a constant 0.8W. For both cases, we optimize the transmit power of the SU for both the relay link and the link from the SU to the SBS to obtain the total energy efficiency of the PU and the SU. It can be seen from the figure that the energy efficiency first increases with the increase of the maximum transmit power of the SU, then after achieving an optimal value, the energy efficiency does not change anymore no matter how big is the maximum power available for the SU. Comparing the two curves, we can see that the one with optimal transmit power of the PU achieves larger energy efficiency compared to that from fixed power case, this shows the impacts of the transmit power of the PU on the energy efficiency.

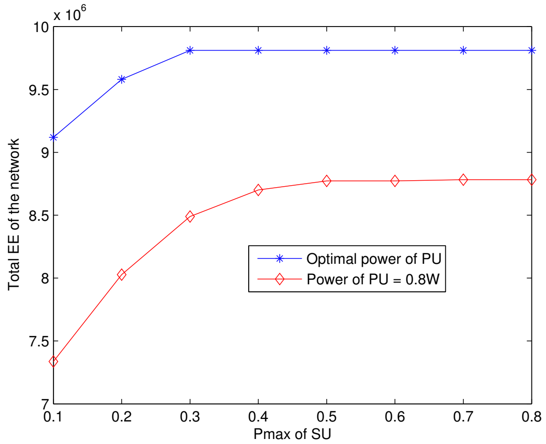

Fig. 6. Total energy efficiency when PU power is kept optimal

In Fig. 7, we plot similar result as Fig. 6 except that we vary the maximum power of the PU from 0.1 to 0.8. We consider the cases that the transmit power of the SU for both relay link and the link from the SU to the SBS is kept at the optimal level, and that the transmit power of the SU on the link from the SU to the SBS is fixed as a constant 0.4W. For both cases, the maximum transmit power of the SU is fixed as 0.8W. It can be seen from the figure that the one with optimal transmit power of the SU offers better performance on energy efficiency compared to that from fixed power case.

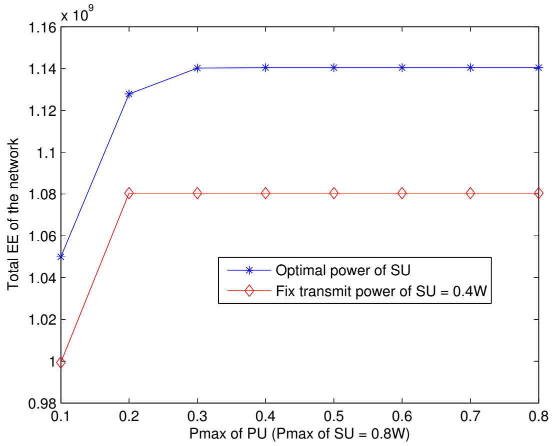

Fig. 7. Total energy efficiency when SU power is kept optimal

VII. CONCLUSIONS

In this paper, we consider a CCRN consisting of multiple PUs and SUs, in which each PU may select one SU as its relay node. To conduct optimal resource allocation for PUs and SUs, a centralized resource management architecture is introduced and an energy efficiency based relay selection and power allocation scheme is proposed. The optimization problem is formulated and solved based on a modified K-M algorithm. Simulation results demonstrate the performance of the network can be enhanced through allowing cooperation between the PUs and SUs. In addition, joint power allocation and relay selection offers better performance compared to fixed transmit power and random relay selection case.

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