# 'Green' Cooperative Spectrum Sharing Communication

Dandan Liu, Wenbo Wang, and Wenbin Guo

***Abstract*—Financial and environmental considerations provide new trends in wireless communication network known as green communication. The main object of green communication is to save energy consumption of the communication system as much as possible with users' quality of service (QoS) guaranteed. In this paper, cooperative spectrum sharing is investigated as a means of energy saving. We present an optimal power and time allocation to minimize the overall energy consumption under service quality constraints in cooperative spectrum sharing network. The proposed technique can achieve energy saving while offering SUs' communication opportunities. Numerical results demonstrate the validity of the proposed technique.**

***Index Terms*—Cooperative systems, green function, resource management.**

## I. Introduction

With the explosive growth of wireless communication networks and the strong expansion of mobile Internet, an exponential surge of consumed energy in wireless communication industry has already been reported in [1]. We need energy-efficient wireless communication network based on the financial and environment considerations. Green communication (GC) has become a new trend in wireless communication network design and operation.

One of the major ways to enable GC is efficient resource allocation. The resource allocation on energy efficiency with QoS guaranteed has been widely addressed in many papers, e.g., in [2] and [3], and so on. Authors of [2] build a general tradeoff framework between energy efficiency (EE) and spectral efficiency (SE) and prove the quasi-concavity of EE with respect to SE. In [3], authors propose a low-complexity suboptimal algorithm to maximize the sum capacity while maintaining proportional fairness. They both skillfully solve the nonlinear optimization problems of energy efficiency with QoS guaranteed in multiple users access networks. However, cooperation of multiple users is not considered.

Cooperative communication is also an efficient way to reduce the energy consumption [4]- [6]. However, only power allocation schemes have been proposed to achieve energy efficient transmission in these literatures and other resources, such as, bandwidth and time, have not been discussed. In [7] and [8], authors propose a real-time adaptive transmission strategy to improve energy efficiency by dynamic selecting direct and cooperative links based on the channel conditions. Furthermore, authors of [9] present a power trading business model based on game theory for local power efficiency in cooperative wireless communication with QoS constraints. In all of these literatures mentioned above, the cognitive radio network, i.e., the relays' transmission requirement, is not discussed.

Although, authors of [10] refer to reduce transmitting power by means of cooperative spectrum sharing technique. To the best of our knowledge, theoretical analysis is still scarce on minimizing the overall energy consumption in cooperative spectrum sharing network with QoS constraints. Herein, cooperative spectrum sharing network involves two aspects: one is the relays' relaying traffics for terminals, the other is the relays' own transmission requirements. Most previous works on cooperative spectrum sharing mainly focus on the improvement of performances in terms of throughput, bit error rate (BER), outage probability and interference [11]-[14]. In this paper, we propose the optimal power and time allocation to minimize the overall energy consumption under QoS constraints in cooperative spectrum sharing network. In the investigated cooperative spectrum sharing network, secondary user (SU) relays traffics for primary user (PU), in exchange for dedicated transmission time for the SU's own communication. On one hand, PU can improve its performance by SU's relaying its traffics, on the the other hand, SU can get transmission opportunities. For both sides in cooperation, it will be win-win.

The rest of this paper is organized as follows. Section II describes the system model under consideration. In Section III, we formulate the problem of minimizing energy consumption and give its solution in cooperative spectrum sharing network. Section IV presents the numerical results and discussion and the paper concludes with Section V.

## II. System Model

We study a cognitive radio network where a secondary unlicensed user (SU) helps a primary licensed user (PU) transmit data and the SU gets dedicated transmission time for its own data transmission, as shown in Fig. 1. Each link entails a user with a dedicated transmitter (T) wishing to communicate with a corresponding receiver (R). The PU has the exclusive usage right of the licensed spectrum band. The cooperation between PU and SU involves three phases as in Fig. 1: phases I and II for the cooperative communications with a total length of time $T$, and phase III for the SU's own transmissions with a length of time $t$. In phase I (i.e., the first half of the cooperative communication period $(T/2)$), the primary transmitter (PT) broadcasts its data to the primary receiver (PR) and the SU's transmitter (ST) that can receive PU's information. In phase II, the ST decodes the data received in phase I and forwards to PR using independently generated

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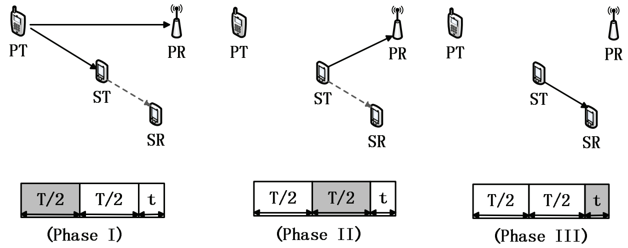


Fig. 1. Cooperative spectrum sharing with three phases.

codebooks in the remaining half of period ($T/2$) [15]. We assume that SU can successfully decode PT's information when the signal-to-noise ration (SNR) at ST ($\varepsilon$) is not less than a give threshold ($\varepsilon_0$). In phase III: the PU rewards the SU with a dedicated time allocation ($t$) for the SU's own data transmission. The SU accesses the spectrum using TDMA. During the period of cooperative spectrum sharing (i.e., phases I, II and III), the relation of transmission time allocation between PU and SU is :

$$T + t = \alpha T. \tag{1}$$

where $\alpha > 1$. The reason is that PU rewards SU with dedicated transmission time ($t$) for SU's relaying traffic (i.e., $t > 0$) in cooperative spectrum sharing.

The channel gain of the link can be expressed as,

$$h = \frac{L(d)|g|^2}{n_0}. \tag{2}$$

The envelope of the channel $|g|$ is given by a Rayleigh process with a slowly varying mean square average of $E[g^2] = \overline{g^2}$. $n_0$ is the power spectral density of the additive noise at the receiver. The pathloss component $L(d)$ for the link is given by the pathloss exponent $\gamma$, i.e., $L(d) = (\frac{1}{d})^\gamma$, where $d$ is the distance of T-R separations [16].

Proposition: The relation of the distances of PT-PR ($d_P$), PT-ST ($d_{PS}$) and ST-PR ($d_{SP}$) should satisfy $|d_P - d_{SP}| < d_{PS} < min\{(d_P + d_{SP}), \sqrt[\gamma]{\frac{\kappa|g_{PS}|^2 P_P}{n_0\varepsilon_0}}\}$ where $g_{PS}$ is the rayleigh fading between PT and ST, $\kappa$ is the power amplifier's (PA's) efficiency that are assumed to be same for PT and ST, and $P_P$ is the PT's maximum transmitting power.

Proof: The ST can decode PT's information if the SNR is sufficiently high, i.e., $\varepsilon \geq \varepsilon_0$. Thus, the maximum value of SNR $\varepsilon_{max} = \kappa p_P h_{PS} \geq \varepsilon_0$. According to Eq. (2), $d_{PS} \leq \sqrt[\gamma]{\frac{\kappa|g_{PS}|^2 P_P}{n_0\varepsilon_0}}$. Additionally, $d_P$, $d_{PS}$ and $d_{SP}$ should satisfy the the triangle inequality, i.e., $|d_P - d_{SP}| < d_{PS} < d_P + d_{SP}$. Based on the above two aspects, $|d_P - d_{SP}| < d_{PS} < min\{(d_P + d_{SP}), \sqrt[\gamma]{\frac{\kappa|g_{PS}|^2 P_P}{n_0\varepsilon_0}}\}$.

We first derive PU's transmission rate during cooperation communication (i.e., phase I and II in Fig. 1). The constraints are assumed to be satisfied in cooperative spectrum sharing. Otherwise, PU transmits its information only by direct link. Thus, we can focus on the relay link between the ST and PR. In phase I, the PR's data rate (per unit time) is

$$R_{PD} = log(1 + \kappa p_P h_P). \tag{3}$$

where $p_P$ is PT's transmitting power, and $h_P$ is channel gain between PT and PR. $R_{PD}$ is the PU's direct transmission rate without cooperation. The total transmission rate for PU during the cooperative communication (phase I and II) is ( [15])

$$R_{PC} = \frac{R_{PD}}{2} + \frac{1}{2}log(1 + \kappa p_{SP} h_{SP}). \tag{4}$$

where $p_{SP}$ is the transmitting power from ST to PR, $h_{SP}$ is the channel gain between ST and PR, and constant $1/2$ is owning to equal partition of cooperative communication time into phase I and phase II.

Next, we compute the PU's average transmission rate during the overall time period (i.e., $\alpha T$). The cooperative communication only occupies $1/\alpha$ fraction of the overall time period. So the PU's average data rate is:

$$R_P = \frac{R_{PC}}{\alpha}. \tag{5}$$

Finally, we compute the average transmission rate of SU in phase III. Because the SU accesses the spectrum using TDMA and occupies $\frac{\alpha-1}{\alpha}$ fraction of the overall time period, the SU's average transmission rate is written as:

$$\begin{aligned} R_S &= \frac{\alpha - 1}{\alpha} R_{SU} \\ &= \frac{\alpha - 1}{\alpha} log(1 + \kappa p_S h_S), \end{aligned} \tag{6}$$

where $p_S$ is the transmitting power of ST to SU's receiver (SR), $h_S$ is channel gain between ST and SR, and $R_{SU}$ is the transmission rate of SU in phase III.

## III. Formulation and Solutions of Problem

In 'green' cooperative spectrum sharing, the object is to minimize the overall energy consumption of the network while guaranteeing users' QoS. The predefined QoS is specified in terms of minimum data transmission rate required by each user. The QoS of the PU and SU are denoted by $Q_P$ and $Q_S$, respectively. We are interested in allocating the available power and time between PU and SU such that the minimum energy is consumed in the network and SU gets transmission opportunity. The energy consumed at the receivers is so low compared to the transmitting power levels that we can ignore it. According to Eq. (1)-Eq. (6), the optimization problem can be formulated as

$$\min_{\mathbf{p}\in\mathcal{P},\alpha} T \cdot \{\frac{1}{2}(p_P + p_{SP}) + (\alpha - 1)p_S\}, \tag{7}$$

$$s.t.\ \frac{1}{2\alpha}(log(1 + \kappa p_P h_P) + log(1 + \kappa p_{SP} h_{SP})) \geq Q_P, \tag{8}$$

$$\frac{\alpha - 1}{\alpha} log(1 + \kappa p_S h_S) \geq Q_S, \tag{9}$$

$$\alpha > 1. \tag{10}$$

where $\mathbf{p} \in \mathcal{P}$ is chosen subject to the transmitting power limits and the set $\mathcal{P} := \{p_m \leq p_P \leq P_P, 0 \leq p_{SP}, p_S \leq P_S\}$. We use bold symbols to denote vectors, e.g., $\mathbf{p} = \{p_P, p_{SP}, p_S\}$. $p_m$ is the PT's minimum transmitting power that the ST can decode its information in phase I where $\varepsilon_{min} = \varepsilon_0$, i.e., $p_m = \frac{\varepsilon_0}{\kappa h_{PS}}$. These maximum power can be regarded as the intrinsic limits for the type of secondary/primary devices, which are normally set out by spectrum regulators. Inequality (8) and inequality (9) are due to the QoS constraints for PU and SU, respectively.

The optimization problem is convex, so it satisfies the Karush-Kuhn-Tucker (KKT) conditions and can be solved via a dual formulation without duality gap [17]. We associate dual variables $\lambda$ with constraint (8), $\mu$ with constraint (9) and $\nu$ with constraint (10). Herein, $T$ is normalized to be 1, so the Lagrangian can be obtained as below:

$$\mathcal{L}(\mathbf{p},\alpha) = \frac{1}{2}(p_P + p_{SP}) + (\alpha-1)p_S + \lambda(\alpha Q_P - \frac{1}{2}log(1+\kappa p_P h_P) - \frac{1}{2}log(1+\kappa p_{SP}h_{SP})) + \mu(Q_S - \frac{\alpha-1}{\alpha}log(1+\kappa p_S h_S)) + \nu(1-\alpha). \tag{11}$$

According to KKT conditions, the optimal power allocation can be obtained

$$p_P^* = \frac{1}{\kappa}(\frac{e^{\alpha Q_P}}{\sqrt{h_P h_{SP}}} - \frac{1}{h_P}), \tag{12}$$

$$p_{SP}^* = \frac{1}{\kappa}(\frac{e^{\alpha Q_P}}{\sqrt{h_P h_{SP}}} - \frac{1}{h_{SP}}), \tag{13}$$

$$p_S^* = \frac{1}{\kappa h_S}(e^{\frac{\alpha Q_S}{\alpha-1}} - 1). \tag{14}$$

The equation with respect to $\alpha$ is also obtained, i.e.,

$$(1-\frac{Q_S}{\alpha-1})e^{\frac{\alpha Q_S}{\alpha-1}} + Q_P\frac{h_S}{\sqrt{h_P h_{SP}}}e^{\alpha Q_P} - 1 = 0. \tag{15}$$

We can apply Newton's method [18] to get optimal $\alpha$ value. We take function $f(\alpha^k)$ as (16) and its derivative $f'(\alpha^k)$ as (17)

$$f(\alpha^k) = (1-\frac{Q_S}{\alpha^k-1})e^{\frac{\alpha^k Q_S}{\alpha^k-1}} + Q_P\frac{h_S}{\sqrt{h_P h_{SP}}}e^{\alpha^k Q_P} - 1 \tag{16}$$

$$f'(\alpha^k) = \frac{Q_S^2}{(\alpha^k-1)^3}e^{\frac{\alpha^k Q_S}{\alpha^k-1}} + Q_P^2\frac{h_S}{\sqrt{h_S h_{SP}}}e^{\alpha^k Q_P} \tag{17}$$

where superscript $k$ represents the $k^{th}$ iteration. Then, a better approximation $\alpha^{k+1}$ value can be obtain as

$$\alpha^{k+1} = \alpha^k - \frac{f(\alpha^k)}{f'(\alpha^k)} \tag{18}$$

Due to $f'(\alpha^k) > 0$ with $\alpha^k > 1$, $f(\alpha^k)$ is monotonically increasing. From Eq. (16), $\lim\limits_{\alpha^k \to 1^+} f(\alpha^k) < 0$. Therefore, one can get the converged optimal value of $\alpha^*$ where $f(\alpha^*) = 0$ base on Newton's method.

Above analysis is based on power allocation in the set $\mathcal{P}$. Considering the transmitting power limits, the PU's power allocation is $p_P = p_m$ if $p_P^* < p_m$, otherwise $p_P = min\{p_P^*, P_P\}$ in phase I; the SU's power allocations are $p_{SP} = 0$ if $p_{SP}^* < 0$, otherwise $p_{SP} = min\{p_{SP}^*, P_S\}$ in phase II, and $p_S = min\{p_S^*, P_S\}$ in phase III.

In non-cooperation ($\alpha = 1$), the optimization problem of minimizing the energy consumption can be correspondingly expressed as

$$\begin{aligned} &min\{p_P\} \\ &s.t. \quad log(1+\kappa p_P h_P) \geq Q_P \\ &\qquad 0 \leq p_P \leq P_P \end{aligned} \tag{19}$$

The optimal power is easy to obtain, i.e.,

$$p_P^* = \frac{1}{\kappa h_P}(e^{Q_P} - 1). \tag{20}$$

Thus, the PU's power allocation is $p_P = min\{p_P^*, P_P\}$.

## IV. Numerical Results and Discussion

In this section, we present the performance of cooperative spectrum sharing network for energy saving. The threshold of SNR at ST ($\varepsilon_0$) that it can decode PT's information is assumed to be $10^{-2}$. The PA's efficiency ($\kappa$) is assumed to be 1. The distances of PT-PR ($d_P$), PT-ST ($d_{PS}$), ST-PR ($d_{SP}$) and ST-SR ($d_S$) links are $0 < d_P \leq 1000$m, $d_{PS} \leq 800$m, $d_{SP} = 300$m and $d_S = 200$m, respectively. For the transmission model, we assume that the path loss exponent $\gamma$ is 3.5, the noisy power spectral density ($n_0$) is 0.5, and $g$ is the small scale fading channel given by a complex Gaussian process where $E[g^2] = \overline{g^2} = 1$. The channel gains are assumed to be constant over the period of cooperative spectrum sharing (i.e., phase I, II and III). The maximum power of PU ($p_P$) and SU ($P_S$) are both assumed to be 30mW. The predefined QoS of PU and SU are $Q_P = 1$bps/Hz and $Q_S = 0.5$bps/Hz, respectively.

We study the performance of optimal power and time allocation scheme in 'green' cooperative spectrum sharing network. The performance metrics are the power consumption ($P_N$), throughput ($R_N$) and power consumption per unit throughput ($P_b$) of the network, and the PU's throughput ($R_{PU}$). The power consumed at the receivers is ignored because it is too low compared to the transmitting power. Thus, the network's power consumption is calculated as $P_N = \begin{cases} \frac{\frac{T}{2}(p_P+p_{SP})+tp_S}{t+T}, & t>0 \\ p_P, & t=0 \end{cases}$. The PU's throughput is $R_{PU} = \begin{cases} R_P, & t>0 \\ R_{PD}, & t=0 \end{cases}$ and the network's throughput is calculated as $R_N = \begin{cases} \frac{TR_{PC}+tR_{SU}}{t+T}, & t>0 \\ R_{PD}, & t=0 \end{cases}$. So the network's power consumption per unit throughput $P_b$ is equal to $\frac{P_N}{R_N}$. We show corresponding results in Fig. 2.

Fig. 2(a) shows the network's power consumption ($P_N$) versus different PT-PR distances ($d_P$) in cooperation and non-cooperation situations. It is observed that the value of $P_N$ by cooperative spectrum sharing is less than that in non-cooperation when the average channel quality between ST and PR is better than that of PU, i.e., $d_P > d_{SP}$ in Fig. 2(a). With $d_P$ decreasing, the difference of $P_N$ is gradually reducing in the two situations. The reason is that the space of reduction of energy consumption gradually decreases by SU relaying PU's traffic when the average channel gain of PT-PR link gradually approaches that of ST-PR link. When $d_P \leq d_{SP}$, the advantage of the channel gain from ST to PR no longer exists. In this situation, cooperative spectrum sharing is not conducive for reducing the overall energy consumption.

In Fig. 2(b), we present the PU's throughput ($R_P$ for cooperation and $R_{PD}$ for non-cooperation) and that of the network ($R_N$) for different PT-PR distances ($d_P$). It is noted that the network's throughput for non-cooperation is $R_N = R_{PD}$ where $t = 0$. The network's throughput is greatly improved by cooperative spectrum sharing in 'green' communication. Although the network's power consumption $P_N$ does not reduce when the average channel gain of PT-PR link is better than that of ST-SR link, i.e., $d_P \leq d_{SP}$ in Fig. 2(b), SU gets transmission time for its own communication by relaying

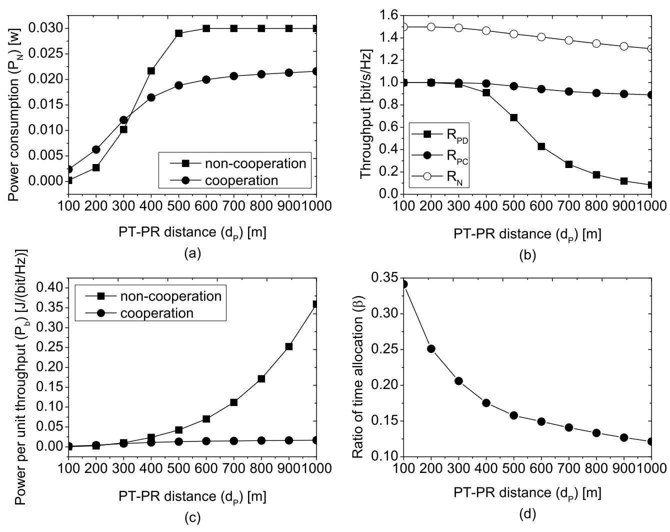


Fig. 2. Variation of (a) minimum power consumption, (b) throughput, (c) minimum power per unit throughput and (d) ratio of time allocation.

PU's traffic. Thus, the network's throughput increases in this case. When the PU's channel quality becomes worse, the PU's throughput is greatly improved by cooperation.

Furthermore, the power consumption per unit throughput ($P_b$) for different PT-PR distances ($d_P$) are shown in Fig. 2(c). We observe that $P_b$ in cooperative spectrum sharing is less than that in non-cooperation where $d_P > 200$m. The PU's transmission power ($p_P$) does not decrease while $P_b$ decreasing by cooperation, when the average channel gains of PT-PR and ST-PR links are comparable, i.e., $d_P = d_{SP} = 300$m in Fig. 2(c). The reason is that SU's transmitting power ($p_S$) for its own data transmission is less than that of PU ($p_P$) because the average channel quality of ST-SR link is better than that of PT-PR link. The performance of $P_b$ outperforms that of the network's power consumption ($P_N$) in Fig. 2(a) because the network's throughput ($R_N$) is improved shown in Fig. 2(b).

Finally, we present the optimal transmission time allocation ratio ($\beta = \frac{t}{T} = \alpha - 1$) for different PT-PR distances ($d_P$) in Fig. 2(d). It is shown that SU can get more transmission time with stronger PU's channel gains. The reason is that: PU's QoS can be guaranteed only with less transmission time when PU's channel quality is stronger. However, the cooperative spectrum sharing does not work for energy saving when $\beta > 0.25$. It means that the improvement of energy efficient is invalid by PU allocating more time to the SU with poor channel quality.

## V. Conclusion

In this paper, we investigate the energy saving problem in a cooperative spectrum sharing communication system, where the cognitive radio node obtains the spectrum access opportunity through helping relaying the primary user's traffic. We obtain the joint optimal power and sharing time allocation strategy in closed form through minimizing the system energy consumption while guaranteeing both primary and cognitive users' quality of service. The results show that cooperative spectrum sharing is always energy efficient when the primary user's channel is poor. Otherwise, the cooperation consumes more energy when the channel of primary user is good and the cooperative relay is not necessary for energy efficiency.

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