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Energy efficient relay selection and power allocation for cooperative cognitive radio networks

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Abstract: Owing to environmental, financial and quality of service (QoS) considerations, energy efficient wireless communications have been paid increasing attention under the background of limited energy resource. This study considers a spectrum sharing cognitive radio network, where the primary system leases its radio spectrum to the secondary system for a fraction of time in exchange for secondary users served as relays to assist the transmission of the primary traffic. Based on the cooperative spectrum leasing protocol, the authors formulate a joint optimisation of relay selection and power allocation under QoS requirements to improve energy efficiency (EE). By employing a greedy spectrum sharing (GSS) algorithm, the optimal relay selection, power and sharing time allocation are readily obtained. Monte–Carlo simulations are performed to demonstrate that significant EE improvement is achieved by the proposed GSS algorithm, and that the network performance is enhanced.

1 Introduction

The ever-emerging wireless services and applications have made the scarce radio spectrum more crowded [1]. In this regard, cognitive radio (CR) has been chosen as a promising solution to realise efficient utilisation of the frequency resource, owing to its capabilities of sensing the surrounding radio environment and adjusting the transmission parameters [2–4]. At the same time, cooperative relaying has been recognised as a crucial physical layer technique to exploit space diversity by forming 'virtual array' through distributed transmission and signal processing [5, 6]. The combination of CR and cooperative relaying has recently spawned a new paradigm between primary and secondary systems, where the primary user (PU) leases its operating band to the secondary users (SUs) for a fraction of time to transmit their own traffic in exchange for the SUs served as relays to assist the transmission of primary traffic [7–12]. As a result, the performance of both primary and secondary systems is improved, and thus, a 'win–win' situation is achieved.

With explosive growth of high-data-rate applications, more and more energy is consumed in wireless networks to guarantee quality of service (QoS). Therefore energy efficient communications have been paid increasing attention under the background of limited energy resource and environmental-friendly transmission behaviours [13]. In a nutshell, energy efficiency (EE) has become an important design goal for wireless systems [14–19]. Su *et al.* in [14] proposed a cooperation-based spectrum leasing protocol to reduce the energy consumption of PUs and enhance the throughput of SUs in a heterogenous cognitive Ad-hoc network. Wang *et al.* in [15] considered a power trading business model based on game theory for maximising the throughput of PU and EE of SU. Lim *et al.* in [16] proposed a spectrum sharing strategy via multi-winner auction with multiple bands to increase the throughput of secondary system under the constraint of minimum EE requirement for primary system. Liu *et al.* in [17] presented an optimal power and time allocation scheme to minimise the overall energy consumption under service quality constraints in cooperative spectrum sharing network. A labour-consumption market based auction was designed in [18] to optimise the power and time trading between PU and multiple SUs, hence the network's energy and spectrum efficiency were both improved. All results in [14–18] mainly focus on the energy consumption of the network, where PU and SUs control their transmit power to improve EE. Here, we modify the energy efficient metric by extending it to a more generalised definition shown as the number of bits transmitted per unit of energy, which reflects EE more fully because of the trade-off between throughput and energy consumption [19].

Motivated by the above observations, in this paper, we investigate a cooperation-based spectrum leasing mechanism where one PU pair shares multiple SUs with energy constraint. To satisfy the QoS requirements of all users in a green manner, we formulate a joint optimisation of relay selection and power allocation in the cooperative spectrum sharing network. The objective is to maximise the weighted sum energy efficiency (WSEE) of all SUs while satisfying the individual QoS requirement for each user [20–22]. Based on this framework, a greedy spectrum sharing (GSS) algorithm is designed to maximally enhance the WSEE, from which the best relay set, optimal power and time allocation are readily obtained, respectively. Finally, numerical results are provided to demonstrate that the significant EE improvement is achieved by the proposed GSS algorithm while guaranteeing QoS of the network.

The remainder of this paper is organised as follows. In Section 2, we introduce the system model, the framework for cooperation-based spectrum leasing and the problem formulation. Section 3 presents the GSS algorithm for the joint relay selection and power allocation problem. Numerical results and discussions are provided in Section 4. Finally, Section 5 concludes the paper.

2 System model

We consider a CR network consisting of primary and secondary systems over Rayleigh fading channels. The channels are invariant within each frame, but generally varying over the frames (block-fading), that is, the fading coefficients are constant for a frame. In the primary system, the base station (PBS) communicates with a primary transmitter (PT) over a dedicated band, and that all N pairs of SUs, that is, ST_k, SR_k, $k \in \{1, \ldots, N\}$, compete with each other to access the band to transmit their own traffic. As compensation for spectrum leasing, the SUs who are granted access to the band provide the benefits of cooperative diversity to the PUs. It is assumed that a central controller is

Table 1 Key notations

P_p	The transmit power of PT for PU's traffic.
$R_p^{\min}$	The minimum QoS requirement of PU.
P_{RD}^k	The relay power of SU k for PU's traffic.
P_S^k	The transmit power of SU k for its own traffic.
$P_k^{\max}$	The maximum power budget of SU k for its whole transmission.
$R_S^{k,\min}$	The minimum QoS requirement of SU k.
P_C^k	The circuit power consumption of SU k.
h_p	The channel power gain of link between PT and PBS.
g_{SR}^k	The channel power gain of link between PT and ST_k.
g_{RD}^k	The channel power gain of link between ST_k and PBS.
g_S^k	The channel power gain of link between ST_k and SR_k.
N_0	The power of additive white Gaussian noise.
$\boldsymbol{R}$	The decoding set of SUs.

available, so that the network channel state information can be reliably gathered for centralised processing [7, 23]. In this paper, we assume that the central controller is embedded with the PBS (herein, a centralised cooperation decision process is performed at the PBS. Afterward, the PBS has to inform all SUs of the cooperation decision by broadcasting the flag messages Success or Failure. If the flag message is 'Success', the corresponding SU participates in the cooperative relaying; otherwise, it remains silent and waits for the next transmission process. D-OFDM is adopted to convey this processed information [24], so that bits in different flag messages can be modulated into different orthogonal subcarriers and multiple channels can be transmitted at the same time. It should be emphasised that each flag message can be encoded by only 3-bit codeword, and strong channel coding can be used. Hence it is reasonable to assume the transmissions of the flag messages are error-free). For ease of clarity, we list key notations in Table 1 and the meaning of each notation will be explained later.

2.1 Cooperation-based spectrum leasing protocol

As illustrated in Fig. 1, the overall protocol of the cooperative and secondary transmissions consists of three phases in a frame. The interference between the primary and secondary systems does not exist, because of the fact that when the primary network collaborates with the secondary network, mutual collisions can be eliminated by exchanging the information transmitted, thus avoiding interference [7–12]. In primary transmission phase, the PT broadcasts its data to the PBS and all the SUs through the dedicated band in the first α fraction of a frame. It is assumed that SU can successfully decode PT's information when the signal-to-noise ratio (SNR) ε is not less a given threshold ε_0 at ST_k, that is, $P_p g_{\mathrm{SR}}^k / N_0 \geq \varepsilon_0$, $k \in \boldsymbol{R}$. In the next α fraction of the frame, relay selection is employed and the SUs that are selected cooperatively relay the PU's over the leased band. Then, the selected SUs transmit their own data to their receivers in secondary transmission phase. In particular, all the selected SUs use time division multiple access for transmission to prevent mutual interference. Therefore, we divide the remaining $1-2\alpha$ fraction of the frame equally as employed in [16], and the divided fractions are allocated to the selected SUs.

A distributed space-time-coded protocol is adopted for cooperative transmission, because of its enhanced bandwidth efficiency and large mutual information [17, 25]. Therefore with a set of cooperating SUs $\mathcal{S}$, the total transmission rate for the PU is expressed as

$$R_{\mathrm{coop}} = \alpha \log_2\left(1 + \frac{P_p h_p}{N_0}\right) + \alpha \log_2\left(1 + \frac{\sum_{k \in \mathcal{S}} P_{\mathrm{RD}}^k g_{\mathrm{RD}}^k}{N_0}\right) \tag{1}$$

It is noteworthy that the cooperating set $\mathcal{S}$ is a subset of the decoding set $\boldsymbol{R}$ in this paper, and $\mathcal{S}$ is equivalent to $\boldsymbol{R}$ when all the SUs in $\boldsymbol{R}$ are selected for transmission. After cooperative transmission, each SU can access the dedicated band for its own traffic in the remaining $1-2\alpha$ fraction of the frame. Without loss of generality, we assume that the number of cooperating SUs is L, that is, $|\mathcal{S}| = L$. Thus, the secondary transmission phase is equally divided into L parts and each part is $(1-2\alpha)/L$. Then, the achievable rate of ST_k, $k \in \mathcal{S}$ is given by

$$R_k = \frac{1-2\alpha}{L} \log_2\left(1 + \frac{P_S^k g_S^k}{N_0}\right) \tag{2}$$

During the whole transmission process in a frame, each SU considers not only the transmit power for its own traffic, but the energy cost in helping the PU's transmission and the circuit power consumption as well. However, the energy consumed at the receivers is so low compared with the transmit power levels that we can ignore it [17]. Therefore, the total power consumption of ST_k, $k \in \mathcal{S}$ in a frame is written as

$$E_S = \alpha P_{\mathrm{RD}}^k + \frac{1-2\alpha}{L} P_S^k + P_C^k \tag{3}$$

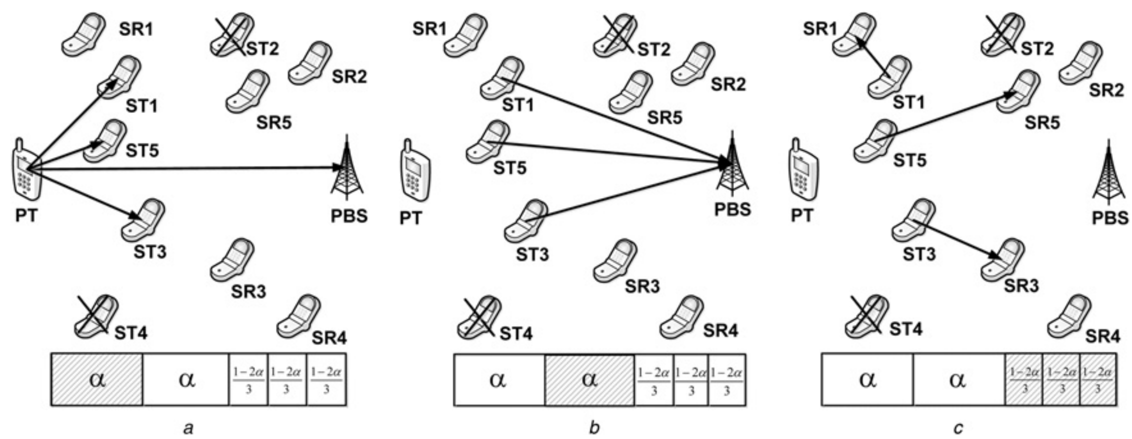

Fig. 1 *Spectrum leasing protocol and frame structure for L = 3 pairs of SUs*

a Primary transmission
b Space-time-coded cooperation
c Secondary transmission

2.2 Problem formulation

In this paper, our objective is not only to optimally allocate available power and frame, but also to choose the best relay set for the PU so as to maximise the WSEE of the secondary network while guaranteeing users' QoS requirements. According to (1)–(3), the new EE optimisation criterion is defined as [20–22]

Problem 1:

$$\max_{\boldsymbol{p}\in\mathcal{P},\alpha,L}\sum_{k\in\mathcal{S}}\beta_k\eta_S^k=\sum_{k\in\mathcal{S}}\beta_k\frac{((1-2\alpha)/L)\log_2(1+(P_S^kg_S^k/N_0))}{\alpha P_{\text{RD}}^k+((1-2\alpha)/L)P_S^k+P_C^k}\quad (4)$$

$$\text{s.t.}\quad \alpha\log_2\left(1+\frac{P_ph_p}{N_0}\right)+\alpha\log_2\left(1+\frac{\sum_{k\in\mathcal{S}}P_{\text{RD}}^kg_{\text{RD}}^k}{N_0}\right)\ge R_p^{\min}\quad (5)$$

$$\alpha P_{\text{RD}}^k+\frac{1-2\alpha}{L}P_S^k+P_C^k\le P_k^{\max}\quad (6)$$

$$\frac{1-2\alpha}{L}\log_2\left(1+\frac{P_S^kg_S^k}{N_0}\right)\ge R_S^{k,\min},\quad \forall k\in\mathcal{S}\quad (7)$$

where $\boldsymbol{p}\in\mathcal{P}$ is chosen subject to the transmit power limits and the set $\mathcal{P}:=\{0\le P_{\text{RD}}^k, P_S^k\le P_k^{\max}\}$. We use bold symbols to denote vectors as $\boldsymbol{p}=\{P_{\text{RD}}^k, P_S^k\}$ and assume that P_C^k is a constant for all the SUs. β_k is the weighting factor associated with the EE of ST_k, $k\in\mathcal{S}$, which is typically included to achieve a certain fairness index among all users [21]. Inequality (6) is the maximum power budget constraint for ST_k, $k\in\mathcal{S}$, and inequalities (5) and (7) are the minimum users' QoS requirements.

After some algebraic simplifications, inequality (5) can be arrived at

$$\sum_{k\in\mathcal{S}}P_{\text{RD}}^kg_{\text{RD}}^k\ge\left(\frac{2^{R_p^{\min}/\alpha}}{1+\gamma_p}-1\right)N_0\quad (8)$$

where $\gamma_p=P_ph_p/N_0$.

Invoking that the remaining $1-2\alpha$ fraction of the frame is equally divided, we adopt the 'equal paying with SNR' rule as employed in [16], such that all the granted SUs for the dedicated band have the relaying transmit power to equally satisfy the divided SNR, that is, $\text{SNR}_i=\text{SNR}_j$, where $\text{SNR}_{i(j)}=P_{\text{RD}}^{i(j)}g_{\text{RD}}^{i(j)}/N_0$, $\forall i,j\in\mathcal{S}$. Therefore the relaying transmit power of ST_k at the dedicated band is shown by

$$P_{\text{RD}}^k\ge\frac{N_0}{Lg_{\text{RD}}^k}\left(\frac{2^{R_p^{\min}/\alpha}}{1+\gamma_P}-1\right)\quad (9)$$

Replacing the constraint (5) with (9), then Problem 1 is resolved via two sub-problems as follows

Problem 2:

$$\max_{\boldsymbol{p}\in\mathcal{P}}\quad\eta_S^k=\frac{((1-2\alpha)/L)\log_2(1+(P_S^kg_S^k/N_0))}{\alpha P_{\text{RD}}^k+((1-2\alpha)/L)P_S^k+P_C^k}\quad (10)$$

$$\text{s.t.}\quad P_{\text{RD}}^k\ge\frac{N_0}{Lg_{\text{RD}}^k}\left(\frac{2^{R_p^{\min}/\alpha}}{1+\gamma_p}-1\right)\quad (11)$$

$$\alpha P_{\text{RD}}^k+\frac{1-2\alpha}{L}P_S^k+P_C^k\le P_k^{\max}\quad (12)$$

$$\frac{1-2\alpha}{L}\log_2\left(1+\frac{P_S^kg_S^k}{N_0}\right)\ge R_S^{k,\min},\quad\forall k\in\mathcal{S}\quad (13)$$

Problem 3:

$$\max_{\alpha,L}\quad\sum_{k\in\mathcal{S}}\beta_k\eta_S^k\quad (14)$$

It can be seen from the overall object (10), η_s^k is a monotonically decreasing function in P_{RD}^k. Thus, to maximise the individual EE, the relaying transmit power of each ST_k should be regulated as

$$P_{\text{RD}}^k=\frac{N_0}{Lg_{\text{RD}}^k}\left(\frac{2^{R_p^{\min}/\alpha}}{1+\gamma_p}-1\right)\quad (15)$$

By substituting (14) into (12), the upper transmit power bound of ST_k is derived as

$$P_S^k\le\frac{L\left(P_k^{\max}-(\alpha N_0/Lg_{\text{RD}}^k)\left((2^{R_p^{\min}/\alpha}/(1+\gamma_p))-1\right)-P_C^k\right)}{1-2\alpha}\quad (16)$$

Using the same rationale in (13), and it follows that

$$P_S^k\ge\frac{N_0}{g_S^k}\left(2^{LR_S^{k,\min}/(1-2\alpha)}-1\right)\quad (17)$$

Then, the transmit power constraint of ST_k for its own traffic can be expressed as

$$\frac{N_0}{g_S^k}\left(2^{LR_S^{k,\min}/(1-2\alpha)}-1\right)\le P_S^k\le\frac{L\left(P_k^{\max}-(\alpha N_0/Lg_{\text{RD}}^k)\left((2^{R_p^{\min}/\alpha}/(1+\gamma_p))-1\right)-P_C^k\right)}{1-2\alpha}\quad (18)$$

Finally, combining the foregoing analyses with (10), the WSEE optimisation problem can be transformed into the following form

Problem 4:

$$\max_{\boldsymbol{p}\in\mathcal{P}}\quad\eta_S^k=\frac{((1-2\alpha)/L)\log_2(1+(P_S^kg_S^k/N_0))}{\alpha P_{\text{RD}}^k+((1-2\alpha)/L)P_S^k+P_C^k}\quad (19)$$

$$\text{s.t.}\quad P_{\text{RD}}^k=\frac{N_0}{Lg_{\text{RD}}^k}\left(\frac{2^{R_p^{\min}/\alpha}}{1+\gamma_p}-1\right)\quad (20)$$

$$\frac{N_0}{g_S^k}\left(2^{LR_S^{k,\min}/(1-2\alpha)}-1\right)\le P_S^k\le\frac{L\left(P_k^{\max}-(\alpha N_0/Lg_{\text{RD}}^k)\left((2^{R_p^{\min}/\alpha}/(1+\gamma_p))-1\right)-P_C^k\right)}{1-2\alpha},\quad k\in\mathcal{S}\quad (21)$$

Problem 5:

$$\max_{\alpha,L}\quad\sum_{k\in\mathcal{S}}\beta_k\eta_S^k\quad (22)$$

Note that the best relay selection is implicitly involved in $\mathcal{P}$, α and L.

3 GSS algorithm-based optimisation

In our model, we assume that the channels are stable and the channel knowledge are detected by the central controller [23]. Based on the information available, the PU can select a proper set of the SUs served as cooperative relays and calculate the optimal portion parameter α^*, from which an optimisation framework with joint relay selection and power allocation is formulated. To this end, we propose a GSS algorithm to effectively solve the optimisation problem considered above. Particularly, this algorithm can be performed in the following two steps. The first step consists of optimal power allocation among the active relays, assuming that a portion of SU relays in the decoding set participates in the relaying process. The second step consists of selecting the best relay set that achieves the highest EE by employing the optimal power allocation determined in the previous step.

3.1 Power allocation of cooperative relays

It is worth noting that a relay that is defined to be selected if it is allocated with transmit power. By considering the condition that $0 \le P_{\rm RD}^k \le P_k^{\max}$, the optimal relaying power of ST_k can be expressed as

$$P_{\rm RD}^{k(*)} = \min\left\{P_k^{\max}, \frac{N_0}{Lg_{\rm RD}^k}\left(\frac{2^{R_p^{\min}/\alpha}}{1+\gamma_p} - 1\right)\right\} \tag{23}$$

Applying (23) into (19), η_S^k can be obtained as a function of P_S^k, that is, $\eta_S^k = f(P_S^k)$. In the following, we will demonstrate that a unique globally optimal transmit power of ST_k exists. First, the concept of quasi-concavity needs to be introduced.

Definition 1: As defined in [26], a function f: $\boldsymbol{R}^n \to \boldsymbol{R}$ is called quasi-concave if its domain and all its superlevel sets

$$S_\alpha = \{x \in \text{dom} f \,|\, f(x) \ge \alpha\} \tag{24}$$

for $\alpha \in \boldsymbol{R}$, are convex.

In the following, Lemma 1 and Lemma 2 characterise $\eta_S(\boldsymbol{p})$ and are proved in Appendix 1 and Appendix 2, respectively.

Lemma 1: If $R(\boldsymbol{p})$ is strictly concave in $\boldsymbol{p}$, $\eta_S(\boldsymbol{p})$ is strictly quasi-concave.

Lemma 2: If $R(\boldsymbol{p})$ is strictly concave in $\boldsymbol{p}$, $\eta_S(\boldsymbol{p})$ is first strictly increasing and then strictly deceasing in any P_S^k in $\boldsymbol{p}$, that is, the local maximum of $\eta_S(\boldsymbol{p})$ for each P_S^k exists at a positive finite value.

From Lemma 1 and Lemma 2, $\eta_S(\boldsymbol{p})$ is quasi-concave and first strictly increases and then strictly deceases in any P_S^k in $\boldsymbol{p}$, hence we obtain that $\eta_S(\boldsymbol{p})$ is unimodality, in which there exists a unique locally maximal value within the range $[0, \infty)$. More specific, this local maxima is also globally optimal [26]. Lemma 3 further tells the existence of the unique global maxima.

Lemma 3: If $R(\boldsymbol{p})$ is strictly concave, there exists a unique globally optimal transmit power vector $\boldsymbol{p}^* = [P_S^{1(*)}, P_S^{2(*)}, \ldots, P_S^{L(*)}]^{\rm T}$, where $\partial\eta_S(\boldsymbol{p})/\partial P_S^k|_{\boldsymbol{p}=\boldsymbol{p}^*} = 0$.

Proof: The proof is provided in Appendix 3. □

According to Lemma 3 and making use of $0 \le P_S^k \le P_k^{\max}$, the optimal transmit power of ST_k for its own traffic in the secondary transmission phase can be calculated as

$$P_S^{k(*)} = \min\{P_k^{\max}, P_S^{k(0)}\} \tag{25}$$

where $P_S^{k(0)}$ is derived from $\partial\eta_S^k/\partial P_S^k = 0$.

3.2 Best relay selection towards EE

Once the optimal power allocation for the SU relays have been computed, the best relay set can be selected to be the one that results in the maximum value of (22). In what follows, we discuss the relay selection method and the updating algorithm.

Step A: At the beginning, the PU takes an initial value of α, that is, $\alpha = 0.5$ $(0 < \alpha < 0.5)$, and then selects the best relay set with the given α.

Now, we consider an ideal situation where the cooperative SUs relay PU's data with its maximum transmit power $P_k^{\max}$. In this case, the received SNR from ST_k at the PBS is expressed as

$$\text{SNR}_k^{\rm ideal} = \frac{P_k^{\max} g_{\rm RD}^k}{N_0} \tag{26}$$

For all the cooperative relays, without loss of generality, we assume that

$$\text{SNR}_1^{\rm ideal} \le \text{SNR}_2^{\rm ideal} \le \ldots \le \text{SNR}_L^{\rm ideal} \tag{27}$$

Meanwhile, the actual SNR at the PBS is found that

$$\text{SNR}_k^{\rm actual} = \frac{P_{\rm RD}^k g_{\rm RD}^k}{N_0} \tag{28}$$

Obviously, we have that

$$\text{SNR}_k^{\rm actual} \le \text{SNR}_k^{\rm ideal} \tag{29}$$

From (20), each cooperative relay satisfies the following equality

$$\frac{LP_{\rm RD}^k g_{\rm RD}^k}{N_0} = \left(\frac{2^{R_p^{\min}/\alpha}}{1+\gamma_p} - 1\right) = L\text{SNR}_k^{\rm actual} \tag{30}$$

Then, we further obtain that

$$L_{\min}^{\rm actual} = \frac{\text{SNR}_{\rm total}}{\text{SNR}_{\max}^{\rm actual}} \tag{31}$$

$$L_{\min}^{\rm ideal} = \frac{\text{SNR}_{\rm total}}{\text{SNR}_{\max}^{\rm ideal}} \tag{32}$$

$$L_{\min}^{\rm ideal} \le L_{\min}^{\rm actual} \tag{33}$$

where $\text{SNR}_{\rm total}$ denotes the minimum SNR value of the cooperating set $\mathcal{S}$ on the condition that PU's QoS requirement is satisfied, and the meanings of $\text{SNR}_{\max}^{\rm actual}$ and $\text{SNR}_{\max}^{\rm ideal}$ are denoted as $\text{SNR}_{\max}^{\rm actual} = \max_{k\in\mathcal{S}}\{\text{SNR}_k^{\rm actual}\}$, $\text{SNR}_{\max}^{\rm ideal} = \max_{k\in\mathcal{S}}\{\text{SNR}_k^{\rm ideal}\}$, respectively. Following this, the number of cooperative relays should satisfy the following condition

$$L \ge L_{\min}^{\rm ideal} = \frac{N_0}{P_k^{\max} g_{\rm RD}^k}\left(\frac{2^{R_p^{\min}/\alpha}}{1+\gamma_p} - 1\right) \tag{34}$$

Besides, we learn from (21) that

$$\frac{N_0}{g_S^k}\left(2^{LR_S^{k,\min}/(1-2\alpha)} - 1\right) \le P_S^k \le P_k^{\max} \tag{35}$$

Thus, we also have that

$$L \le \frac{(1-2\alpha)\log_2(1 + (P_k^{\max} g_S^k/N_0))}{R_S^{k,\min}} \tag{36}$$

Combining (34) with (36), we can obtain a preliminary scope of

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INPUT: candidate SUs in the decoding set R,
OUTPUT: optimal cooperating SU set S_opt.
// Initialisation
STEP 1:
for k = 1 : M
    if SNR_k^ideal < SNR_k^actual
        S(k) = 0
    end
end
N_select = length(S(S > 0))
STEP 2:
if N_select < L
    S_opt ←[ ]
else
for k = 1 : M
    if S(k) = 0
        P*_RD(k) = 0, P*_S(k) = 0, η_S(k) = 0
    else
        P*_RD(k) and P*_S(k) computed by (23) and (25)
        calculate η_S(k)
    end
end
η_S^max = η_S(η_S > 0)
STEP 3:
for k = 1 : M
    S(k) = S(find(η_S == η_S^max(k)))
end
S_opt ← S
```

Fig. 2 *Relay set selection algorithm*

relay number with the given α arrived at

$$L_{\min} = \frac{N_0}{P_k^{\max} g_{\mathrm{RD}}^k}\left(\frac{2^{R_p^{\min}/\alpha}}{1+\gamma_p} - 1\right) \le L \le \frac{(1-2\alpha)\log_2(1+(P_k^{\max} g_S^k/N_0))}{R_S^{k,\min}} = L_{\max} \tag{37}$$

Step B: With the preliminary scope of the relay number, we verify the validity of each relay number and present the relay selection in this step. For ease of simplicity, we denote $|\boldsymbol{R}| = M$ and $L \in [L_{\min}, L_{\max}]$. The proposed relay selection algorithm is detailed in Fig. 2.

In Step 1, an initial cooperating number of SUs N_{select} is determined with considering the minimum QoS requirement of PU. Assuming each SU in the decoding set $\boldsymbol{R}$ is selected, the constraint of (29) is checked for $1 \le k \le M$. The one that does not satisfy (29) will not be considered in all subsequent operations.

In Step 2, the desired SU number N_{select} is first examined. If $N_{\text{select}} < L$, the cooperating SUs is a null set with the considered L. Otherwise, the optimal transmit powers for PU's traffic and its own traffic are allocated by applying the foregoing power allocation scheme. Then, the WSEE for each SU in the decoding set is calculated.

In Step 3, by choosing the non-zero value of $\eta_S^{\max}(k)$ for $1 \le k \le M$, a final cooperating SU combination $\mathcal{S}_{\text{opt}}$ is decided.

Step C: Based on the transmit powers of P_{RD}^k and P_S^k as well as the given α, enumerate all the possible cooperative relay set $\mathcal{S}$ from the universal decoding set $\boldsymbol{R}$.

Step D: Update α with iteration step size δ and repeat *Step A–Step C*. It is obvious that a value that lies in the interval $(\alpha^* - \delta, \alpha^* + \delta)$ is finally achieved, we can approximately regard the obtained value as α^* when δ is small enough.

Step E: Compute the WSEE in (22) of all the possible relay sets, from which the one that owns the maximum value is considered to be the best relay set, at the same time, the optimal frame division α^* and transmit powers $P_{\mathrm{RD}}^{k(*)}$ and $P_S^{k(*)}$ are set to be the corresponding parameters with the best relay set.

4 Numerical results

In this section, numerical results are presented to evaluate the performance of EE for the cooperative spectrum sharing network. We consider a simple geometrical model that consists of one PT, one PBS and 20 pairs of SUs, and that other simulation parameters are the same as [17]. In particular, the SNR threshold ε_0 is 10^{-2} and the iteration step size δ is 0.05. The distances of PT-PBS (d_P), PT-ST (d_{PS}), ST-PBS (d_{SP}) and ST-SR (d_S) are set as $0 < d_P \le 1000$ m, $d_{\mathrm{PS}} \le 800$ m, $d_{\mathrm{SP}} = 300$ m and $d_S = 200$ m, respectively. All channels are assumed to undergo path loss and small scale Rayleigh fading, and that the path loss exponent is 3.5 and the average power gain over all channels equals to 1. The power spectral density of Gaussian noise N_0 is 0.5. The maximum transmit power of PU (P_p) and power budget of SU k ($P_k^{\max}$) are both assumed to be 30 mW. The minimum QoS requirements for PU and SU k are $R_p^{\min} = 1$ bps/Hz, $R_S^{k,\min} = 0.5$ bps/Hz, respectively. The weighted factor β_k is unity for any k [20, 21].

Fig. 3 depicts the power per unit throughput of the CRN with varying distance of the direct transmission link (d_P) from 100 to 1000 m. It is first observed that total power consumption in cooperative spectrum sharing is less than in non-cooperation situation where $d_P > 200$ m. The reason is that the channel condition of ST-PBS link is better than that of PT-PBS link with the increased d_P, and thus considerable energy saving is attained. The case is opposite when $d_P < 200$ m. One also observes that the proposed scheme outperforms the coop-reference in [17] by a significant margin. In particular, compared with the coop-reference scheme, about 50% power per unit throughput is saved in our proposed scheme. This can be explained that the authors of [17] only consider minimising the overall power consumption of the network, while we balance a better trade-off between throughput and power consumption.

In Fig. 4, the EE of the CRN against various PT-PBS distances (d_P) is presented. It is observed that a decline trend of the EE of

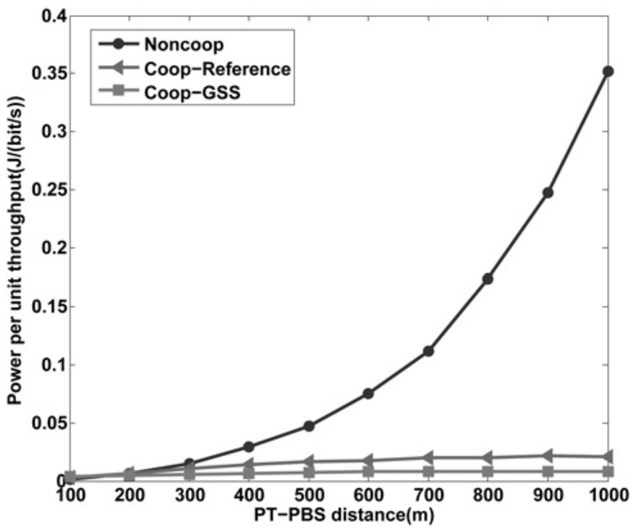

Fig. 3 *Power per unit throughput of the whole network*

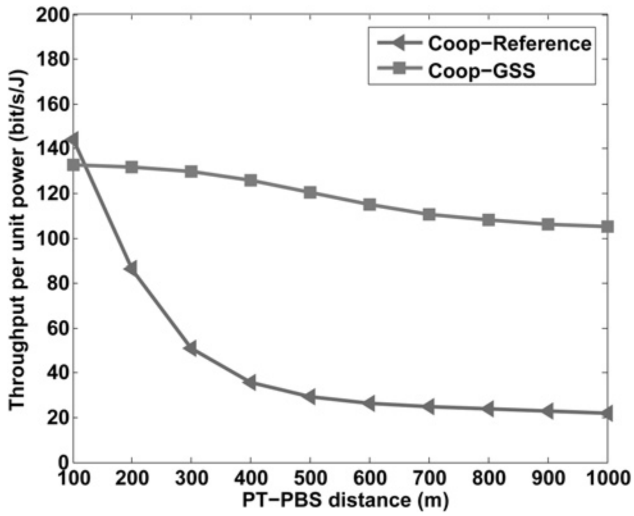

Fig. 4 *EE of the CRN*

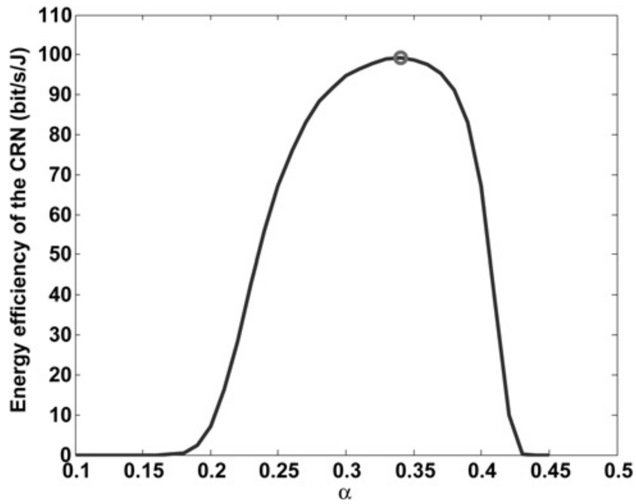

Fig. 6 *EE of the CRN against α*

the CRN follows with the increased d_P. This is because of the fact that the average channel quality of the direct transmission link gradually becomes worse as d_P increases, indicating that a large amount of relaying power is consumed to satisfy the QoS requirement for the primary system under the predefined total power budget. As a result, less transmit power is provided for its own traffic and the EE of the CRN is low. Moreover, the EE of the proposed scheme is larger than that in [17], since the proposed scheme takes both power consumption and achievable throughput into consideration in terms of energy efficient communications.

Fig. 5 plots the total power consumption of the whole network for different PT-PBS distances (d_P) with cooperation and non-cooperation situations. At a first glance, as the distance (d_P) between PT and PBS increases, the total power consumption of the network grows accordingly. Particularly, the cooperative scheme consumes less power than the non-cooperative scheme from the whole perspective. This improvement is as the remuneration for cooperative diversity and space-time coding gain that the secondary system provides to the primary system. However, when $d_P < d_{SP}$ the difference of the power consumption is gradually reducing in the three situations. Since in this case, the average channel gain of PT-PBS link approaches that of ST-PBS link and the advantage of channel gain from cooperation no longer exists. Furthermore, the power consumption of the network in this paper is higher than that in [17], but this drawback can be compensated for the improvement of the overall throughput indicated by Fig. 3.

Fig. 6 unveils the EE of the CRN according to α varies from 0.1 to 0.5. The distance of PT-PBS (d_P) is assumed to be 1000 m. As can be perceived, $\alpha^* = 0.35$ and the corresponding optimal EE value is approximately 100 bit/s/Joule. In addition, in the case of small value α, the cooperative SUs cost much relaying power to assist PU's traffic for the given QoS requirement, thus resulting in a low EE; while $\alpha = 0.5$, the PU remains the whole frame for its own transmission, so that SUs will have no incentive to take part in the cooperation and the EE is 0. Therefore it is of the essence to implement the cooperation with parameter α to be α^*.

The performance of the PU's throughput in cooperation and non-cooperation situations is compared in Fig. 7. It is clearly shown that the proposed scheme is comparable with [17] in terms of the PU's throughput, because of the same QoS requirement for PU's transmission in both of the two schemes. What is more, note that when the average channel quality of the PU becomes worse, the capacity loss through direct transmission can be made up for the SU's cooperation. At the same time, the SUs who participate in the cooperation win a fraction of time for their own communications. Consequently, the throughput of the network is improved in this case.

Fig. 8 shows the EE of cooperative relay against the maximum power of SU, where the distances of PT-PBS link are $d_p = 600$ m, $d_P = 800$ m and $d_P = 1000$ m, respectively. As seen, the EE of cooperative relay increases rapidly first and then levels off as the

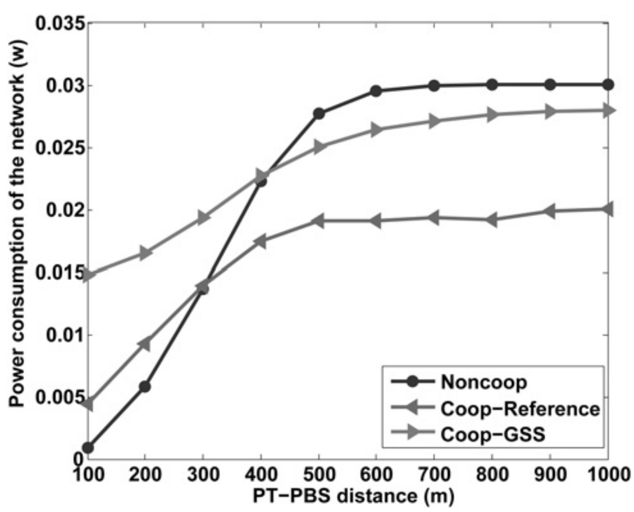

Fig. 5 *Power consumption the whole network*

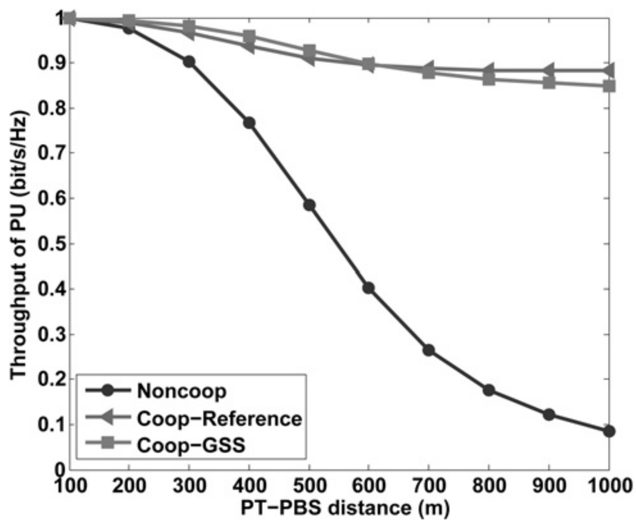

Fig. 7 *Throughput of the PU*

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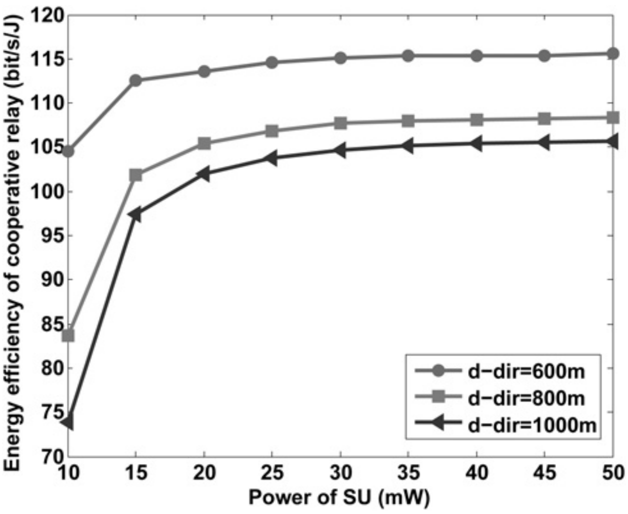

Fig. 8 *EE of cooperative relay against the maximum power of SU*

maximum power of SU grows. After reaching the optimum, the value is no longer increasing since the object of maximising EE of the proposed scheme. Moreover, the EE of cooperative relay decreases when the average channel quality of PT-PBS link gets worse. It indicates that the improvement of EE is invalid by SU raising its maximum power level $P_k^{\max}$ under poor channel condition.

5 Conclusion

In this paper, we investigate an energy efficient cooperation mechanism in a spectrum sharing network, where the primary system leases portion of a frame to the secondary system for its own traffic in exchange for the SUs assisting the transmission of the PU as relays. Considering the individual QoS requirement of each user, a joint optimisation of joint relay selection and power allocation towards energy efficient communications is formulated. After employing the GSS algorithm, the optimal relay selection, power and sharing time allocation are determined, respectively. Numerical results are provided to demonstrate that significant EE improvement is achieved by the proposed GSS algorithm, and that the network performance is enhanced. In future work, it will be interesting to study a more general spectrum sharing network with multiple PUs and incomplete channel information.

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8 Appendix

8.1 Appendix 1: Proof of Lemma 1

Proof: Denote the EE expression of (19) can be rewritten as

$$\eta_S(\boldsymbol{p}) = \frac{R(\boldsymbol{p})}{P_C + \boldsymbol{p}} \tag{38}$$

where $P_C = (L/(1-2\alpha))(\alpha P_{\rm RD}(\boldsymbol{p}) + P_C(\boldsymbol{p}))$, and $R(\boldsymbol{p}) = \log_2(1 + (\boldsymbol{p} g_S/N_0))$.

Then, the superlevel sets of $\eta_S(\boldsymbol{p})$ can be expressed as

$$S_\alpha = \{\boldsymbol{p} \succeq \boldsymbol{0} | \eta_S(\boldsymbol{p}) \ge \alpha\} \tag{39}$$

where symbol $\succeq$ denotes vector inequality and $\boldsymbol{p} \succeq \boldsymbol{0}$ means each element of $\boldsymbol{p}$ is non-negative. According to Definition 1, $\eta_S(\boldsymbol{p})$ is strictly quasi-concave if and only if S_α is strictly convex for any real number α. When $\alpha < 0$, no points exist on the superlevel $\eta_S(\boldsymbol{p}) = \alpha$. When $\alpha = 0$, only $\boldsymbol{0}$ is on the superlevel $\eta_S(\boldsymbol{0}) = \alpha$. Hence, S_α is strictly convex when $\alpha \le 0$. Now, we investigate the case when $\alpha > 0$. Since

$$\eta_S(\boldsymbol{p}) = \frac{R(\boldsymbol{p})}{P_C + \boldsymbol{p}} \geq \alpha \tag{40}$$

S_α is equivalent to

$$S_\alpha = \{\boldsymbol{p} \succeq \boldsymbol{0} | \alpha P_C + \alpha \boldsymbol{p} - R(\boldsymbol{p}) \leq 0\} \tag{41}$$

Owing to the fact that $\boldsymbol{p}$ is affine and $-R(\boldsymbol{p})$ is strictly convex in $\boldsymbol{p}$, S_α is also strictly convex. This completes the proof.

8.2 Appendix 2: Proof of Lemma 2

Proof: The partial derivative of $\eta_S(\boldsymbol{p})$ with P_S^k is

$$\frac{\partial \eta_S(\boldsymbol{p})}{\partial P_S^k} = \frac{R'(\boldsymbol{p})(P_C + \boldsymbol{p}) - R(\boldsymbol{p})}{(P_C + \boldsymbol{p})^2} = \frac{\beta(\boldsymbol{p})}{(P_C + \boldsymbol{p})^2} \tag{42}$$

where $\beta(\boldsymbol{p}) = R'(\boldsymbol{p})(P_C + \boldsymbol{p}) - R(\boldsymbol{p})$, and $R'(\boldsymbol{p})$ is the first partial derivative of $R(\boldsymbol{p})$ with respect to P_S^k.
Then, the derivative of $\beta(\boldsymbol{p})$ is

$$\beta'(\boldsymbol{p}) = R''(\boldsymbol{p})(P_C + \boldsymbol{p}) \tag{43}$$

where $R''(\boldsymbol{p})$ is the second partial of $R(\boldsymbol{p})$ with respect to P_S^k. Since $R(\boldsymbol{p})$ is concave, we derive that $\beta'(\boldsymbol{p}) < 0$, so that $\beta(\boldsymbol{p})$ is strictly decreasing.

According to the L'Hopital's rule [27], it is easy to show that

$$\begin{aligned}\lim_{P_S^k \to \infty} \beta(\boldsymbol{p}) &= \lim_{P_S^k \to \infty} \{R'(\boldsymbol{p})(P_C + \boldsymbol{p}) - R(\boldsymbol{p})\} \\ &= \lim_{P_S^k \to \infty} \left\{\frac{R'(\boldsymbol{p})(P_C + \boldsymbol{p}) - R(\boldsymbol{p})}{P_S^k} P_S^k\right\} \\ &= \lim_{P_S^k \to \infty} \left\{\frac{R''(\boldsymbol{p})(P_C + P_S\boldsymbol{p})}{1} P_S^k\right\} < 0\end{aligned} \tag{44}$$

In addition

$$\begin{aligned}\lim_{P_S^k \to 0} \beta(\boldsymbol{p}) &= \lim_{P_S^k \to 0} \{R'(\boldsymbol{p})(P_C + \boldsymbol{p}) - R(\boldsymbol{p})\} \\ &= \lim_{P_S^k \to 0} \{P_C R'(\boldsymbol{p})\} > 0\end{aligned} \tag{45}$$

Combining (44) with (45), we see that $P_S^{k(*)}$ exists and $\eta_S(\boldsymbol{p})$ is strictly increasing and then strictly decreasing in P_S^k. Hence, we have Lemma 2. □

8.3 Appendix 3: Proof of Lemma 3

Proof: From Lemma 2, $\eta_S(\boldsymbol{p})$ is unimodality hence a unique locally maximal value exists within the range $[0, \infty]$, denoted by $P_k^{(*)}$. Considering the finite value constraint of P_S^k, the relation between $P_k^{\max}$ and $P_k^{(*)}$ consists of three cases: (a) when $P_k^{\max} < P_k^{(*)}$, since the monotonically increasing characteristic of η_S in $[0, P_k^{\max}]$, the optimal solution in this case is arrived at $P_k^{\max}$; (b) when $P_k^{\max} = P_k^{(*)}$, the locally maximal value $P_k^{(*)}$ overlaps the upper bound of P_S^k, and then the optimal solution is obtained at $P_k^{(*)}$ $(P_k^{\max})$; (c) when $P_k^{\max} > P_k^{(*)}$, the locally maximal value is just located at $P_k^{(*)}$.
Hence, we obtain that the optimal parameter $P_S^{k(*)}$ is achieved in the interior area of the domain, if and only if the local maximum point falls into the interior range of P_S^k's domain, which is given by

$$0 \leq P_S^k \leq P_S^{\max} \tag{46}$$

Then, local maximum point is also the global maxima [28], shown by

$$\eta_S(P_S^k) \leq \eta_S(P_S^{k(*)}) \tag{47}$$

Lemma 3 is readily obtained. □

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