

# Robust Spectrum-Energy Efficiency for Green Cognitive Communications



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## 1 Introduction

Cognitive radio technologies are envisaged to alleviate the problems of both inefficient utilization and relative scarcity of spectrum by opportunistically exploiting the existing licensed spectrum. However, due to the growth of low power consumption devices in massive Internet of Things and 5G communication environments, energy efficiency also faces the serious challenges and attracts the researchers more attention. Therefore, in a wireless communication system, two major challenges are to achieve high spectral and energy efficiency.

To enhance both spectrum and energy efficiencies of the wireless communication system, so that to achieve green cognitive communication in the future wireless networks, one of the possible solution for these two challenges is radio frequency (RF) energy harvesting cognitive radio network (EH-CRN) [1]. For this EH-CRN technique, it allows cognitive users to harvest electromagnetic waves from ambient radio frequency sources, and convert them into power energy which can be used for wireless transmission. In cognitive radio networks (CRNs), the radio frequency signals transmitted by the licensed users (also named as primary users, PUs) would be no longer give rise to interference for the cognitive radio users (also named as secondary users, SUs) provided that the capability of energy harvesting is integrated

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into SUs, but can be identified as a green energy harvesting resources. By taking advantage of this technology, SUs can get the utmost out of both the spectrum and energy of PUs. As for the state-of-art of EH-CRNs research, they have been studied operating in interweave mode in [2–4], overlay mode in [5–7] and underlay mode in [7–10].

In interweave mode EH-CRNs, SUs first harvest RF energy from ambient PUs, and then sense the state of PUs and opportunistically access the licensed spectrum if PUs are inactive. In [2], the selection problem of dynamic channels in a multi-channel RF-powered CRN was discussed to obtain the optimal channel by formulating a Markov decision process problem. Then, a dynamic centralized cooperative spectrum sensing scheme and its corresponding access policy were proposed to achieve the maximized throughput with the available energy for EH-CRNs in [3]. In [4], under energy causality and collision constraints, the authors proposed an optimal spectrum sensing policy to maximize the expected total throughput of SUs in EH-CRNs.

In overlay mode EH-CRNs, SUs supply RF energy to both PUs and SUs on condition that there are harmonious collaboration between PUs and SUs. On this aspects, the maximization of sum-throughput is studied in [5], wherein a hybrid access point first transfers wireless energy for a number of SUs and supplies information for PUs, and then collects sensed data from SUs. Similarly, the maximization of energy efficiency was discussed in [6], at the same time, the uplink scheduling and cooperative power control were also considered. In [7], a hybrid underlay-overlay EH-CRNs was modeled, and also the access strategy combined with the framework of partially observable Markov decision process was proposed to maximize the system long-term throughput.

In underlay mode EH-CRNs, SUs work utilizing their harvested RF energy until the interference to PUs exceed a tolerable threshold value. In [8], an efficient strategy of relay selection was designed to determine when and which relay should be selected to minimize outage transmission probability in EH-CRNs with spatial randomly distributed SUs. Moreover, the maximization problem of end-to-end throughput in terms of optimal time and power allocation is studied for multi-hop EH-CRNs in [9]. Recently, an optimal offline harvest-or-transmit strategy is proposed in [10] to maximize the achievable rate of SU under energy causality and interference constraints for an underlay EH-CRN which operates in slotted fashion.

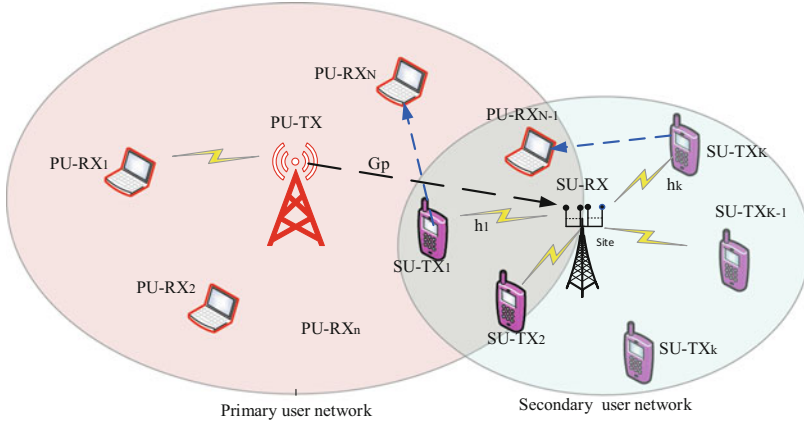
Based on the comparative analysis of the above, we can observe that these studies almost separately focus on various problems. In contrast, this paper is to study a green cognitive communications network, where PUs coexist with SUs, to enhance spectrum efficiency and green energy utilization efficiency simultaneously. To be specific, we set up an underlay EH-CRN with multi antennas and multiple battery-free SUs to lower transmit powers of SUs. Based on our previous works, we further design a new EH-CRN model which operates in the dynamic and variable scheduling mechanism of time division multiple access (DV-TDMA) [11], each SU first senses whether PU is active or inactive, then harvests energy from the RF signals energy of PU transmitter if PU is in active, or else, transmits data in the allocated time sequentially or keep idle.

The rest of this paper is organized as follows. In Sect. 2, we describe a heterogeneous model of EH-CRN with 5G. An optimal energy efficiency scheme is proposed to achieve the maximization of the system throughput by discussing the optimal power splitting scheme in Sect. 3. Then the simulation analysis and performance evaluation is provide in Sect. 4. Finally, the comprehensive conclusions are drawn in Sect. 5.

## 2 System Model

We consider a multichannel EH-CRN architecture in 5G communications scenarios, as shown in Fig. 1, where primary user network coexists with cognitive radio network. Femtocell is assumed as cognitive radio network with multichannel, it consists of  $K$  cognitive radio users (act as secondary users Transmitter, SU-TXs) and one cognitive radio base with  $M$  antennas (acts as secondary users receiver, SU-RX),  $M \geq K$ . Pico cell is assumed as primary user network, it consists of  $N$  PU receivers (named as PU-RXs) and one PU Transmitter (named as PU-TX) with  $L$  antennas. Both PU-RXs and SU-TXs are set up with one single antenna, the  $n^{th}$  PU-RX and  $k^{th}$  SU-TX indexed by PU-RX <sub>$n$</sub>  and SU-TX <sub>$k$</sub> , respectively, and  $n \in \mathcal{N} \triangleq \{1, \dots, N\}$ ,  $k \in \mathcal{K} \triangleq \{1, \dots, K\}$ . The SU-RX employs zero-forcing receiver to sense the multiple simultaneous signals transmitted by the  $k^{th}$  SU-TXs at the same frequency band. In addition, each of SU-TXs first estimates its received power energy from PU-TXs to decide to adopt the individual sensing or cooperative spectrum sensing scheme corresponding to the strong or weak signal transmitted by PU-TXs. The data fusion center SU-RX collects all detected results and the cross information between PU-TX and SU-RX for cooperative spectrum sensing and centralized power control. Here, we assume that all SUs employ a separate control channel to avoid overlapping with PUs' channels when the control signals, such as sensing results and the channel information, are in the process of transmission and reception.

In the proposed EH-CRN architecture, we consider all PUs operate in time division duplexing mode with slot duration  $T$ , each of PUs alternates in ON/OFF switch channels, their busy and idle durations follow independent and identically distributed exponential distributions with mean  $1/\lambda_0$  and  $1/\lambda_1$ . The busy and idle status of PUs at  $n^{th}$  channel (PU-RX <sub>$n$</sub> ) are denoted by  $I_1^n = 1$  and  $I_0^n = 0$ , respectively. The CRN is synchronized with one primary user network. The time framework of the CRN adopting the DV-TDMA scheduling fashion in [11], which includes two phases: (1) a cooperative spectrum sensing phase with duration  $t_s$  and (2) a data transmission phase with duration  $T_a - t_s$  or energy harvesting phase with duration  $T_h - t_s$ . The uncertainty of the available energy for SUs are obtained by the active probability  $p_a$ , which means is that SUs have sufficient energy to finish their task during the period of data transmission provided that PU is sensed to be inactive. In one time frame duration, any of SUs is to sense the status of PUs if it has enough energy to perform spectrum sensing and data transmission, or remains idle otherwise. According to the sensing result, SUs may transmit data if the PU



**Fig. 1** 5G Heterogeneous Cognitive Radio Network Model

detected is in OFF state, or it switches into energy harvesting mode if PU is in ON state. Similarly, the SU also enters the energy harvesting mode when it runs out of energy.

The designed spectrum sensing time framework describes that SU-TXs sense PUs are in ON state or OFF state with sensing time  $t_s$  within one time frame duration  $T = [T_a, T_h]$  as shown in Fig. 2, where  $T_a$  stands for one sensing frame duration and  $T_h$  stands for one radio energy harvesting frame duration, and  $t_s$  follows the dynamic and variable time division multiple access in [11]. The Fig. 2 depicts two kinds of sequences for PU in ON/OFF periods, as well the corresponding operations of SU. In the first instance, the time slots of SU consists of the sensing time  $t_s$  and a data transmission slot  $T_a - t_s$  when SU senses an inactive PU. However, due to the unslotted PU model, the PU can unexpectedly return to its channel that allowed the SU to transmit, this may result in a collision between the two transmissions. Therefore, SU-TX should stop data transmission avoiding the conflict with the PU, and switch to radio energy harvesting with a harvesting slot duration  $T_h - t_s$  if the channel of PU found busy as shown in the second instance. But, when the PU is idle during the energy harvesting period of SU, the SU cannot harvest radio frequency energy.

The detection probability  $p_{11}^{(n)}$  and the false alarm probability  $p_{01}^{(n)}$  for the SU-TX<sub>k</sub> at the  $n^{\text{th}}$  channel, under the dual collaborative spectrum sensing (DCS) scheme with energy detection if it first estimates its received weak power from PU-TX, can be obtained as follows [11],

$$p_{11}^{(n)} = \sum_{x=l}^K \binom{K}{x} (p_{c,k}^{(n)})^x (1 - p_{c,k}^{(n)})^{K-x} \quad (1)$$

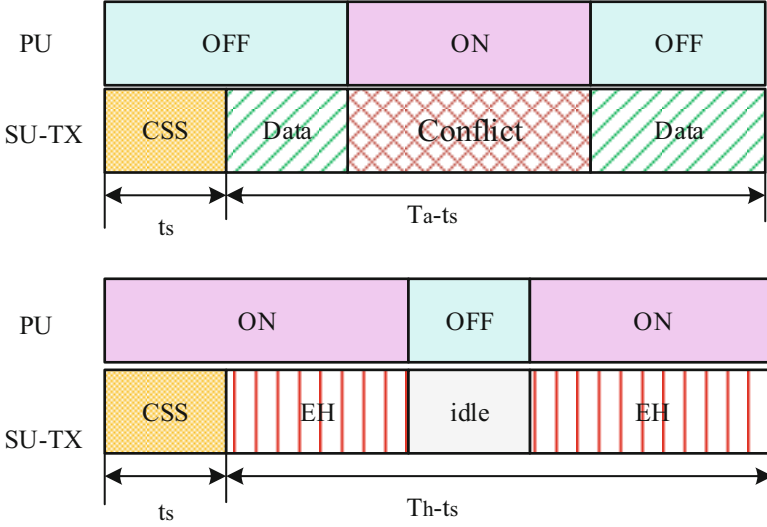


Fig. 2 Time structure of spectrum sensing and energy harvesting

$$p_{01}^{(n)} = \sum_{x=l}^K \binom{K}{x} (p_{f,k}^{(n)})^x (1 - p_{f,k}^{(n)})^{K-x} \tag{2}$$

where  $p_{c,k}^{(n)}, p_{f,k}^{(n)}$  denotes the detection probability and  $f$  the false alarm probability for the SU-TX<sub>k</sub> at the  $n^{th}$  channel under the single cooperative sensing (SCS) scheme. Then, according to the sensing results  $\hat{I}_j, j \in \mathcal{B} \triangleq \{0, 1\}$ , SU-RX decided the transmitted power  $P_{k,j}^{(n)}$  for the SU-TX<sub>k</sub> at the  $n^{th}$  channel.

According to the renewal process theory, when the PU channel is actually in OFF state during a transmission slot of the SU, if it is sensed to be idle at the beginning of the slot, the corresponding average duration  $T_{00}$  can be written as [12],

$$T_{00}(T_a) = T_a - t_s - u \left( T_a - t_s - \frac{1 - \exp[-(\lambda_0 + \lambda_1)(T_a - t_s)]}{\lambda_0 + \lambda_1} \right) \tag{3}$$

where  $u = \lambda_0/(\lambda_0 + \lambda_1)$  is the channel utility of PU in ON state. Similar to  $T_{11}$ , when the PU channel is actually in ON state during an energy harvesting slot of the SU, if it was busy at the beginning of the slot, then the corresponding average duration  $T_{11}$  is given by,

$$T_{11}(T_h) = T_h - t_s - u \left( T_h - t_s - \frac{1 - \exp[-(\lambda_0 + \lambda_1)(T_h - t_s)]}{\lambda_0 + \lambda_1} \right) \tag{4}$$

The average duration  $T_{10}$  means that the PU channel is busy but it is sensed to be idle, its corresponding formulation is  $T_{10}(T_a) = T_a - t_s - T_{11}(T_s)$ , and the average

duration  $T_{01}$  for which the PU channel is idle, but the detection results is in busy, its corresponding formulation is  $T_{01}(T_h) = T_h - t_s - T_{00}(T_h)$ .

### 3 Energy Efficiency Optimization

During the process of data transmission, according to the sensing results  $\hat{I}_j$ , SU-RX received the  $M \times 1$  signal vectors [12],

$$y_r = \begin{cases} \sum_{k \in \mathcal{K}} h_k \sqrt{P_{k,j}} x_{s,k} + w_r, & \text{when } I_0 \\ \sum_{k \in \mathcal{K}} h_k \sqrt{P_{k,j}} x_{s,k} + G_p q x_p + w_r, & \text{when } I_1 \end{cases} \quad (5)$$

where  $h_k$  denotes the instantaneous channel gain between SU-TX<sub>k</sub> and SU-RX (i.e. the  $k^{\text{th}}$  SU-TX<sub>s</sub> and the secondary user receiver),  $G_p$  denotes the instantaneous channel gain between the primary user transmitter (PU-TX) and the secondary user receiver SU-RX, the normalized beamforming vector at the primary user transmitter PU-TX is denoted as  $q$ ,  $x_{s,k} \sim CN(0, 1)$  stands for Gaussian random signal transmitted by the SU-TX<sub>k</sub>,  $w_r \sim CN(0, \sigma_r^2 I)$  is Gaussian random noise received by SU-RX. Assumed  $U = (H^H H)^{-1} H^H$ ,  $H = [h_1, \dots, h_K]$  are  $M \times K$  channel gain matrix between the SU-TX<sub>s</sub> and the SU-RX, according to the pairs of sensing results  $(I_i, \hat{I}_j)$ ,  $i, j \in \mathcal{B} \triangleq \{0, 1\}$ , the achievable rate of the  $k^{\text{th}}$  SU-TX<sub>s</sub> at the  $n^{\text{th}}$  channel is given by [13],

$$\begin{aligned} (I_0, \hat{I}_0) &: r_{k,00} \left( P_{k,0}^{(n)} \right) = \rho_{00} \log_2 \left( 1 + \gamma_{k,0}^{(n)} P_{k,0}^{(n)} \right) \\ (I_1, \hat{I}_0) &: r_{k,10} \left( P_{k,0}^{(n)} \right) = \rho_{10} \log_2 \left( 1 + \gamma_{k,1}^{(n)} P_{k,0}^{(n)} \right) \\ (I_0, \hat{I}_1) &: r_{k,01} \left( P_{k,1}^{(n)} \right) = \rho_{01} \log_2 \left( 1 + \gamma_{k,0}^{(n)} P_{k,1}^{(n)} \right) \\ (I_1, \hat{I}_1) &: r_{k,11} \left( P_{k,1}^{(n)} \right) = \rho_{11} \log_2 \left( 1 + \gamma_{k,1}^{(n)} P_{k,1}^{(n)} \right) \end{aligned} \quad (6)$$

where  $\rho_{00} = T_{00}/T$ ,  $\rho_{10} = T_{10}/T$ ,  $\rho_{01} = 1 - T_{01}/T$ ,  $\rho_{11} = 1 - T_{11}/T$ ,  $\gamma_{k,0}^{(n)} = \left( [\sigma_r^2 U U^H]_{k,k} \right)^{-1}$  and  $\gamma_{k,1}^{(n)} = \left( \left[ U \left( \sigma_p^2 G_p q q^H G_p^H + \sigma_r^2 I \right) U^H \right]_{k,k} \right)^{-1}$  are effective channel power gain for the  $k^{\text{th}}$  SU-TX<sub>s</sub> under  $I_0$  and  $I_1$ , respectively. Considering all possible combinations of pair  $(I_i, \hat{I}_j)$ , the average achievable throughput of the  $k^{\text{th}}$  SU-TX<sub>s</sub> at the  $n^{\text{th}}$  channel is,

$$\bar{r}_k^{(n)}(P_k) = \sum_{i \in \mathcal{B}} \sum_{j \in \mathcal{B}} p_a p_{ij} r_{k,ij} \left( P_{k,j}^{(n)} \right) \quad (7)$$

where  $P_k = \left[ P_{k,0}^{(n)}, P_{k,1}^{(n)} \right]$  are the transmitted power matrix vector of the  $k^{\text{th}}$  SU-TX<sub>s</sub> (SU-TX<sub>k</sub>) at the  $n^{\text{th}}$  channel, and  $p_{ij} = \Pr \left[ \hat{I}_j | I_i \right] \cdot \Pr [I_i]$  is the probability of

$(I_i, \hat{I}_j)$ . From above, then the average energy efficiency function of the SU-TX<sub>k</sub> at the  $n^{\text{th}}$  channel at the  $n^{\text{th}}$  channel can be expressed as,

$$\eta_k^{(n)}(P_k) = \sum_{i \in B} \sum_{j \in B} p_a p_{ij} \eta_{k,ij} (P_{k,j}^{(n)}) \quad (8)$$

For  $k \in \kappa$ , where

$$\eta_{k,ij} (P_{k,j}^{(n)}) = \frac{r_{k,ij} (P_{k,j}^{(n)})}{\rho_{ij} P_{k,j}^{(n)} + P_{k,c}^{(n)}} \quad (9)$$

is the instantaneous energy efficiency of the SU-TX<sub>k</sub> under  $(I_i, \hat{I}_j)$ , and  $P_{k,c}^{(n)}$  is the circuit power consumed by SU-TX<sub>k</sub>. It should be noted that, we only consider users' energy efficiency rather than the system's energy efficiency because each individual secondary user transmitter SU-TX gets its own throughput  $r_{k,ij} (P_{k,j}^{(n)})$ , but at the cost of its own power consumption  $(\rho_{ij} P_{k,j}^{(n)} + P_{k,c}^{(n)})$ , for  $k \in \kappa, i, j \in B \triangleq \{0, 1\}$ .

The optimized objective function is given by,

$$\max_{\{P_k\}_{k=1}^K} \eta \triangleq [\eta_1(P_1), \dots, \eta_K(P_K)] \quad (10)$$

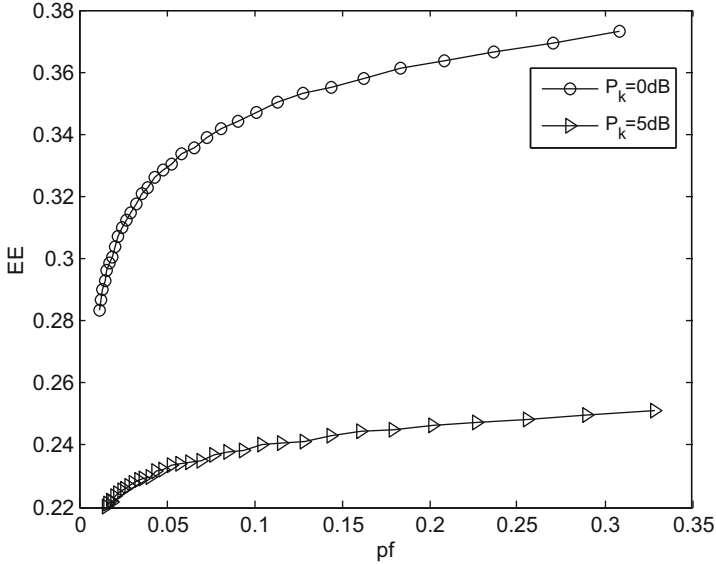
Subject to,

$$\begin{aligned} C_1 : p_a \left[ (\rho_{00} p_{00} + \rho_{10} p_{10}) P_{k,0}^{(n)} + (\rho_{01} p_{01} + \rho_{11} p_{11}) P_{k,1}^{(n)} \right] &\leq P_{\max,k}, k \in \kappa \\ C_2 : p_a \sum_{k \in \kappa} |g_{k,n}|^2 \left( \rho_{10} p_{10} P_{k,0}^{(n)} + \rho_{11} p_{11} P_{k,1}^{(n)} \right) &\leq P I_{\max,k}, n \in \mathbb{N} \\ C_3 : 1 - p_{11}^{(n)} + p_{01}^{(n)} &\leq \varepsilon, n \in \mathbb{N} \end{aligned} \quad (11)$$

where  $P_{\max,k}$  and  $P I_{\max,k}$  denote the maximum transmitted power and the maximum inference power,  $g_{k,n}$  stands for instantaneous channel gain between the SU-TX<sub>k</sub> and PU-RX<sub>n</sub>, and  $\varepsilon$  denotes sensing error rate allowed by the communication system.

## 4 Simulation Analysis and Evaluation

In this section, we evaluate the performance of our solution by experimental simulation. In this simulation, we assume the active and idle probability of PU



**Fig. 3** Energy efficiency (EE) vs. false alarm probability (pf) for different transmitted power

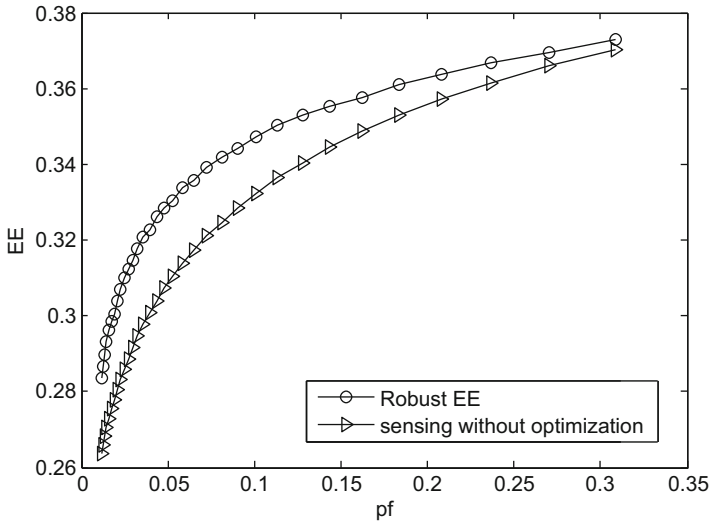
in each channel is  $p(H_1^n) = p(H_0^n) = p_a = 0.5$ ,  $T = 100ms$ ,  $\varepsilon = 0.01$ ,  $P_{\max,k} = 10dB$ .

Figure 3 depicts the curves of optimal energy efficiency in terms of false alarm probability. It is clearly observed that the energy efficiency for  $P_k = 0dB$  outperform that of  $P_k = 5dB$ , it's suggest that the energy efficiency is more robust for the lower transmitted power. At another figure, shown as Fig. 4, the energy efficiency of proposed robustness solution outperforms that of no optimization, while meeting the requirement of sensing error rate  $\varepsilon \leq 0.01$ .

## 5 Conclusion

In this paper, we study a green cognitive communication networks which PUs coexist with SUs to enhance spectrum efficiency and energy utilization efficiency simultaneously. An opportunistic RF energy harvesting capability of SU is incorporated into sensing time framework, the transmission and RF energy harvesting durations have been obtained based on the traffic pattern of PU. Further, both spectrum and energy efficiency function with respect to transmission power, sensing time, and channel status are formulated. The simulation analysis show that the higher spectrum and energy efficiency can be attained as compared with another schemes.





**Fig. 4** Robust EE scheme vs. no optimization EE scheme

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