Adaptive Energy-Efficient Power Allocation under Imperfect Channel Sensing in OFDM-Based Cognitive Opportunistic Relaying Links

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Abstract: This paper investigates energy efficient power allocation scheme for OFDM-based cognitive opportunistic relaying links (CORL), where secondary users (SUs) may incorrectly sense the unlicensed spectrum and hence transmit data in collision. We aim to maximize the energy efficiency (EE) by optimal and low complexity power allocation design. At first, an energy efficient power allocation optimization problem with imperfect sense is formulated, under the individual power budget and peak primary user's (PU's) interference constraints. Then, we focus on the analysis of the optimal non-convex power allocation problem, which is of great concern for the EE in CORL. At last, with the aid of the fractional programming method, an EE-oriented power allocation policy with low complexity is proposed which used the bisection method to speed up the search of the optimum. Numerical results are provided to corroborate our theoretical analysis and to demonstrate the effectiveness of the proposed schemes.

Key-Words: Cognitive Opportunistic Relay, OFDMA, Energy Efficiency, Power Allocation, Spectrum Sensing Errors, Low Complexity.

1 Introduction

Incorporating cooperation into cognitive radio networks results in substantial performance gains in terms of spectrum efficiency (SE) for both primary users (PUs) and secondary users (SUs) [1]. Besides the SE, the EE becomes a key issue for future wireless networks since energy cost imposes both financial and ecological burden on its development. Especially, EE power allocation is of crucial importance for cognitive relaying network [2].

In recent years, the academia and industry have realized the importance of green communication technologies. For instance, the EE maximization problem in an OFDMA system under a maximum total power constraint in frequency-selective channels is addressed [3]. In [4], the authors studied the trade-off between EE and SE in the downlink of OFDMA networks. They showed that the EE is quasi-concave in the SE. Then based on this observation, a power and subcarrier allocation algorithm is proposed. In the uplink of an OFDMA system, the EE is addressed in [5]. Furthermore, in [6], the EE of two-way relaying was compared with those of the one-way relaying, showing that two-way relay transmission is not always more energy-efficient than one-way relay transmission. Nevertheless, [3]-[6] aims at maximizing the EE of system without taking the interference by SUs in CRNs into account. In [7] proposed a method named as water-filling factor aided search (WFAS) was proposed to maximize EE under multiple constraints with perfect channel state information (CSI) at CR source, but relaying was not considered. In our previous work [8], we propose an optimal power allocation scheme to maximize the EE of OFDMA opportunistic relay which is first proposed in [9] to better exploit the frequency-selective channels. However, [8] has not consider the peak primary PU's interference constraints and spectrum sensing errors. Note that [10] and [11] also studied the EE optimization problem in CR system with imperfect spectrum sensing, but they all focus on the frame design including optimal sensing duration and data transmission duration, as well as the optimal transmission power instead of the power allocation among each subcarriers. Besides, authors in [12] analyze the EE performance of CRNs with imperfect spectrum sensing while relay strategies are not applied. Although a solution for EE maximization problem in relay-aided CRN is proposed [13] and [14], the authors only consider the ideal situation, i.e., ignoring sensing errors.

Based on research in CR relaying system, the motivation of this paper is expressed as follows. In order to further improve the SUs' performance in terms of EE metric, we introducing the opportunistic DF relaying strategy [9] to CR relay-aided networks to better exploit the frequency-selective channels, unlike [5] and [10] where always-relaying protocol was considered. On the other hand, we assume that the SUs can coexist with the PU in the presence of both idle and busy sensing decisions while adapting their transmission power according to the imperfect sensing results, which differs from [12] and [14]. In fact, the perfect spectrum sensing results are unavailable in practice, which makes the past research too idealistic to achieve feasible schemes for real system. Our main contributions of this paper are summarized as follows:

1) An EE system model with imperfect sensing results for CORL is established, subject to the individual power budget and peak primary user's interference constraints.

2) We probe into the optimal power allocation scheme with incorrectly sense. A novel EE-oriented optimal power allocation iterative algorithm is proposed to completely solve the optimization problem.

3) Finally, extensive numerical simulation results corroborate our theoretical analysis and demonstrate the effectiveness of the proposed schemes.

The remainder of this paper is organized as follows. System model is described in Section 2. The EE optimization problem is formulated and solved respectively in Section 3 and 4. Finally, numerical and simulation results are provided in Section 5, followed by conclusions in Section 6.

2 System Model and Problem Formulation

2.1 System Model

We consider a scenario where a two-hop OFDM-based CR system co-exists with a PU in the same geographical location, which comprises one PU, one SU-transmitter (ST), one SU-relay (SR), and one SU-destination (SD). Let denotes the set of the PU's bands $\mathbf{K}=\{1,2,\cdots,|\mathbf{K}|\}$ including the occupied subcarriers set $\mathbf{K_O}$ and spectrum holes (unoccupied subcarriers by PU) set $\mathbf{K_U}$. Thus, we can obtain $\mathbf{K}=\mathbf{K_O}\cup\mathbf{K_U}, \mathbf{K_U}\neq\Phi$. Each of PU's band has a fixed bandwidth of Δf Hz. The opportunistic DF protocol in [9] is used assists ST transmission to SD. The data frame structure for the considered CORL is different from the always relay-aided transmission protocol which is always idle for ST in the second slot. Specifically, every data-transmission session takes two consecutive equal-duration time slots ($TS1$, $TS2$) and OFDM with $k\in\mathbf{K_u}$ subcarrier is used. In the first time slot, the ST radiates OFDM symbols using $P_{s,k}$ as the transmit power for subcarrier k while the SR and SD receive. The ST-to-SD and ST-to-SR channel coefficients for subcarrier k are $h_{sd,k}$ and $h_{sr,k}$, respectively. In the second time slot, we define the subcarriers transmission mode indicator θ_k, which is a binary integer variable, i.e., $\theta_k\in\{0,1\}$, can be expressed as

$$\theta_k=\begin{cases}0, & \text{if subcarrier } k \text{ is selected for DTM}\\ 1, & \text{if subcarrier } k \text{ is selected for RTM}\end{cases} \tag{1}$$

where $\theta_k=1$ represents relay transmission mode (RTM) which means that the SR retransmit OFDM symbols using $P_{r,k}$ as the transmit power. The SR-to-SD channel coefficient is $h_{rd,k}$ for subcarrier k. In band with $\theta_k=0$ represent direct transmission mode (DTM) which means transmission is solely undertaken by the ST in two successive time slots, and the SR is inactive for subcarrier k. Here, we define $\boldsymbol{\theta}\triangleq\{\theta_k\}_{k\in\mathbf{K_U}}$ to facilitate further description. Based on the two signaling intervals, the SD exploits maximum ratio combining (MRC) to retrieve the message. We further assume noise variance within one OFDM subcarrier to be σ_r^2 at SR and σ_d^2 at SD. According to the Shannon capacity formula, the secondary achievable data rate for DTM and RTM over subcarrier k are respectively expressed as

$$R^{sd}=\mathcal{C}\left(P_{s,k}G_{sd,k}\right) \tag{2}$$

$$R_{co}^{sd}=\frac{1}{2}\min\left(\underbrace{\mathcal{C}\left(P_{s,k}G_{sr,k}\right)}_{R^{sr}},\underbrace{\mathcal{C}\left(P_{s,k}G_{sd,k}+P_{r,k}G_{rd,k}\right)}_{R_{co}^{srd}}\right) \tag{3}$$

where $\mathcal{C}(x)\triangleq\log_2(1+x)$, $G_{sd,k}=|h_{sd,k}|^2/\sigma_d^2$, $G_{sr,k}=|h_{sr,k}|^2/\sigma_r^2$ and $G_{rd,k}=|h_{rd,k}|^2/\sigma_d^2$ denote the normalized signal-to-noise ratio (SNR) of each link. Hence, the achievable sum data rate for CORL can be derived as

$$R_{\mathrm{T}}=\sum\nolimits_{k\in\mathbf{K_U}}(1-\theta_k)R^{sd}+\sum\nolimits_{k\in\mathbf{K_U}}\theta_k R_{co}^{sd} \tag{4}$$

where $\mathbf{P_S}\triangleq\{P_{s,k}\}_{k\in\mathbf{K_U}}$ and $\mathbf{P_R}\triangleq\{P_{r,k}\}_{k\in\mathbf{K_U}}$ denote the power allocation policy on ST and SR.

2.2 Interference with Spectrum Sensing Errors

In CR system, PU can access the licensed spectrum at any time and the probability of PU using subcarrier j is denoted by P_j^O. The false alarm probability and detection of subcarrier j is denote as Q_j^f and Q_j^d [15], respectively. Let α_j be the posterior probability of the SU detects subcarrier as being used by PU which is indeed occupied. According to Bayes formula [16], α_j can be derived as

$$\begin{aligned}\alpha_j &= \Pr\left\{H_j = 1 \middle| \widehat{H}_j = 1\right\} \\ &= \frac{\Pr\left\{\widehat{H}_{j,1} \middle| H_{j,1}\right\}\Pr\left\{H_{j,1}\right\}}{\sum_{\Delta=\{0,1\}}\Pr\left\{\widehat{H}_{j,\Delta} \middle| H_{j,\Delta}\right\}\Pr\left\{H_{j,\Delta}\right\}} \\ &= \frac{Q_j^d P_j^O}{Q_j^f\left(1-P_j^O\right)+Q_j^d P_j^O}\end{aligned} \quad (5)$$

where $H_{j,1}$ and $H_{j,0}$ represent the events that PU is active and idle on subcarrier j, and $\widehat{H}_{j,1}$, $\widehat{H}_{j,0}$ are the sensing results that subcarrier j is occupied or unoccupied by PU, respectively. The β_k is the posterior probability of the evidence subcarrier j is really idle given that SU senses it to be unoccupied, which can be expressed as

$$\begin{aligned}\beta_j &= \Pr\left(H_j = 0 \middle| \widehat{H}_j = 0\right) \\ &= \frac{\Pr\left\{\widehat{H}_{j,0} \middle| H_{j,1}\right\}\Pr\left\{H_{j,1}\right\}}{\sum_{\Delta=\{0,1\}}\Pr\left\{\widehat{H}_{j,\Delta} \middle| H_{j,\Delta}\right\}\Pr\left\{H_{j,\Delta}\right\}} \\ &= \frac{\left(1-Q_j^f\right)\left(1-P_j^O\right)}{\left(1-Q_j^d\right)\left(1-P_j^O\right)+\left(1-Q_j^f\right)P_j^O}\end{aligned} \quad (6)$$

There exit two cases subcarrier k may introduce interference to PU. One is subcarrier k is sensed correctly to be occupied by PU, the other is subcarrier k is sensed incorrectly to be unoccupied by PU. Taking above into account, the average interference over subcarrier k with unit transmission power [17] can be written as

$$I_k = \sum_{j\in\mathbf{K_O}} \alpha_i I_{k,j}\left(\theta_k\right) + \sum_{j\in\mathbf{K_U}}\left(1\text{-}\beta_j\right) I_{k,j}\left(\theta_k\right) \quad (7)$$

where $I_{k,j}\left(\theta_k\right)$ indicates that the interference introduced into PU on subcarrier j when ST or SR transmits on subcarrier k with unit transmission power, and it can be expressed as [18]

$$I_{k,j}\left(\theta_k\right) = \int_{\left(k-j-\frac{1}{2}\right)\Delta f}^{\left(k-j+\frac{1}{2}\right)\Delta f}\left(\left(1-\theta_k\right)G_{sp,k} + \theta_k G_{rp,k}\right)\phi(f)df \quad (8)$$

where $G_{sp,k}$ and $G_{rp,k}$ is respectively denoted as the channel gain from ST-to-PU and SR-to-PU over subcarrier k, respectively. $\phi(f) = T_s\left(\sin\left(\pi f T_s\right)/\pi f T_s\right)^2$ represents the power spectral density (PSD) of OFDM transmitted signal, and T_s represents the duration of OFDM symbol.

2.3 Problem Formulation in CORL

The overall transmission power consumption in a unit frame contains the transmit power on ST and SR, which is calculated by

$$P_{tr} = \frac{1}{2}\left(\sum_{k\in\mathbf{K_U}} P_{s,k} + \sum_{k\in\mathbf{K_U}}\left(\left(1-\theta_k\right)P_{s,k} + \theta_k P_{r,k}\right)\right) \quad (9)$$

To transmit data, we assume that the circuit power consumption of equipment has nothing to do with the state of transmission system, and its average value is constant [11][19]. In conclusion, the system total power consumption consists of overall transmit power P_{tr} and circuit consumptions P_{cc}. Therefore, considering power amplifier efficiency $\rho\in[0,1]$, the total circuit power consumption can be expressed as

$$P_{TC} = \underbrace{\frac{1}{\rho}\sum_{k\in\mathbf{K_U}}\frac{1}{2}\left(\left(2-\theta_k\right)P_{s,k} + \theta_k P_{r,k}\right)}_{\text{overall transmit power on SUs, } P_{tr}} + \underbrace{P_{\mathrm{C}}^{\mathrm{S}} + P_{\mathrm{C}}^{\mathrm{R}}}_{\text{circuit power, } P_{cc}} \quad (10)$$

where P_C^S, P_C^R are denoted as the ST and SR circuit consumption. Like [10]-[14], [19], the EE measured by the 'Throughput per Joule' metric is defined as radio of total throughput and total power. Hence, maximizing the average EE metric for the CORL system can be written as

$$\left\{\mathbf{P_S^*}, \mathbf{P_R^*}\right\} = \arg\max_{\{\mathbf{P_S},\mathbf{P_R}\}} EE^{(\theta)}\left(\mathbf{P_S},\mathbf{P_R}\right)\left(= \frac{R_T\left(\mathbf{P_S},\mathbf{P_R}\right)}{P_{TC}}\right) \quad (11)$$

where $\mathbf{P_S^*} \triangleq \left\{P_{s,k}^*\right\}_{k\in\mathbf{K_U}}$ and $\mathbf{P_R^*} \triangleq \left\{P_{r,k}^*\right\}_{k\in\mathbf{K_U}}$ represent the optimal power allocation policy on ST and SR.

3 Problem Analysis on EE Power Allocation

Here again, our goal is to maximize the SUs' transmission EE while meeting the interference constraints due to the PU. Let us define $\mathbf{D} \triangleq \left\{\boldsymbol{\theta}, \mathbf{P_S}, \mathbf{P_R}\right\}$ for easy of presentation. Hence, we can formulate the EE maximization problem for CORL as

$$\mathcal{OP}1: \max_{\mathbf{D}} \frac{\sum_{k\in\mathbf{K_U}}\left(1-\theta_k\right)R^{sd} + \frac{1}{2}\sum_{k\in\mathbf{K_U}}\theta_k \min\left(R^{sr}, R_{co}^{srd}\right)}{\frac{1}{2\rho}\sum_{k\in\mathbf{K_U}}\left(\left(2-\theta_k\right)P_{s,k} + \theta_k P_{r,k}\right) + P_C^S + P_C^R} \quad (12)$$

$$s.t. \quad \sum_{k\in\mathbf{K_U}} P_{s,k} \le P_S^{\max} \quad (13)$$

$$\sum_{k\in\mathbf{K_U}} P_{r,k} \le P_R^{\max} \quad (14)$$

$$\sum_{k\in\mathbf{K_U}} P_{s,k} I_k\left(\theta_k\right) \le I_P^{th} \quad (15)$$

$$\sum_{k\in\mathbf{K_U}}\left(\left(1-\theta_k\right)P_{s,k} + \theta_k P_{r,k}\right) I_k\left(\theta_k\right) \le I_P^{th} \quad (16)$$

$$\theta_k \in \{0,1\}, \quad k\in\mathbf{K_U} \quad (17)$$

$$P_{s,k} \ge 0, \ P_{r,k} \ge 0, \quad k\in\mathbf{K_U} \quad (18)$$

where $P_S^{\max}$ and $P_R^{\max}$ are denoted as the individual power limitations at ST and SR, respectively. I_P^{th} signifies the maximum interference power threshold prescribed by the PU. The constraint Eq.(15) and

Eq.(16) in $\mathcal{OP}1$ assure that interference to PU is less than a specified threshold in TS1 and TS2. In its current form Eq.(12), it's obvious that the joint optimization problem $\mathcal{OP}1$ is a non-convex mixed-integer nonlinear program (MINLP) which is NP-hard. However, the aim of this work is to maximize the EE metric of Eq.(12) subject to under the individual power budget and peak PU's interference constraints. According to the idea of subcarrier transmission mode indicator in [9], we introduced a straightforward method for CORL system for which the subcarrier k is selected RTM if $G_{sd,k} \le G_{sr,k}$ and $G_{sd,k} \le G_{rd,k}$. Otherwise, the DTM offers a better capacity. Therefore, we denoted two sets $\mathbf{S_{DT}}$ and $\mathbf{S_{RT}}$ to represent DTM and RTM, respectively, which are defined as follows:

$$\mathbf{S_{DT}} = \left\{ k \left| \begin{matrix} \left[G_{sd,k} > G_{sr,k} \right] \\ or \\ \left[G_{sd,k} < G_{sr,k} \ and \ G_{sd,k} > G_{rd,k} \right] \end{matrix} \right. \right\} \tag{19}$$

$$\mathbf{S_{RT}} = \left\{ k \mid G_{sd,k} \le G_{sr,k} \ and \ G_{sd,k} \le G_{rd,k} \right\} \tag{20}$$

In addition, taking account of the total rate relay-assisted cooperating transmission system is limited by the smaller link, the most economical choice is $\mathcal{C}\left(P_{s,k}G_{sd,k} + P_{r,k}G_{rd,k}\right) = \mathcal{C}\left(P_{s,k}G_{sr,k}\right)$, meaning, we have the following relationship

$$P_{s,k}G_{sr,k} = P_{s,k}G_{sd,k} + P_{r,k}G_{rd,k} \ \ if \ \theta_k = 1 \tag{21}$$

then $P_{r,k} = \chi_k P_{s,k}$, where

$$\chi_k = \left(G_{sr,k} - G_{sd,k}\right) / G_{rd,k} \tag{22}$$

Based on this classification, $\mathcal{OP}1$ can be reformulated as

$$\mathcal{OP}2: \max_{\mathbf{P_S}} \frac{R_T\left(\mathbf{P_S}\right)}{\frac{1}{2\rho}\left(\sum_{k\in\mathbf{S_{DT}}} 2P_{s,k} + \sum_{k\in\mathbf{S_{RT}}} \left(1+\chi_k\right)P_{s,k}\right) + P_C} \tag{23}$$

$$s.t. \ \ \sum\nolimits_{k\in\mathbf{S_{DT}}} P_{s,k} + \sum\nolimits_{k\in\mathbf{S_{RT}}} P_{s,k} \le P_S^{\max} \tag{24}$$

$$\sum\nolimits_{k\in\mathbf{S_{RT}}} P_{s,k} \le P_R^{\max} \tag{25}$$

$$\sum\nolimits_{k\in\mathbf{S_{DT}}} P_{s,k}I_k + \sum\nolimits_{k\in\mathbf{S_{RT}}} P_{s,k}I_k \le I_P^{th} \tag{26}$$

$$\sum\nolimits_{k\in\mathbf{S_{RT}}} \left(1+\chi_k\right)P_{s,k}I_k \le I_P^{th} \tag{27}$$

$$P_{s,k} \ge 0, \quad k \in \mathbf{S_{DT}} \cup \mathbf{S_{RT}} \tag{28}$$

where $P_C = P_C^S + P_C^R$, $R_T\left(\mathbf{P_S}\right)$ represents the capacity for CORL system. It can be expressed as

$$R_T\left(\mathbf{P_S}\right) = \sum\nolimits_{k\in\mathbf{S_{DT}}} R^{sd}\left(\mathbf{P_S}\right) + \sum\nolimits_{k\in\mathbf{S_{RT}}} R_{co}^{sd}\left(\mathbf{P_S}\right) \tag{29}$$

From $\mathcal{OP}2$, we observe that constraints are either linear or convex, but the objective function Eq.(23) is not a concave function. Actually, $\mathcal{OP}2$ belongs to the quasi-concave programming, which has been proved in our previous work [8]. In the next section, we will show that we can obtain optimal solution of EE maximization problem by exploiting special structure of the objective function. Firstly, to this end, the monotonically increasing and strictly concave characteristic of the numerator $R_T\left(\mathbf{P_S}\right)$ in Eq.(23) is summarized in Theorem1.

Theorem 1. Given $\boldsymbol{\theta}$, $R_T\left(\mathbf{P_S}\right)$ for CORL is monotonically increasing and strictly concave with respect to (w.r.t.) $\mathbf{P_S}$.

Proof: From Eq.(4), $R_T\left(\mathbf{P_S}\right)$ can be expressed as

$$R_T\left(\mathbf{P_S}\right) = (1-\boldsymbol{\theta})R^{sd}(\mathbf{P_S}) + \boldsymbol{\theta}R_{co}^{sd}\left(\mathbf{P_S}\right) \tag{30}$$

According to [20], it is easy to know that R^{sd}, R^{sr} and R_{co}^{srd} are monotonically increasing and strictly concave w.r.t $\mathbf{P_S}$. On the other hand, we observe that the subcarriers transmission mode indicator $\boldsymbol{\theta} = \left\{\theta_k \in \{0,1\}\right\}_{k\in\mathbf{K_U}} \ge 0$ is defined as nonnegative integers, so we only need to prove that the second item in Eq.(30), i.e., $R_{co}^{sd}\left(\mathbf{P_S}\right)$ is monotonically increasing and strictly concave w.r.t $\mathbf{P_S}$. Considered the relationships in Eq.(21) and Eq.(22), we can rewrite Eq.(3) as $R_{co}^{sd}\left(\mathbf{P_S}\right) = \min\left\{R^{sr}\left(\mathbf{P_S}\right), R_{co}^{srd}(\chi_k\mathbf{P_S})\right\}$. Then we have

$$\begin{aligned} R_{co}^{sd}\left(\xi p_1 + (1-\xi)p_2\right) &= \min\left\{R^{sr}\left(\xi p_1 + (1-\xi)p_2\right),\right. \\ &\qquad \left. R_{co}^{srd}\left(\xi\chi_1 p_1 + (1-\xi)\chi_2 p_2\right)\right\} \\ &> \min\left\{\xi R^{sr}\left(p_1\right) + (1-\xi)R^{sr}\left(p_2\right),\right. \\ &\qquad \left. \xi R_{co}^{srd}\left(\chi_1 p_1\right) + (1-\xi)R_{co}^{srd}\left(\chi_2 p_2\right)\right\} \\ &\ge \xi\min\left\{R^{sr}\left(p_1\right), R_{co}^{srd}\left(\chi_1 p_1\right)\right\} + \\ &\qquad (1-\xi)\min\left\{R^{sr}\left(p_2\right), R_{co}^{srd}\left(\chi_2 p_2\right)\right\} \\ &= \xi R_{co}^{sd}\left(p_1\right) + (1-\xi)R_{co}^{sd}\left(p_2\right) \end{aligned} \tag{31}$$

where $0 \le \xi \le 1$, $\forall p_1, p_2 \in \mathbf{dom}R_{co}^{sd}(\mathbf{P_S})$. Hence, $R_T\left(\mathbf{P_S}\right)$ is increasing and strictly concave w.r.t. $\mathbf{P_S}$.

4 Adaptive Power Allocation to Maximize EE

4.1 Adaptive Power Allocation

From Theorem 1, we follow that the numerator $R_T\left(\mathbf{P_S}\right)$ in Eq.(24) is a concave function, and the denominator of Eq.(24) is affine function of SUs' power. Besides, all the constraints are convex set. Inspired by the Dinkelbach's algorithm in [21], we can transform this problem into a parameterized convex maximization problem. Primarily, a new objective function is defined as

$$T\left(\mathbf{P_S},q\right)=R_T\left(\mathbf{P_S}\right) -q\left(\frac{1}{2\rho}\left(\sum_{k\in\mathbf{S_{DT}}}2P_{s,k}+\sum_{k\in\mathbf{S_{RT}}}\left(1+\chi_k\right)P_{s,k}\right)+P_C^S+P_C^R\right) \tag{32}$$

where q is a positive parameter and can be interpreted as a pricing factor for SUs' power consumption. Hence, another problem is written as

$$\mathcal{OP}3:\max_{\mathbf{P_S},q}T\left(\mathbf{P_S},q\right) \quad s.t.\ (27),\ (28),\ (29),\ (30),\ (31) \tag{33}$$

Let $\mathcal{S}$ denote the feasible region of $\mathcal{OP}2$ and $\mathcal{OP}3$. Define $F\left(q\right)=\max_{\mathbf{P_S}}\left\{T\left(\mathbf{P_S},q\right)\middle|\mathbf{P_S}\in\mathcal{S}\right\}$ as the maximum value of $\mathcal{OP}3$ with each fixed q. Then, the optimal value and solution of $\mathcal{OP}3$ can be define as

$$f\left(q\right)=\arg\max_{\mathbf{P_S}}\left\{T\left(\mathbf{P_S},q\right)\middle|\mathbf{P_S}\in\mathcal{S}\right\} \tag{34}$$

The following lemma introduced by Dinkelbach's algorithm [21] can relate $\mathcal{OP}2$ and $\mathcal{OP}3$, and the detailed proof of Lemma 1 can also be found in [21].

Lemma 1. The optimal solution $\mathbf{P_S^*}$ achieves the optimal value q^* of $\mathcal{OP}2$, i.e., $q^*=\max_{\mathbf{P_S}}\left\{T\left(\mathbf{P_S},q\right)\middle|\mathbf{P_S}\in\mathcal{S}\right\}=EE^{(\mathbf{0})}(\mathbf{P_S^*})$, if and only if

$$F\left(q^*\right)=0 \ \ and \ \ f\left(q^*\right)=\mathbf{P_S^*} \tag{35}$$

This Lemma indicates that at the optimal parameter q^*, the optimal solution to $\mathcal{OP}3$ is also the optimal solution to $\mathcal{OP}2$. Hence, solving $\mathcal{OP}2$ can be realized by finding the optimal power allocation of $\mathcal{OP}3$ for a given q and then update q until Eq.(34) is established. For a given q, the optimal power allocation can be obtained using convex theory [20] because of the convex characteristic of $\mathcal{OP}3$. Hence, the existing water-filling power allocation approach gives the solution to it [22]. However, besides adapting the power policies on all subcarriers, we need to consider subcarrier transmission mode. The Lagrange function for $\mathcal{OP}3$ is constructed as

$$\begin{aligned}\mathcal{L}\left(\mathbf{P_S},q,\boldsymbol{\lambda}\right)=&-T\left(\mathbf{P_S},q\right)\\ &+\lambda_1\left(\sum_{k\in\mathbf{S_{DT}}}P_{s,k}+\sum_{k\in\mathbf{S_{RT}}}P_{s,k}-P_S^{\max}\right)\\ &+\lambda_2\left(\sum_{k\in\mathbf{S_{RT}}}P_{s,k}-P_R^{\max}\right)\\ &+\lambda_3\left(\sum_{k\in\mathbf{S_{DT}}}P_{s,k}I_k+\sum_{k\in\mathbf{S_{RT}}}P_{s,k}I_k-I_P^{th}\right)\\ &+\lambda_4\left(\sum_{k\in\mathbf{S_{RT}}}\left(1+\chi_k\right)P_{s,k}I_k-I_P^{th}\right)\end{aligned} \tag{36}$$

where with nonnegative Lagrangian multipliers λ_1, λ_2, λ_3 and λ_4 for constraints Eqs.(24)-(28). The dual problem of $\mathcal{OP}3$ is given by

$$\mathcal{D}=\min_{\{\lambda_i\}_{i=1}^4}\max_{q,\mathbf{P_S}}\mathcal{L}\left(q,\left\{P_{s,k}\right\}_{k\in\mathbf{K_U}},\left\{\lambda_i\right\}_{i=1}^4\right) \tag{37}$$

Using the Karush-Kuhn-Tucker (KKT) conditions [20], we can obtain the optimal power allocation as

$$P_{s,k}^*=\left[\frac{\rho\log_2 e}{\rho\xi_k+q}-\frac{1}{G_{sd,k}}\right]^+,\ \forall k\in\mathbf{S_{DT}} \tag{38}$$

$$P_{s,k}^*=\left[\frac{\rho\log_2 e}{\rho\vartheta_k+q\left(1+\chi_k\right)}-\frac{1}{G_{sr,k}}\right]^+,\ \forall k\in\mathbf{S_{RT}} \tag{39}$$

where $\vartheta_k=2\left(\lambda_1+\lambda_2+\left(\lambda_3+\lambda_4\left(1+\chi_k\right)\right)I_k\right)$ and $\xi_k=\lambda_1+\lambda_3 I_k$, and $[x]^+$ denotes $\max\{0,x\}$. In addition, combining with the proportional relation revealed in Eq.(22), when subcarrier k is used RTM communication, i.e., $k\in\mathbf{S_{RT}}$. The corresponding relay transmission power can be expressed as

$$P_{r,k}^*=\chi_k P_{s,k}^*,\ \forall k\in\mathbf{S_{RT}} \tag{40}$$

To derive the optimal Lagrange multipliers $\boldsymbol{\lambda}^*=\left\{\lambda_i^*\right\}_{i=1}^4$, the incremental-update based subgradient method can be used in [23], that is, we iteratively update $\boldsymbol{\lambda}$ based on the following iteration procedure

$$\lambda_1^{[l+1]}=\lambda_1^{[l]}-\mu^{[l]}\left(P_S^{\max}-\sum_{k\in\mathbf{S_{DT}}}P_{s,k}-\sum_{k\in\mathbf{S_{RT}}}P_{s,k}\right) \tag{41}$$

$$\lambda_2^{[l+1]}=\lambda_2^{[l]}-\mu^{[l]}\left(P_R^{\max}-\sum_{k\in\mathbf{S_{RT}}}P_{s,k}\right) \tag{42}$$

$$\lambda_3^{[l+1]}=\lambda_3^{[l]}-\mu^{[l]}\left(I_P^{th}-\sum_{k\in\mathbf{S_{DT}}}P_{s,k}I_k-\sum_{k\in\mathbf{S_{RT}}}P_{s,k}I_k\right) \tag{43}$$

$$\lambda_4^{[l+1]}=\lambda_4^{[l]}-\mu^{[l]}\left(I_P^{th}-\sum_{k\in\mathbf{S_{RT}}}\left(1+\chi_k\right)P_{s,k}I_k\right) \tag{44}$$

where l refers to the iteration index and $\mu^{[l]}>0$ denotes a sufficiently small positive step size for the *l-th* iteration, and it is a sequence of step size which is defined in many types in [23]. It should to mention that small step size leads to slow convergence.

Besides, each element of the gradient depends on the corresponding subcarrier's channel gain, which potentially differs from each other by orders of magnitude. Hence, a line search of the optimal step size needs to cover a large range to assure global convergence on all subcarriers, which is computationally expensive. Therefore, in order to find the optimal step size, like [3], we define $f_l\left(u\right)=\left[\boldsymbol{\lambda}^{[l]}-u\nabla\mathcal{L}\left(\boldsymbol{\lambda}^{[l]}\right)\right]^+$, which has also been proved to be concave in $\mu^{[l]}$, and can quickly obtain the optimal step value of $u^{[l]*}$ by using bisection search algorithm summarized in [3]. So, jointing the fractional programming and bisection methods, an EE-oriented power allocation iterative optimization algorithm for CORL called ECORL is provided, which is described in the Table 1 to solve the power allocation of $\mathcal{OP}1$.

Table1. Iterative Power Allocation for $\mathcal{OP}1$.

Algorithm 1 EE power allocation for CORL

Input: the error tolerance $\varsigma > 0$, $\delta > 0$ and the maximum iteration number *MaxIter*;

Output: optimal EE power allocation of $\mathcal{OP}1$;

Initialize maximum EE $q^{[0]} = q_0$, the iteration index $n = 0$ and $l = 0$, dual variables $\boldsymbol{\lambda}^{[0]} = \boldsymbol{\lambda}_{initial}$;

Compute $G_{sr,k}, G_{sd,k}, G_{rd,k} \left| \forall k \right.$, **Then**

Obtain $\boldsymbol{\theta}$ using Eq.(19) and Eq.(20);

While ($\left| F\left(q^{[n]}\right) \right| > \varsigma$ and $n \le MaxIter$) **do**

Update $\boldsymbol{\lambda}$ via the subgradient method as follow:

Repeat

Step1 Compute $P_{s,k}^{[l]}, \forall k \in \mathbf{S_{DT}}$ and $P_{s,k}^{[l]}, \forall k \in \mathbf{S_{RT}}$ through Eqs.(38)-(39) respectively;

Step2 Find the optimal step size $u^{[l]*}$ by using the bisection algorithm described in [23] ;

Step3 Update $\boldsymbol{\lambda}$ according to Eqs.(41)-(44);

Step4 Calculate $\Delta\boldsymbol{\lambda} = \Delta\boldsymbol{\lambda}^{[l+1]} - \Delta\boldsymbol{\lambda}^{[l]}$ and Set $l = l + 1$;

Until $\left\| \Delta\boldsymbol{\lambda} \right\| < \delta$ ($\boldsymbol{\lambda}$ converges)

Set $n = n + 1$, Obtain $\mathbf{P_S^*}$ by Eqs.(38)-(39);

Calculate $\mathbf{P_R^*}$ on SR according to the Eq.(22);

Update $q^{[n]} = EE^{(\boldsymbol{\theta})}\left(\mathbf{P_S^*}, \mathbf{P_R^*}\right)$ through Eq.(23);

End while

Return $q^* = q^{[n]}$, the ξ-optimal solution $\mathbf{P_S^*}, \mathbf{P_R^*}$ of $\mathcal{OP}1$ and calculate the EE and capacity for CROL.

Remark1. Note that in the case of $q = 0$, EE maximization problem is equivalent to SE maximization. Consequently, for given maximum iteration number *MaxIter* and error tolerance ς and δ, the optimal EE and SE power allocation policy of $\mathcal{OP}1$ can be easily obtained by ECORL, which will be validated by the simulation in Section 5.

4.2 Coverage and Complexity Analysis

The proposed algorithm ECORL summarized in Table1 will always converge to optimal provided by Theorem 2. Meaning, for every ς, the power policy set $\mathbf{P_S}$ that maximizes $T(\mathbf{P_S}, q)$ is found. The algorithm execution stops if q is zero or less than the ς value.

Theorem 2. The ECORL will always converge to optimal.

Proof: To proof the convergence of ECORL, we let

$$T(\mathbf{P_S}, q) = R_T(\mathbf{P_S}) - qE(\mathbf{P_S}) \tag{45}$$

for ease of presentation, where $E(\mathbf{P_S})$ denotes the energy consumption in CORL system, and can be written as

$$E(\mathbf{P_S}) = \frac{1}{2\rho}\left(\sum_{k\in\mathbf{S_{DT}}} 2P_{s,k} + \sum_{k\in\mathbf{S_{RT}}} (1+\chi_k)P_{s,k}\right) + P_C^S + P_C^R \tag{46}$$

Before going into the proof of convergence, we will first discuss an observation that $F(q)$ is decreasing in q. For the sake of generality, we assume $q_1 < q_2, (q_1, q_2 \in \mathcal{S})$, then

$$\begin{aligned} F(q_2) &= \max_{\mathbf{P_S}} \left\{ R_T(\mathbf{P_S}) - q_2 E(\mathbf{P_S}) \middle| \mathbf{P_S} \in \mathcal{S} \right\} \\ &= R_T(\mathbf{P_S^*}) - q_2 E(\mathbf{P_S^*}) < R_T(\mathbf{P_S^*}) - q_1 E(\mathbf{P_S^*}) \\ &< \max_{\mathbf{P_S}} \left\{ R_T(\mathbf{P_S}) - q_1 G(\mathbf{P_S}) \middle| \mathbf{P_S} \in \mathcal{S} \right\} = F(q_1) \end{aligned} \tag{47}$$

From Eq.(47), we know that $F(q)$ is decreasing in q. To proof the convergence of ECORL, we only need to show that $F(q)$ becomes smaller than ς with the number of iterations. We now show that q is non-increasing in successive iterations of the algorithm. We have

$$\begin{aligned} T\left(\mathbf{P_s^{*[n-1]}}, q^{[n]}\right) &\le \max\left\{ T\left(\mathbf{P_s^{*[n-1]}}, q^{[n]}\right) \middle| \mathbf{P_S} \in \mathcal{S} \right\} \\ &= F\left(q^{[n]}\right) = R_T\left(\mathbf{P_S^{*[n]}}\right) - q^{[n]} E\left(\mathbf{P_S^{*[n]}}\right) \\ &= q^{[n+1]} E\left(\mathbf{P_S^{*[n]}}\right) - q^{[n]} E\left(\mathbf{P_S^{*[n]}}\right) \\ &= \left(q^{[n+1]} - q^{[n]}\right) E\left(\mathbf{P_S^{*[n]}}\right) \end{aligned} \tag{48}$$

Now, it follows that $q^{[n+1]} \ge q^{[n]}$, because $G\left(\mathbf{P_S^{*[n]}}\right) > 0$. From above observation, we have $F(q)$ is decreasing in q and q is non-increasing in successive iterations of ECORL. Therefore, $F(q)$ is non-increasing in successive iterations. Furthermore, $F\left(q^{[n]}\right)$ does become zero from Lemma 1, which follows that $F\left(q^{[n]}\right)$ does become smaller than ς. Therefore, The ECORL algorithm will always converge to optimal.

In addition, as shown in Table1, the ECORL has two iterations, one is for the total individual power constraint and the other is for the Lagrange multiplier $\boldsymbol{\lambda}$ for the total power constraint. The complexity of ECORL can be expressed as $O\left(N_f N_s N_c\right)$, where N_f, N_s respectively denote the iteration numbers of the while-loop and repeat-loop in ECORL and N_c represent the number of subcarrier realizations. Specially, N_f and N_s rely on the choice of the corresponding error tolerance ς and δ, respectively.

5 Simulation Results

In this section, we present numerical results to illustrate the performance of the proposed EE-maximizing power adaptation methods. Consider the scenario as following, the location of ST is (0,0)*m*, the coordinate of PU, SR and SD are fixed on (500,288)*m*, (500,-288)*m* and (1000,0)*m* respectively. We consider the CR relay-aided system consists of $\mathbf{K}=64$ subcarriers, the probability of subcarrier vacant $\geq 50\%$. The bandwidth of each subcarrier Δf and the duration of the OFDM symbol T_s in $TS1$, $TS2$ are assumed as $0.3125MHz$, $4us$, respectively. Further define circuit power consumption $P_C^S=3W$, $P_C^R=2W$, $\rho=1$, $P_S^{\max}=P_R^{\max}=P^{th}$ and the noise variance $\sigma_d^2=\sigma_r^2=\sigma_p^2=10^{-6}W$. In the primary network, we assume the activity probability $H_{j,1}$ equals to $0.8\cdot\exp\left(-(i-c)^2/50\right)$, where $c=16$. For ease of analysis, the detection Q_j^d and false alarm Q_j^f are uniformly distributed over $[0.95,0.99]$ and $[0.05,0.1]$. Channel complex gains h_k are picked from a Rayleigh fading channel with the following distribution $h_k=\mathcal{CN}\left(0,1/L(1+d)^{\alpha}\right)$ [9], where the path loss exponent $\alpha=3$, distance d *m*, and the number of taps $L=16$. Finally, given $|h_k|^2$, σ_d^2, σ_r^2, σ_p^2 the channel gains to noise power ratios $G_{sd,k}$, $G_{sr,k}$, $G_{rd,k}$, $G_{sp,k}$ and $G_{rp,k}$ are calculated as described in Section 2.

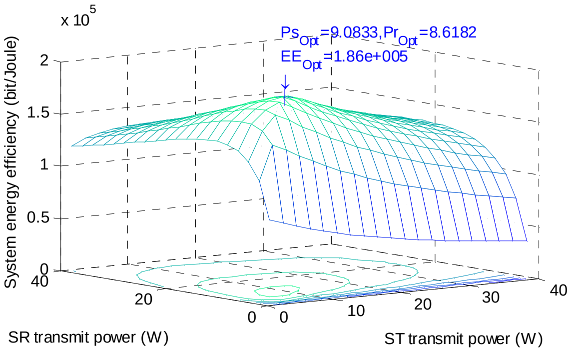

Fig.1 System EE versus both Ps and Pr.

First, the three-dimensional diagram is shown in Fig.1 to analyze the joint variations EE, Ps and Pr while satisfying the individual power budget and peak PU's interference constraints. It can be clearly seen that the curve first increase dramatically and then decrease gradually, which is consistent with quasi-concavity property of the $EE^{(0)}(\mathbf{P_S},\mathbf{P_R})$ function of CORL system. Hence, there exists an global optimal value for energy efficient transmission which maximizes the average EE metric. It can also be noted that $EE_{opt}=1.86\times10^5\,bit/Joule$, corresponding power allocation policy on the ST and SR values obtained are $Ps_{Opt}=9.0833W$ and $Pr_{Opt}=8.6182W$. Besides, we also found that we should use low power transmission to guarantee high EE rather than augment the transmission power budget.

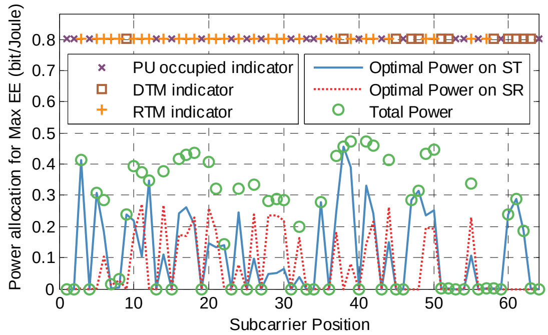

Fig.2 Power allocation on SU's each subcarrier link with maximizing EE

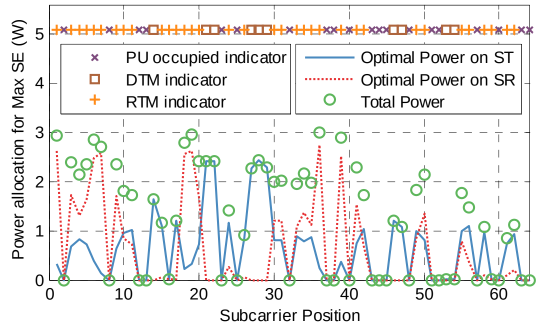

Fig.3 Power allocation on SU's each subcarrier link for maximizing SE

Second, Fig.2 and Fig.3 respectively present the power allocation for maximize EE (EE-Max) and maximize SE (SE-Max) versus each subcarrier link when running ECORL algorithm. As shown in Fig.2 and Fig.3, the notation (×) indicates the subcarrier is occupied by PU, and the notation (+) and (□) at the top of the figure signify the opportunistic relay link transmission mode, i.e., $\theta_k=1$ and $\theta_k=0$ respectively. It is needed to mention that the corresponding power on SR has to be used over two successive time slots (value shown by the solid curve) when notation (□) is active. It can be shown that under the power limitations and peak PU's interference constraints, the individual power budget is split ted among ST power (solid line) and SR power (dotted line) appropriately and effectively, which demonstrates that ECORL algorithm has excellent performance on power allocation both for EE-Max and SE-Max schemes. Meanwhile, EE-Max problem is equivalent to SE-Max when we set

$q=0$ in ECORL algorithm, which confirms the conclusions in Remark1.

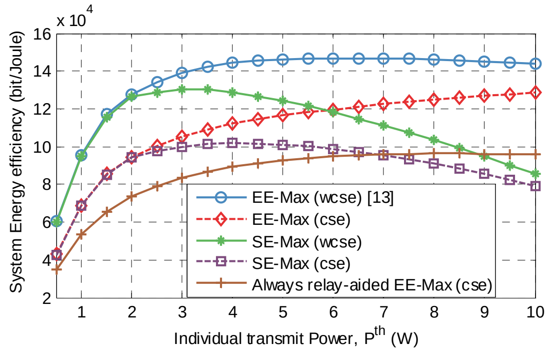

Fig.4 System EE versus P^{th}

Third, Fig.4 demonstrates the EE-Max and SE-Max solved by the proposed ECORL algorithm with/without considering sensing errors (cse/wcse) with respect to P^{th} where the interference threshold $I_P^{th}=1\times10^{-3}W$. Here, the maximizing EE without considering sensing errors is obtained by the proposed in [13] to facilitate comparison. In Fig.4, as P^{th} increases, the EE is first increasing and then decreasing, because when P^{th} becomes larger, the EE performance is subject not to the individual power constraint, but the interference constraint. Besides, the interference constraint is first gradually bound and then strictly bound. From the figure, we observe that the EE by the proposed method first is the same as that by maximizing SE, while is larger than the later when transmitted power goes larger. It also conveys that the EE without sensing errors is better than that with sensing errors. More importantly, we found that the opportunistic relay protocol as compared to always relay-aided transmission protocol is able to effectively improve performance in terms of EE metric. This is because that introducing the opportunistic DF relaying strategy into CR relay-aided networks can be better exploit the frequency-selective channels.

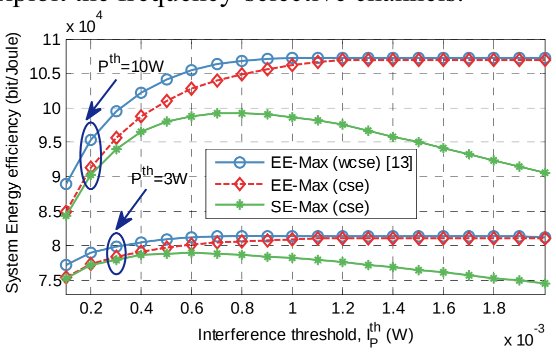

Fig.5 System EE versus I_P^{th}

In Fig.5, we illustrate the EE versus the interference threshold I_P^{th} with/without considering sensing errors (cse/wcse) under different individual total transmit power. It can be observed that the greater total individual transmit power, the higher EE. When the transmit power is relatively high, e.g., $P^{th}=10W$, the EE performance is mainly decided by the interference threshold. However, when the transmit power is low enough, e.g., $P^{th}=3W$, the EE is constrained by the total transmit power and will be constant as the interference threshold increases. Also, the figure shows that the performance of ECORL which have taken spectrum sensing errors into consideration have a reasonable loss than that without considering sensing errors depending on the value of the total transmit power. When the interference I_P^{th} constraints are relatively small, the EE achieved without considering sensing errors [13] is about 6.5% larger than that gained considering sensing errors. This is due to the fact that the strategy proposed in [13] is EE-Max with the total power and interference constraints, and it does not consider sensing errors. Besides, we found the error gap caused by imperfect sensing will become smaller as I_P^{th} increases.

6 Conclusion

In this paper, we have studied the resource allocation problem for EE power allocation in CORL with spectrum sensing errors considered. To maximize the EE of the SUs under joint individual transmit power and interference constraints, we proposed an optimal power allocation algorithm using equivalent conversion and transform the equivalent problem into a corresponding Lagrangian dual problem. The simulation results show that when imperfect spectrum sensing is not taking into account, excessive interference will be introduced to PU, however, the EE is about 6.5% larger than obtained by ECORL method. Meanwhile, the proposed strategy can improve EE significantly compared to the always relay-aided scheme in CR networks. Future research work will involve energy efficient rate-constraint resource allocation for green heterogeneous cognitive radio system.

Acknowledgments

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