Li et al. J Wireless Com Network (2021) 2021:48
https://doi.org/10.1186/s13638-021-01903-9

EURASIP Journal on Wireless Communications and Networking

RESEARCH Open Access

Energy-efficient time and energy resource allocation in non-selfish symbiotic cognitive relaying sensor network with privacy preserving for smart city

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Abstract

Energy efficiency and privacy preserving have become essential for the wireless sensor networks. In this paper, a joint energy and time resource allocation problem for the cognitive users (CUs) in a non-selfish symbiotic cognitive relaying scheme (NSCRS) is considered. We aim to maximize the total energy efficiency (EE) of the primary user and CUs with the consideration of information privacy under the total energy constraints of CUs. With full channel state information (CSI), an optimal energy and time resource allocation algorithm is proposed based on the exhaustive searching. Besides, in order to reduce the overhead of CSI feedback, a suboptimal algorithm, in which only the partial instantaneous CSI is required, is additionally proposed. Simulation results demonstrate the EE of primary and CUs in the NSCRS with consideration of information privacy can be greatly improved by the proposed algorithms.

Keywords: Wireless sensor network, Energy efficiency, Primary user, Cognitive relaying, Privacy preserving

1 Introduction

Recently, the wireless sensor network (WSN) with privacy preserving has been widely considered in the civilian fields [1, 2]. However, due to the limited power supply for sensor nodes, energy efficiency of relay assisted WSN has attracted more and more attention [3, 4]. In addition, owing to better spectrum efficiency via relays with cognitive function, the radio resource management for EE of cognitive relay assisted WSN with privacy preserving is valuable for researching.

Owing to a larger service coverage and a higher system capacity at a relatively low deployment cost, relays had been widely considered into WSN to prolong the lifetime of network [5–10]. There are usually two kinds of relays, amplify-and-forward (AF) relay and decoded-and-forward (DF) relay. The AF relay simply forwards the received signal to the destination, whereas the DF relay needs to decode the signals before the transmission [11]. In [12], a three-layered architecture was proposed for randomly deployed heterogeneous wireless sensor networks, where a minimum energy consumption algorithm for relay node selection was presented to improve the network lifetime. The author in [13] investigated a load balancing strategy of optimal number of relays for deploying for a longer network lifetime. Meanwhile, a minimum number of relay nodes, which is utilized to enhance the outage probability, was obtained by the proposed relay deployment algorithm [14]. Besides, a novel connectivity-aware approximation algorithm for best relay node placement was proposed to offer a major step forward in saving system overhead in the wireless sensor networks [15]. And a non-orthogonal AF (NAF) scheme, where all the relays were allowed to transmit signals in the same time and frequency simultaneously, was considered and a higher spectral efficiency could be achieved compared to the orthogonal AF scheme [16–18]. However, the EE as well as transmission model with privacy preserving was not considered in [5–18].

Meanwhile, a demand-based load balancing algorithm was addressed for energy-efficiency in WSN to improve the network life-cycle and ensure the communication quality simultaneously in [19]. A cooperative privacy preserving scheme, in which an opportunistic user selection policy was investigated to optimize the secrecy performance, was proposed in multiuser relay network [20]. However, the cognitive relay function as well as the NAF relaying was not further considered in [19, 20]. Furthermore, cognitive radio is regarded as an effective approach for enhancing the utilization of the radio electromagnetic spectrum [21]. In [22], a distributed connection restoration algorithm, in which cognitive function based relays were considered, was proposed to ensure the connection of WSN with a minimum number of relays. The authors in [23] considered a WSN, where a cognitive relay assisted the primary transmitter was assumed, and thus, the throughput for both primary and secondary systems could be maximized. By optimizing the sensing time as well as the power allocation in multi-channels, the EE of the WSN could be maximized with the assistance of multi-hops DF relay [24]. However, all the investigated schemes or algorithms in [22–24] only considered the orthogonal transmission among relays and the NAF relaying as well as the privacy preserving was not taken into account.

In this paper, we intend to maximize the overall energy efficiency by optimally allocating the energy and time among CUs, while minimizing the required interaction between primary and cognitive networks as well as the overhead of CSI feedback, in a WSN with consideration of privacy preserving, in which an access point (AP) is utilized to broadcast the artificial noise and such noise is eliminated at the destination node to protect the information privacy. We first formulate the energy and time allocation problem to maximize the energy efficiency of NSCRS [25] with privacy preserving under a sum energy constraint at CUs. Then, an optimal energy and time allocation algorithm is proposed based on the full CSI feedback. In order to reduce the overhead of CSI feedback, another optimal algorithm based on partial CSI feedback, in which only the instantaneous CSI of PU_s-PU_d, instantaneous CSI of PU_s-CU_s, and the average value of CSI between CUs and PU_d for each fading block rather than an instantaneous value are required, is proposed for the slow fading channel environment.

The remainder of this paper is organized as follows. Section 2 gives a detailed description of the system model. In Sect. 3, the optimal joint energy and time resource allocation problem for NSCRS is addressed. In Sect. 4, the proposed optimal and suboptimal algorithms are given in details. Intensive simulations are conducted to evaluate the proposed algorithms in Sect. 5. Finally, the paper is concluded in Sect. 6.

2 System model

In this section, the system model, including system architecture and transmission models for both conventional cognitive radio scheme (CCR) and NSCRS with consideration of privacy preserving, for the network with coexistence of primary and cognitive users is presented in detail.

2.1 System architecture for coexistence of primary and cognitive networks with consideration of privacy preserving

We consider a system that consists of primary and cognitive networks as shown in Fig. 1. We assume that the primary network is a time division multiple address (TDMA)-based half-duplex network, in which the PU_s transmits messages to different PUs, i.e., PU_d , in different time slots and nodes cannot transmit and receive simultaneously. In the cognitive network, CUs seek opportunities to access the AP of cognitive network and CUs will cooperate with PU_s when the energy efficiency is better than that of the direct transmission from PU_s to PU_d. For the symbiotic architecture, CUs can send messages to AP only when CUs have incentive time obtained from the cooperative transmission to the PU. Besides, there are undesired nodes, which are viewed as potential eavesdroppers, around PU_d. Therefore, to prevent privacy leakage, it is assumed that the AP broadcasts two kinds of artificial noise (AN) in phases 1 and 2, respectively, when CUs are considered as relays. While the privacy preserving is assumed to be based on the acknowledgement of CSI at AP, which can be obtained by the handshake procedure [20]. Moreover, for simplicity, we assume that the channels among PU_s, CUs, AP, and PU_d are quasi-static, independent and identically distributed (i.i.d.), which means that the channel state will remain constant within a fading block and vary independently and identically from one fading block to another. In addition, the flat Rayleigh fading channel is assumed, that is, the fading channel will remain almost unchanged over long enough duration for channel estimation, cooperation, and data transmission. Besides, a control channel for the delivery of CSI, cooperation parameters and incentive time allocation is also considered [25, 26].

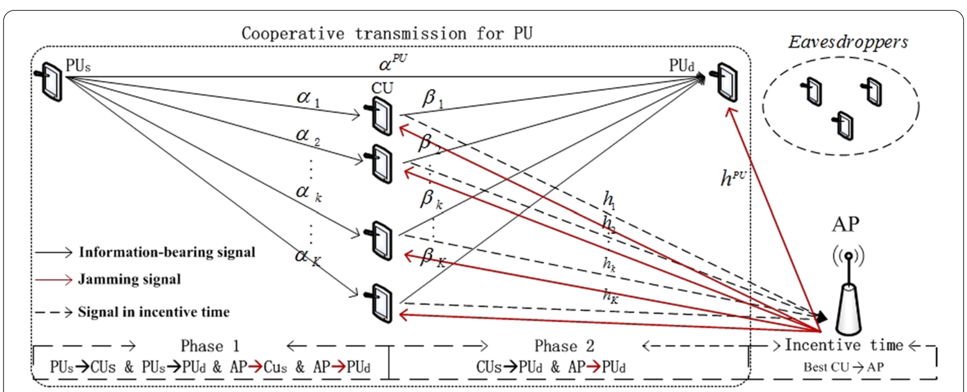

Fig. 1 System architecture for coexistence of primary and cognitive networks with privacy preserving

2.2 Transmission methods for CCR and NSCRS with privacy preserving

The transmission method of CCR is shown in Fig. 2a. The PU_s has a constant power of P_{PU} for both CCR and NSCRS. And the transmission time is assumed to be T seconds. For the privacy preserving, it is assumed that the AP will broadcast the AN, which is known at the PU_d, in CCR. Therefore, the additive variable of AN at PU_d can be eliminated owing to the acknowledgement of AN. However, for the undesired nodes, the AN cannot be removed. Thus, the received signal power at desired PU, i.e., PU_d, can be given as P_D,

$$P_D = P_{PU}\alpha^{PU} = \frac{E_{PU}\alpha^{PU}}{T}, \quad (1)$$

where E_{PU} denotes the total transmission energy at PU over time of T and α^{PU} is the channel gain of PU_s-PU_d due to fading, path loss and shadowing. In addition, the energy consumption of AP in CCR is assumed to be E_{AP}.

And the received signal-to-noise ratio (SNR) at PU_d for CCR, γ_{PU}, can be given as

$$\gamma_{PU} = \frac{P_D}{N} = \frac{E_{PU}\alpha^{PU}}{NT}, \quad (2)$$

where N represents the power of additive white Gaussian noise (AWGN). Then, the rate of primary transmission at PU_d in CCR can be given as

$$R_{PU} = \log_2(1 + \gamma_{PU}). \quad (3)$$

Thus, the number of transmitted information bits for the CCR can be represented as $R_{PU}T$.

Figure 2b depicts the transmission method of NSCRS with NAF relaying, in which the time slot consists of two phases with identical durations and incentive time. In phase 1, the PU_s sends pilots and information to the PU_d. Then the CUs will estimate the energy efficiency by the received pilot and cooperate with PU_s in phase 2 if the energy efficiency of cooperation is better than that of CCR. Because of the higher transmission rate with

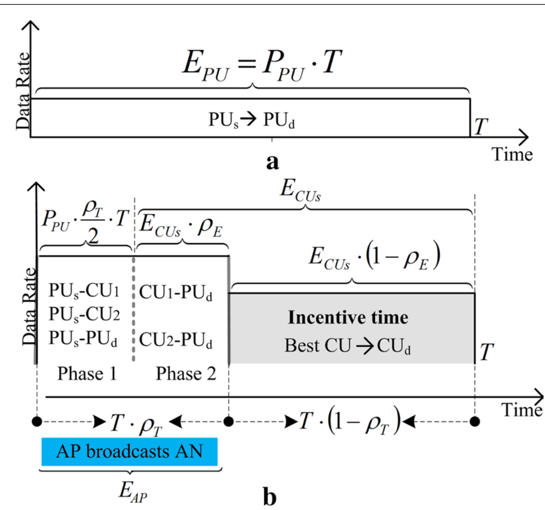

Fig. 2 Transmission methods for CCR and NSCRS

cooperation, the time consumption of transmission for PU_d can be reduced to $\rho_T T$, where ρ_T is a time allocation ratio parameter. The rest time $(1-\rho_T)T$ is named as incentive time, in which the CUs can send their own information to the AP. The energy consumption of PU_s is denoted as $E_\mathrm{PU}\rho_T/2$ in phase 1 and E_CUs is considered as the total energy constraint of CUs. $E_\mathrm{CUs}\rho_E$ is the energy consumption of CUs used for cooperation for PU_d in phase 2 and the rest energy of $E_\mathrm{CUs}(1-\rho_E)$ at CUs is utilized to transmit their own information to the AP, where ρ_E is the energy allocation ratio parameter.

Moreover, to prevent information leakage, AP broadcasts two kinds of AN x_N^1 and x_N^2 in phase 1 and phase 2, respectively. Depending on the CSI information, x_N^1 can be successfully eliminated by the x_N^2 at the PU_d. The energy consumption of AP during phases 1 and 2 is assumed to be E_AP. Thus, the transmit power of AP for AN can be described as $P_\mathrm{AP}=E_\mathrm{AP}/(\rho_T T)$.

As shown in Fig. 1, α_k, β_k, h_k represent the channel gains of PU_s-CU_k, CU_k-PU_d and CU_k-AP, respectively. Besides, the energy consumption at the kth CU for the cooperative transmission is denoted by E_{cu}^k.

In phase 1, the PU_s transmits a signal to CUs and PU_d, and AP broadcasts jamming signal x_N^1. Thus, the signal received at the kth CU can be given as

$$y_{cu}^k=\sqrt{\frac{E_\mathrm{PU}\alpha_k}{T}}\cdot x_S+\sqrt{P_\mathrm{AP}h_k}\cdot x_N^1+n_k, \tag{4}$$

where x_S denotes the desired signal from PU_s and n_k is the AWGN. Thus, the signal received at the PU_d in phase 1, y_d^1, can be described as,

$$y_d^1=\sqrt{\frac{E_\mathrm{PU}\alpha^\mathrm{PU}}{T}}\cdot x_S+\sqrt{P_\mathrm{AP}h^\mathrm{PU}}\cdot x_N^1+n_d. \tag{5}$$

In phase 2, the received signals at CUs are, respectively, amplified and retransmitted to the PU_d, where the non-orthogonal AF relaying is considered and all the CUs are allowed to transmit their signals simultaneously. And AP broadcasts jamming signal x_N^2. In order to remove the effect of AN at PU_d, x_N^2 is designed as

$$x_N^2=-\frac{\sum_{k=1}^K\left(\sqrt{\frac{2E_{cu_k}\beta_k h_k}{\rho_T E_\mathrm{PU}\alpha_k+E_\mathrm{AP}h_k+\rho_T TN}}\right)+\sqrt{h^\mathrm{PU}}}{\sqrt{h^\mathrm{PU}}}x_N^1. \tag{6}$$

And the signal transmitted from the kth CU to the PU_d can be described by

$$s_{cu_k}=\sqrt{\frac{2E_{cu_k}}{\rho_T E_\mathrm{PU}\alpha_k+E_\mathrm{AP}h_k+\rho_T TN}}\cdot\left(\sqrt{\frac{E_\mathrm{PU}\alpha_k}{T}}\cdot x_S+\sqrt{P_\mathrm{AP}h_k}\cdot x_N^1+n_k\right). \tag{7}$$

Delay diversity can be used to combine the received signals from CUs in phase 2. It is assumed that the transmitted signals from CUs may arrive at the PU_d with different delays. Then, the PU_d can coherently combine the entire received signals along the paths by the Rake receiver with maximum ratio combining (MRC). Thus, the signal received at PU_d in phase 2 can be given by

$$
\begin{aligned}
y_d^2 &= \sum_{k=1}^{K}\left(\sqrt{\beta_k}s_{cu_k} + n_k'\right) + \sqrt{P_{\mathrm{AP}}h^{\mathrm{PU}}}x_N^2 + n_d' \\
&= \sum_{k=1}^{K}\left(\sqrt{\frac{2E_{cu_k}\beta_k}{\rho_T E_{\mathrm{PU}}\alpha_k + E_{\mathrm{AP}}h_k + \rho_T TN}}\left(\sqrt{\frac{E_{\mathrm{PU}}\alpha_k}{T}}x_S + \sqrt{P_{\mathrm{AP}}h_k}x_N^1 + n_k\right) + n_k'\right) \\
&\quad + \sqrt{P_{\mathrm{AP}}h^{\mathrm{PU}}}x_N^2 + n_d'.
\end{aligned} \tag{8}
$$

Thus, based on (5) the total signal received at PU_d can be expressed as

$$
\begin{aligned}
y_d = y_d^1 + y_d^2 &= \sqrt{\frac{E_{\mathrm{PU}}\alpha^{\mathrm{PU}}}{T}}x_S + \sqrt{P_{\mathrm{AP}}h^{\mathrm{PU}}}x_N^1 + n_d \\
&\quad + \sum_{k=1}^{K}\left(\sqrt{\frac{2E_{cu_k}\beta_k}{\rho_T E_{\mathrm{PU}}\alpha_k + E_{\mathrm{AP}}h_k + \rho_T TN}}\left(\sqrt{\frac{E_{\mathrm{PU}}\alpha_k}{T}}x_S + \sqrt{P_{\mathrm{AP}}h_k}x_N^1 + n_k\right) + n_k'\right) \\
&\quad + \sqrt{P_{\mathrm{AP}}h^{\mathrm{PU}}}x_N^2 + n_d'.
\end{aligned} \tag{9}
$$

After substitute (6) into (9), we can get (10), since (11) is satisfied.

$$
\begin{aligned}
y_d &= \sqrt{\frac{E_{\mathrm{PU}}\alpha^{\mathrm{PU}}}{T}}\cdot x_S + n_d \\
&\quad + \sum_{k=1}^{K}\left(\sqrt{\frac{2E_{cu_k}\beta_k}{\rho_T E_{\mathrm{PU}}\alpha_k + E_{\mathrm{AP}}h_k + \rho_T TN}}\cdot\left(\sqrt{\frac{E_{\mathrm{PU}}\alpha_k}{T}}\cdot x_S + n_k\right) + n_k'\right) + n_d'.
\end{aligned} \tag{10}
$$

$$
\begin{aligned}
&\sum_{k=1}^{K}\left(\sqrt{\frac{2E_{cu_k}\beta_k}{\rho_T E_{\mathrm{PU}}\alpha_k + E_{\mathrm{AP}}h_k + \rho_T TN}}\cdot\sqrt{P_{\mathrm{AP}}h_k}\cdot x_N^1\right) \\
&\quad + \sqrt{P_{\mathrm{AP}}h^{\mathrm{PU}}}\cdot x_N^1 + \sqrt{P_{\mathrm{AP}}h^{\mathrm{PU}}}\cdot x_N^2 = 0.
\end{aligned} \tag{11}
$$

For the received signal at the undesired nodes, the AN cannot be canceled since channel characteristics are unknown. Thus, the SNR of the undesired nodes is heavily degraded and the privacy preserving can be guaranteed.

Thanks to the excellent autocorrelation property of well-designed spreading code or interference cancellation, the interference at the PU_d from CUs can be neglected. Then, after combining the received signals in phases 1 and 2 with MRC [27], the received SNR at the PU_d with cooperation from CUs, γ^{cu}, and the corresponding transmission rate, R^{cu}, can be, respectively, expressed as

$$
\gamma^{cu} = \frac{E_{\mathrm{PU}}\alpha^{\mathrm{PU}}}{TN} + \frac{\sum_{k=1}^{K}\frac{E_{\mathrm{PU}}}{T}\cdot\frac{2E_{cu}^k}{\rho_T T}\cdot\alpha_k\cdot\frac{T}{E_{\mathrm{PU}}\alpha_k + P_{\mathrm{AP}}T + TN}\cdot\beta_k}{\sum_{k=1}^{K}\frac{2E_{cu}^k}{\rho_T T}\cdot\frac{T}{E_{\mathrm{PU}}\alpha_k + P_{\mathrm{AP}}T + TN}\cdot\beta_k N + N}, \tag{12}
$$

$$
R^{cu} = \frac{1}{2}\cdot\log_2(1+\gamma_{cu}). \tag{13}
$$

The right two terms of (12) represent the received SNR at the PU_d in phase 1 and phase 2, respectively. Also, the received noises amplified by the CUs still remain in the denominator of the second term, while the interference from other CUs is neglected. The coefficient of 1/2 in (13) is caused by the half duplex AF relaying scheme with two identical duration phases.

Owing to the cooperation by the CUs, the required transmission time can be reduced to $\rho_T T$ and the rest of original time $(1-\rho_T)T$ will be allocated to CUs as the incentive time. Simultaneously, to get the maximal transmission rate in the incentive time, the incentive time $(1-\rho_T)T$ will be allocated to the best CU, i.e., the hlCU which has the highest SNR to the AP among all the CUs. As a result, the k_i-th CU is selected based on (14).

$$k_1 = \arg \max_{i \in (1,2,...,K)} \frac{E_{\mathrm{CUs}}(1-\rho_E)h_i}{(1-\rho_T)TN}, \tag{14}$$

where h_i, $i \in [1, 2, ..., K]$, represents the channel gain from the i-th CU to the AP. Thus, the corresponding transmission rate in the incentive time can be given as

$$R_{inc} = \log_2\left(1 + \frac{E_{\mathrm{CUs}}(1-\rho_E)h_{k_1}}{(1-\rho_T)TN}\right). \tag{15}$$

3 Problem formulation

3.1 Energy efficiency of NSCRS

As a reward, an incentive time will be allocated to CUs if the cooperative transmission by CUs can offer a higher energy efficiency for the system. Otherwise, the PU_s will occupy the entire duration and no incentive time will be allocated to the CUs, i.e., CCR. So the energy efficiency, which is defined as the total number of transmitted bits divided by the total consumed energy, in NSCRS can be given as

$$\eta = \max(\eta^{\mathrm{PU}}, \eta^{cu}), \tag{16}$$

where the function max(·, ·) will return the maximum value of the arguments. η^{PU} and η^{cu}, respectively, represent the energy efficiency of CCR and NSCRS. η^{PU} and η^{cu} can be given as

$$\eta^{\mathrm{PU}} = R_{\mathrm{PU}}/(E_{\mathrm{PU}} + E_{\mathrm{AP}}), \tag{17}$$

$$\eta^{cu} = \frac{\frac{1}{2}\log_2(1+\gamma^{cu}) \cdot \rho_T T + R_{inc} \cdot (1-\rho_T)T}{E_{\mathrm{PU}} \cdot \frac{\rho_T}{2} + E_{\mathrm{CUs}} + E_{\mathrm{AP}}}. \tag{18}$$

The denominator of (18) represents the total consumed energy of NSCRS and the numerator of (18) is the total throughput of both primary and cognitive networks.

3.2 Problem formulation for NSCRS with privacy preserving

In this paper, we aim to maximize the energy efficiency of NSCRS through optimally allocating the time and energy resource of PU_s and CUs. According to (18), the energy efficiency optimization problem of NSCRS can be formulated as

$$\max_{\rho_T,\rho_E,E_{cu}^k:k=1,\cdots,K} \frac{\frac{1}{2}\log_2(1+\gamma^{cu})\cdot\rho_T T + R_{inc}\cdot(1-\rho_T)T}{E_{\text{PU}}\cdot\frac{\rho_T}{2}+E_{\text{CUs}}+E_{\text{AP}}}, \tag{19a}$$

$$\text{s.t.}\ \frac{\frac{1}{2}\log_2(1+\gamma^{cu})\cdot\rho_T T + R_{inc}\cdot(1-\rho_T)T}{E_{\text{PU}}\cdot\frac{\rho_T}{2}+E_{\text{CUs}}+E_{\text{AP}}} > \frac{\log_2(1+\gamma_{\text{PU}})\cdot T}{E_{\text{PU}}}, \tag{19b}$$

$$\frac{1}{2}\log_2\left(1+\gamma^{cu}\right)\cdot\rho_T T \geq \log_2\left(1+\frac{E_{\text{PU}}\alpha^{\text{PU}}}{TN}\right)\cdot T, \tag{19c}$$

$$\sum_{k=1}^{K} E_{cu}^k \leq \rho_E E_{\text{CUs}}, E_{cu}^k \geq 0. \tag{19d}$$

The objective function in (19a) intends to maximize the energy efficiency of NSCRS by optimally allocating the energy of CUs and time of PU_s for the data transmission to the PU_d. The constraint in (19b) means that the energy efficiency of NSCRS should be better than that of CCR. Constraint in (19c) implies that the total transmission bits of NSCRS should be larger than that of CCR. Constraint in (19d) denotes the summed as well as the individual power constraint of CUs. With the fixed ρ_E and ρ_T, we can get the maximum of EE for NSCRS as (20a)-(20d), and the related Proof is given in "Appendix".

$$\frac{\frac{1}{2}\log_2\left(1+\gamma^{cu'}\right)\cdot\rho_T T + \log_2\left(1+\frac{E_{\text{CUs}}(1-\rho_E)h_{k_1}}{(1-\rho_T)TN}\right)\cdot(1-\rho_T)T}{E_{\text{PU}}\cdot\frac{\rho_T}{2}+E_{\text{CUs}}+E_{\text{AP}}}, \tag{20a}$$

$$\text{s.t.}\ \frac{\frac{1}{2}\log_2\left(1+\gamma^{cu'}\right)\cdot\rho_T T + \log_2\left(1+\frac{E_{\text{CUs}}(1-\rho_E)h_{k_1}}{(1-\rho_T)TN}\right)\cdot(1-\rho_T)T}{E_{\text{PU}}\cdot\frac{\rho_T}{2}+E_{\text{CUs}}+E_{\text{AP}}} > \frac{\log_2(1+\gamma_{\text{PU}})\cdot T}{E_{\text{PU}}}, \tag{20b}$$

$$\frac{1}{2}\log_2\left(1+\gamma^{cu'}\right)\cdot\rho_T T \geq \log_2\left(1+\frac{E_{\text{PU}}\alpha_m^{\text{PU}}}{TN}\right)\cdot T, \tag{20c}$$

$$E_{\text{CUs}} \geq 0. \tag{20d}$$

where

$$\gamma^{cu'} = \frac{E_{\text{PU}}\alpha^{\text{PU}}}{TN} + \frac{\frac{E_{\text{PU}}}{T}\cdot\frac{2\rho_E E_{\text{CUs}}}{\rho_T T}\cdot\alpha_{k'}\cdot\frac{T}{E_{\text{PU}}\alpha_{k'}+P_{\text{AP}}T+TN}\cdot\beta_{k'}}{\frac{2\rho_E E_{\text{CUs}}}{\rho_T T}\cdot\frac{T}{E_{\text{PU}}\alpha_{k'}+P_{\text{AP}}T+TN}\cdot\beta_{k'}N+N}, \tag{21}$$

and

$$k' = \arg\max_{k=1,2,\ldots,K} \frac{\frac{E_{\mathrm{PU}}}{T} \cdot \frac{2\rho_E E_{\mathrm{CUs}}}{\rho_T T} \cdot \alpha_k \cdot \frac{T}{E_{\mathrm{PU}}\alpha_k + P_{\mathrm{AP}}T + TN} \cdot \beta_k}{\frac{2\rho_E E_{\mathrm{CUs}}}{\rho_T T} \cdot \frac{T}{E_{\mathrm{PU}}\alpha_k + P_{\mathrm{AP}}T + TN} \cdot \beta_k N + N}. \tag{22}$$

According to (16), we can decompose the optimization problem into two cases.

Case 1. Consider $\eta = \eta^{\mathrm{PU}}$ as PU_s transmits the signals to the PU_d without the cooperation from CUs as in CCR.

Case 2. Consider $\eta = \eta^{cu}$ as PU_s transmits the signals to the PU_d with the cooperation of CUs.

4 Proposed energy efficiency algorithm with full or partial CSI

If the CSI of α_k and β_k can be estimated by the CUs, then the full CSI of α^{PU}, α_k, and β_k will be available for the AP, which is called "Scenario 1" for NSCRS. Nevertheless, instantaneous β_k may not be available at the AP. Thus, we further consider a "Scenario 2" for the NSCRS with only the partial CSI, that is, α^{PU}, α_k and an averaged CSI of by long-term observation rather than an instantaneous value. In this section, the energy and time allocation algorithms for both scenarios are investigated. In addition, an equal energy allocation algorithm (EPA), in which the total available energy of the CUs is equally distributed to the CUs, that is, $E_{cu}^k = E_{\mathrm{CUs}} \cdot \rho_E / K$, is also considered.

4.1 Optimal energy and time allocation algorithm with full CSI

With full CSI, we can obtain the optimal solution of $\rho_T = 0$ and $\rho_E = 0$ for case 1. And for case 2, the optimal algorithm is proposed as follows, by which the optimal ρ_T and ρ_E can be obtained.

Optimal energy and time allocation algorithm with full CSI (OPA)

(1) Collect α^{PU}, α_k, and β_k at the AP

(2) For $\rho_T = 0 : 0.01 : 1$, $\rho_E = 0 : 0.01 : 1$.

(3) Calculate the optimal SNR of PU_s-CU_k-PU_d to choose k'th CU by formula (22)

(4) Calculate the total number in bits of transmitted messages by $R^{cu} \cdot \rho_T \cdot T + R_{inc} \cdot (1 - \rho_T)T$ and the energy efficiency of OPA by formula (20a)

(5) Calculate the summed bits and energy efficiency in CCR by $R_{\mathrm{PU}} \cdot T$ and $\eta^{\mathrm{PU}} = R_{\mathrm{PU}}/(E_{\mathrm{PU}} + E_{\mathrm{AP}})$

(6) Compare η^{cu} with η^{PU}, $R^{cu} \cdot \rho_T \cdot T + R_{inc} \cdot (1 - \rho_T)T$ with $R_{\mathrm{PU}} \cdot T$.

if $\eta^{cu} > \eta^{\mathrm{PU}}$ and $[R^{cu} \cdot \rho_T \cdot T + R_{inc} \cdot (1 - \rho_T)T] > R_{\mathrm{PU}} \cdot T$, then choose NSCRS

else choose CCR

end for

(7)Select the optimal ρ_T and ρ_E with which we can get the best energy efficiency

Firstly, the CSI of α^{PU}, α_k and β_k is collected at the AP. Then, we calculate the optimal SNR of PU_s-CUk-PU_d to choose k'th CU by formula (22) with given pair of ρ_T and$\rho_E$in the range of [0, 1]. Then, the total number in bits of transmitted messages and energy efficiency of OPA and CCR will be calculated, respectively. If the transmitted information bits as well as the energy efficiency of OPA are both larger than these of CCR, the NSCRS will be chosen. Otherwise, the CCR will be chosen. Finally, the optimal ρ_T and ρ_E can be obtained for the best energy efficiency.

4.2 Suboptimal energy and time allocation algorithm with partial CSI feedback

Although OPA is able to achieve the optimal solution in scenario 1, the full instantaneous CSI feedback is needed. Sometimes it is hard to get the feedback of β_k immediately. For such case, it is assumed that the channel quality of CUs-PU$_d$ is much better than that of PU$_s$-CUs, i.e., $P_C \cdot \beta_k >> P_{\mathrm{PU}} \cdot \alpha_k$and $P_C \cdot \beta_k >> N$, then $2\rho_E E_{\mathrm{CUs}}\beta_k/(\rho_T T) >> E_{\mathrm{PU}}\alpha_k/T$ and $2\rho_E E_{\mathrm{CUs}}\beta_k/(\rho_T T) >> N$ can be satisfied. Thus, x_N^2 can be described as

$$x_N^2 = -\frac{\sum_{k=1}^{K}\left(\sqrt{\frac{2E_{cu_k}\beta_k}{E_{\mathrm{AP}}}}\right) + \sqrt{h^{\mathrm{PU}}}}{\sqrt{h^{\mathrm{PU}}}} x_N^1. \tag{23}$$

However, due to the lack of β_k, x_N^2 is hard to be perfectly eliminated at the PU$_d$. Rather than considering an instantaneous value of β_k, an averaged value of $\bar{\beta}_k$, which could be obtained by a long-term observation, is assumed to be adopted. Then, the interference power introduced by the AN can be given as $2E_{cu_k}\left|\beta_k - \overline{\beta_k}\right|/(\rho_T T)$. Therefore, the received SNR at PU$_d$ with cooperation from CUs, γ_{cu}, can be transformed to

$$\gamma_{cu} = \frac{E_{\mathrm{PU}}\alpha^{\mathrm{PU}}}{TN} + \frac{\frac{E_{\mathrm{PU}}}{T}\alpha_k}{N + \frac{2E_{cu_k}|\beta_k - \overline{\beta}|}{\rho_T T}}. \tag{24}$$

Since the i.i.d slow block fading channel is considered in this paper, $\beta_k \approx \overline{\beta_k}$ can be satisfied during each fading block. Compared with the case with instantaneous value of β_k, $\overline{\beta_k}$ is more easy to obtained via a long-term observation, and thus, the CSI feedback overhead of $\beta_k$can be obviously reduced during each fading block. So the γ_{cu} and the index of the selected CUs for incentive time can be, respectively, transformed to

$$\gamma_{cu} = \frac{E_{\mathrm{PU}}\alpha^{\mathrm{PU}}}{TN} + \frac{E_{\mathrm{PU}}\alpha_k}{TN}, \tag{25}$$

$$k^{''} = \arg \max_{k=1,2,\ldots,K} \frac{E_{\mathrm{PU}}\alpha_k}{TN}. \tag{26}$$

Here, we define a ratio parameter,$\theta = \alpha_k/\alpha^{\mathrm{PU}}$, to decide whether the $\alpha_k$is much better thanα^{PU} or not and the suboptimal algorithm for partial CSI feedback can be given as below.

Partial CSI feedback based suboptimal energy and time allocation algorithm (PPA)

(1) Collect α^{PU}, α_k and $\overline{\beta_k}$ at the AP

(2) For $\rho_T = 0:0.01:1$, $\rho_E = 0:0.01:1$

(3) Decide the optimal method by comparing θ with θ_{th}, where θ_{th} is a predetermined threshold for deciding whether the cooperation from CUs to the PU$_d$ is effective or not

i)if $\theta < \theta_{th}$, choose CCR

ii)if $\theta > \theta_{th}$, calculate the parameters as follows

(4) Calculate the total number in bits of transmitted messages and the energy efficiency of both PPA and CCR by the $k^{''}$th CU

(5) Compare η^{cu} with η^{PU}, $R^{cu} \cdot \rho_T \cdot T + R_{inc} \cdot (1-\rho_T)T$ with $R_{\mathrm{PU}} \cdot T$

if $\eta^{cu} > \eta^{\mathrm{PU}}$ and $[R^{cu} \cdot \rho_T \cdot T + R_{inc} \cdot (1-\rho_T)T] > R_{\mathrm{PU}} \cdot T$, then choose NSCRS

Partial CSI feedback based suboptimal energy and time allocation algorithm (PPA)
else choose CCR
end for
(6)Select the optimal ρ_T and ρ_E with which we can get the best energy efficiency

Firstly, the CSI of α^{PU}, α_k, and $\overline{\beta_k}$ are collected at the AP, where $\overline{\beta_k}$ is not needed to be feedback during a fading block. Then, θ and θ_{th} are compared with each other to decide the optimal method. if $\theta < \theta_{th}$ is satisfied, the CCR will be chosen. Otherwise, we further calculate the total number of bits of transmitted messages as well as the energy efficiency for both PPA and CCR. If the summed bits and energy efficiency of OPA are both larger than these of CCR, the NSCR will be selected. Otherwise, the CCR will be chosen. Finally, the optimal ρ_T and ρ_E can be obtained.

5 Methods

Figure 3 shows the simulation model for the networks of PUs, CUs, and AP. PU_s, PU_d, AP and CUs are placed within a 2-dimensional area (500m*500m). PU_s and PU_d are, respectively, fixed at (0, 250) and(500, 250). 10 CUs are randomly placed within this region. In addition, we place a AP at (0, 0). A simple pass loss model of $1/d^3$, where d is the distance between two points, is considered. Block Rayleigh fading channels are assumed among PU_s, CUs, PU_d, and AP. The AWGN power in this region is assumed to be -50dBm and the P_{AP} is set to be 15dBm. We consider energy with a unit dBJ, where $\mathrm{dBJ} = 10\log_{10}\mathrm{J}$. The data to be transmitted from PU_s to PU_d are assumed large enough to guarantee the full time transmission between PU_s-PU_d in case of CCR. Therefore, CUs have no chance to access the AP in the case of CCR. In addition θ_{th} is with a range of $[10^{-10} < \theta_{th} < 10^{10}]$ for a given pair of (ρ_T, ρ_E).

6 Simulation results and discussion

Figure 4 shows the energy efficiency for NSCRS with OPA, PPA, and EPA compared to CCR under the constraint of $P_{\mathrm{PU}} = 30\mathrm{dBm}, E_{\mathrm{CUs}} = 0\mathrm{dBJ}$.The CCR has the lowest EE compared to the OPA, PPA, and EPA. OPA always outperforms the others owning to the

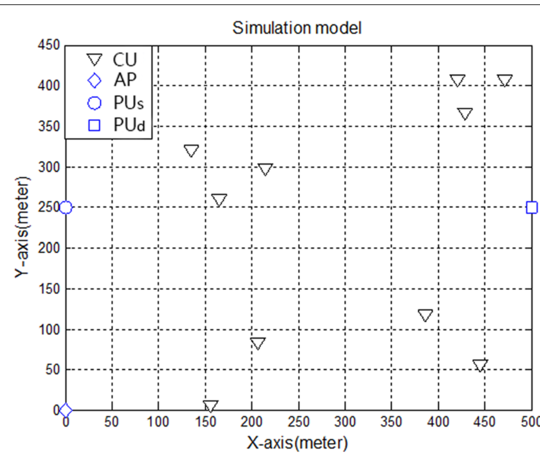

Fig. 3 The simulation model of NSCRS

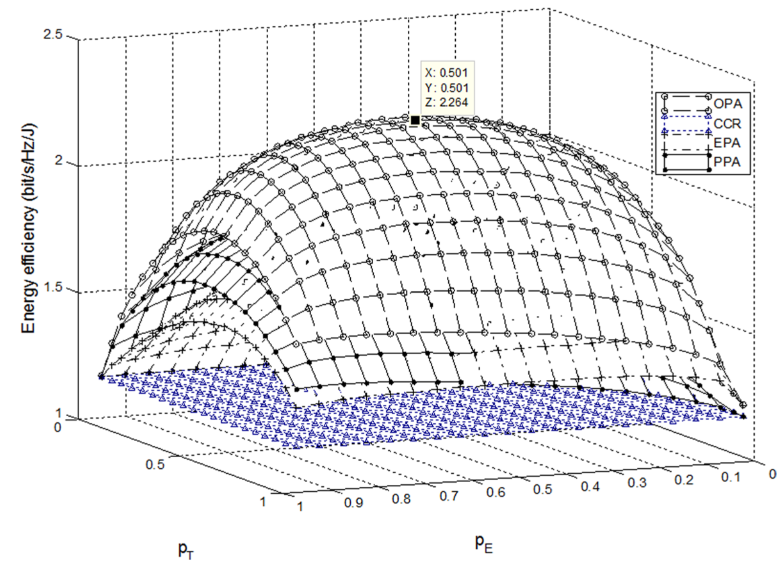

Fig. 4 Energy efficiency for NSCRS with OPA, PPA, and EPA compared to CCR

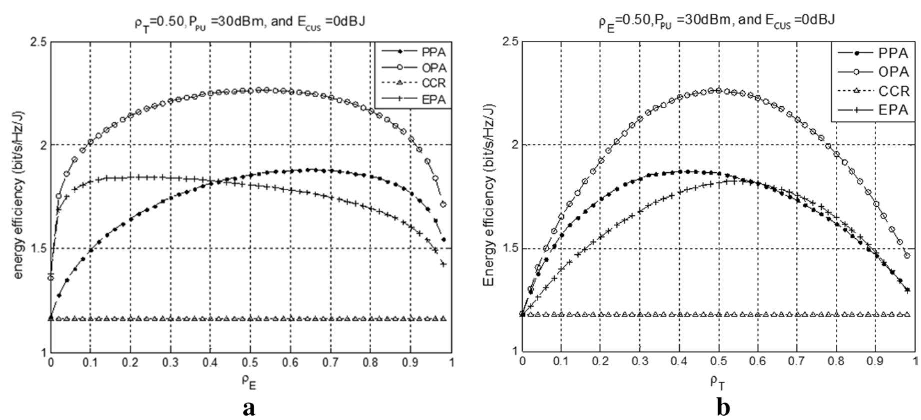

Fig. 5 Energy efficiency for different algorithms as a function of ρ_E and ρ_T, respectively

full CSI feedback and an optimal EE of NSCRS can be achieved at x=0.501, y=0.501, and z=2.264. Compared with the OPA, a small performance gap can be observed between OPA and PPA, since only partial CSI is fed back for the PPA rather than the full CSI feedback of OPA.

Figure 5a, b describe the energy efficiency for different algorithms as a function of ρ_E and ρ_T, respectively. As ρ_E changes in Fig. 5a, the energy efficiencies of OPA, PPA and EPA increase at first, since the cooperation from CUs is effective. However, when ρ_E becomes very large, the transmission rate for CU's data transmission becomes worse, which results in a decrease in terms of overall energy efficiency. In addition, when ρ_E is small, EPA performs better than PPA, because condition that $2\rho_E E_{\mathrm{CUs}}\beta_k/(\rho_T T) >> E_{\mathrm{PU}}\alpha_k/T$ is not satisfied. However, when ρ_E becomes larger, the condition of $2\rho_E E_{\mathrm{CUs}}\beta_k/(\rho_T T) >> E_{\mathrm{PU}}\alpha_k/T$ is satisfied and the performance of PPA becomes better than that of EPA. And as ρ_T changes in Fig. 5b, the energy efficiencies of OPA, PPA and EPA increase at first owing to the transmission time allocated to PUs. However, when ρ_T becomes large enough, the energy efficiencies decrease, because that there is too little incentive time allocated to CUs. Besides, when ρ_T is small, PPA performs better than EPA, because condition that $2\rho_E E_{\mathrm{CUs}}\beta_k/(\rho_T T) >> E_{\mathrm{PU}}\alpha_k/T$ is satisfied. However, with the increase in ρ_T, that condition is not satisfied, which results that EPA performs better than PPA.

Figure 6 shows the energy efficiency for different algorithms as a function of P_{PU} under constraints of $\rho_E = \rho_T = 0.5$ and $E_{\mathrm{CUs}} = 0$dBJ. The OPA always performs better than PPA and EPA owning to the full CSI feedback. When P_{PU} is small, OPA, EPA and PPA can perform the transmission with the aid of CUs, which results in better performances compared to that of CCR. When E_{PU} is smaller than E_{CUs}, the condition of $2\rho_E E_{\mathrm{CUs}}\beta_k/(\rho_T T) >> E_{\mathrm{PU}}\alpha_k/T$ is satisfied, so the performance of PPA is better than that of EPA. However, the condition of $2\rho_E E_{\mathrm{CUs}}\beta_k/(\rho_T T) >> E_{\mathrm{PU}}\alpha_k/T$ cannot be satisfied when E_{PU} is larger than E_{CUs}, and a better performance of EPA can be observed compared to the PPA. Moreover, when E_{PU} becomes large enough, CUs are not needed for cooperation, thus the EE of OPA, PPA, and EPA becomes the same, i.e., $P_{\mathrm{PU}} \geq 50$dBm.

Figure 7 shows the energy efficiency for different algorithms as a function of under constraints of $\rho_E = \rho_T = 0.5$ and $E_{\mathrm{PU}} = 0$dBJ. When E_{CUs} is small, none of CUs can be utilized for the PU transmission in the cases of OPA, EPA and PPA. Thus, a similar EE can be observed among them. As the E_{CUs} increases, OPA, EPA and PPA perform better than CCR owing to the assistance of CUs. When E_{CUs} becomes much larger than that of PUs, the condition of $2\rho_E E_{\mathrm{CUs}}\beta_k/(\rho_T T) >> E_{\mathrm{PU}}\alpha_k/T$ is satisfied, which results in a better performance of PPA than that of EPA and the performance of PPA becomes similar to that of OPA. However, when E_{CUs} becomes large enough, e.g., $E_{\mathrm{CUs}} \geq 15$dBJ, the performances of OPA, PPA and EPA will decrease to the level of CCR, since the energy consumption of CUs is too big to decrease the EE.

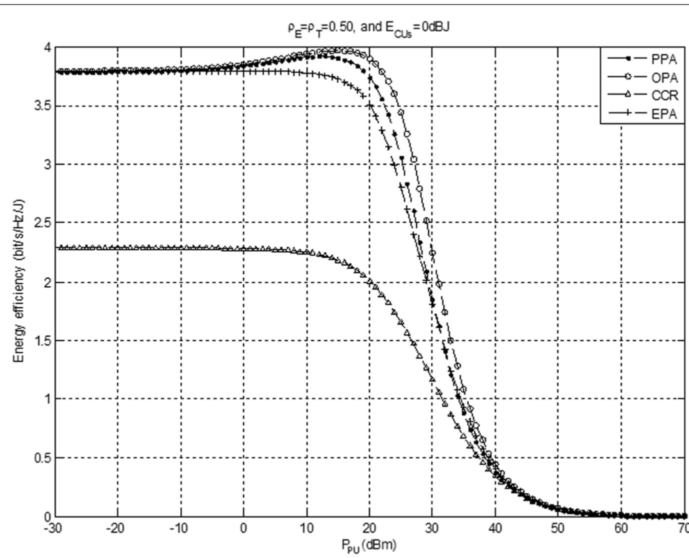

Fig. 6 Energy efficiency for different algorithms as a function of P_{PU}

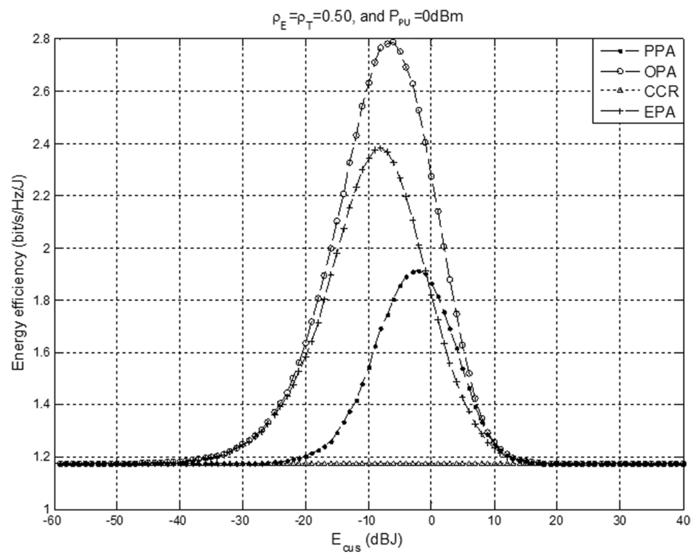

Fig. 7 Energy efficiency for different algorithms as a function of E_{CUs}

Figure 8 compares the normalized performance gain of OPA and PPA with an increase trend of E_{CUs}. For a better realization, the performance of EE for both OPA and PPA are normalized by that of CCR. When E_{CUs} is very small, there is a big gap of performance gain between OPA and PPA as shown in Fig. 8a, b, since the condition of $2\rho_E E_{\mathrm{CUs}}\beta_k/(\rho_T T) >> E_{\mathrm{PU}}\alpha_k/T$ is not satisfied. However, as the E_{CUs} increases, e.g.,$E_{\mathrm{CUs}} = 20dBJ$, the approximation of $2\rho_E E_{\mathrm{CUs}}\beta_k/(\rho_T T) >> E_{\mathrm{PU}}\alpha_k/T$ can be almost achieved. Thus, similar performance gains of OPA and PPA can be observed as shown in Fig. 8e, f. It implies that if the link quality from CUs to the PU_d is much better than those from PU_s to CUs, then the proposed PPA could be an alternative choice with lower instantaneous CSI feedback.

7 Conclusions

In this paper, the optimal energy and time allocation algorithm in NSCRS with consideration of privacy preserving was first investigated for energy efficiency maximization in the case of full CSI. To further reduce the overhead from CSI exchanging, a suboptimal energy and time allocation algorithm, where the instantaneous CSI from CUs to PU is not required to be fed back, is alternatively introduced. Simulation results demonstrated that the energy efficiency of primary and cognitive users in the NSCRS can be greatly improved by the proposed OPA and PPA algorithms with the consideration of privacy preserving. Moreover, compared with the OPA, the PPA could achieve a similar performance as that of OPA with a smaller CSI feedback overhead.

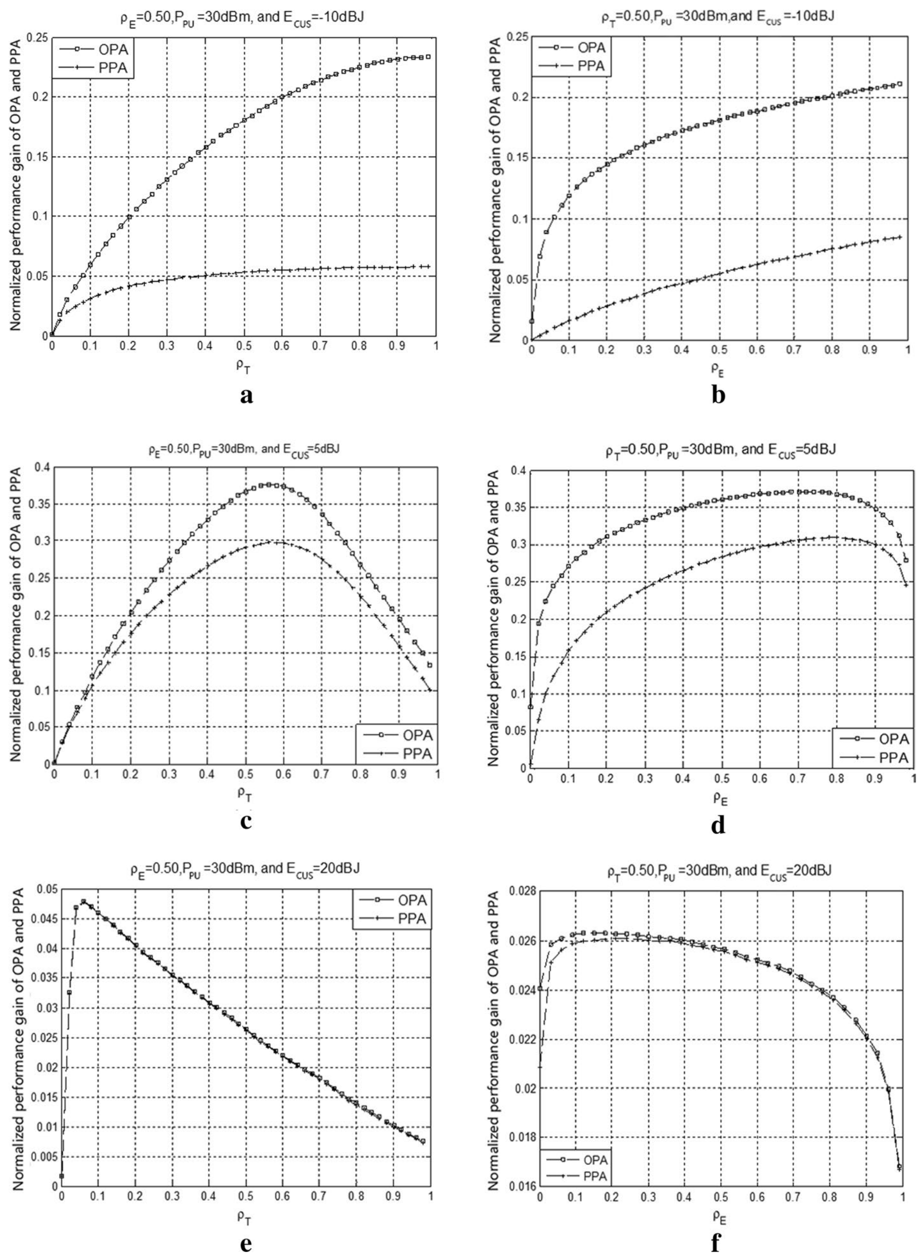

Fig. 8 Performance gain of EE normalized by that of CCR for different algorithms as a function of ρ_E and ρ_T, respectively

Appendix

First, when we fix ρ_T and ρ_E the problem can be rewritten in the following form:

$$\max_{E_{cu}^k, k=1,\cdots,K} \frac{\frac{1}{2}\log_2(1+A+L)\cdot\rho_T T + B}{C+D}, \tag{27}$$

where A, B, C and D are all nonnegative constants.

$$L = \frac{\sum_{k=1}^{K} \frac{E_{\mathrm{PU}}}{T} \cdot \frac{2E_{cu}^k}{\rho_T T} \cdot \alpha_{m,k} \cdot \frac{T}{E_{\mathrm{PU}}\alpha_{m,k}+P_{\mathrm{AP}}T+TN} \cdot \beta_{m,k}}{\sum_{k=1}^{K} \frac{2E_{cu}^k}{\rho_T T} \cdot \frac{T}{E_{\mathrm{PU}}\alpha_{m,k}+P_{\mathrm{AP}}T+TN} \cdot \beta_{m,k}N + N}. \tag{28}$$

Obviously, due to the monotonicity of $\log_2(x)$ with respect to x, the problem in (27) can be converted to maximizing L, where

$$\max L = \max_{E_{cu}^k} \frac{\sum_{k=1}^{K} \frac{E_{\mathrm{PU}}}{T} \cdot \frac{2E_{cu}^k}{\rho_T T} \cdot \alpha_{m,k} \cdot \frac{T}{E_{\mathrm{PU}}\alpha_{m,k}+P_{\mathrm{AP}}T+TN} \cdot \beta_{m,k}}{\sum_{k=1}^{K} \frac{2E_{cu}^k}{\rho_T T} \cdot \frac{T}{E_{\mathrm{PU}}\alpha_{m,k}+P_{\mathrm{AP}}T+TN} \cdot \beta_{m,k}N + N}. \tag{29}$$

We can rewrite (29) as

$$\max_{E_{cu}^k} f(E_{cu}^1, E_{cu}^2, ..., E_{cu}^K) = \max_{E_{cu}^k} \frac{a_0 + \sum_{k=1}^{K} a_k E_{cu}^k}{b_0 + \sum_{k=1}^{K} b_k E_{cu}^k}, \tag{30}$$

where a_0, a_k and $b_k$are nonnegative coefficients, but b_0 is a positive coefficient. Then, we only need to prove the equation as follows

$$\max_{E_{cu}^k} \frac{a_0 + \sum_{k=1}^{K} a_k E_{cu}^K}{b_0 + \sum_{k=1}^{K} b_k E_{cu}^K} = \max_{k=1,2...,K} \frac{a_0 + a_k E_{\mathrm{CUs}}}{b_0 + b_k E_{\mathrm{CUs}}}. \tag{31}$$

We prove (31) by means of the mathematical induction.

Firstly, in the case of $K = 2$, we will prove the following equation

$$\max_{E_{cu}^k} \frac{a_0 + a_1 E_{cu}^1 + a_2 E_{cu}^2}{b_0 + b_1 E_{cu}^1 + b_2 E_{cu}^2} = \max\left(\frac{a_0 + a_1 E_{\mathrm{CUs}}}{b_0 + b_1 E_{\mathrm{CUs}}}, \frac{a_0 + a_2 E_{\mathrm{CUs}}}{b_0 + b_2 E_{\mathrm{CUs}}}\right). \tag{32}$$

It indicates that the maximum is obtained at either $(E_{cu}^1, E_{cu}^2) = (0, E_{\mathrm{CUs}})$ or $(E_{cu}^1, E_{cu}^2) = (E_{\mathrm{CUs}}, 0)$. By plugging $E_{cu}^2 = E_{\mathrm{CUs}} - E_{cu}^1$ into $f(E_{cu}^1, E_{cu}^2, ..., E_{cu}^K)$ for $K = 2$, we get the equivalent form

$$g(E_{cu}^1) = f(E_{cu}^1, E_{\mathrm{CUs}} - E_{cu}^2) = \frac{E_{cu}^1(a_1 - a_2) + E_{\mathrm{CUs}} a_2 + a_0}{E_{cu}^1(b_1 - b_2) + E_{\mathrm{CUs}} b_2 + b_0}. \tag{33}$$

Therefore, (33) has the maximum at one of the boundary points $E_{cu}^1 = 0$ or $E_{cu}^1 = E_{\mathrm{CUs}}$ as long as we prove the monotonicity of $g(E_{cu}^1)$. We differentiate $g(E_{cu}^1)$ with respect to E_{cu}^1

$$\frac{dg(E_{cu}^1)}{dE_{cu}^1} = \frac{(a_1 - a_2)(E_{\mathrm{CUs}} b_2 + b_0) - (b_1 - b_2)(E_{\mathrm{CUs}} a_2 + a_0)}{\left(E_{cu}^1(b_1 - b_2) + E_{\mathrm{CUs}} b_2 + b_0\right)^2}. \tag{34}$$

The denominator of (34) is constant positive. Hence, the monotonicity of $g(E_{cu}^1)$ depends on the sign of the numerator, which proves (32).

We assume that (31) is true of $K = L$, and we prove that (32) is also true of $K = L + 1$. For $K = L + 1$, we have

$$f(E_{cu}^1, E_{cu}^2, ..., E_{cu}^L, E_{cu}^{L+1}) = \frac{a_0 + \sum_{k=1}^{L} a_k E_{cu}^k + a_{L+1} E_{cu}^{L+1}}{b_0 + \sum_{k=1}^{L} b_k E_{cu}^k + b_{L+1} E_{cu}^{L+1}}, \tag{35}$$

with constraints of $\sum_{k=1}^{L+1} E_{cu}^k = E_{\text{CUs}}$ and $E_{cu}^k \geq 0$. We Apply (31) for $K = L$ to (35) and obtain

$$\begin{aligned}
&\max_{\sum_{k=1}^{L+1} E_{cu}^k = E_{\text{CUs}}} \frac{a_0 + \sum_{k=1}^{K+1} a_k E_{cu}^k}{b_0 + \sum_{k=1}^{K+1} b_k E_{cu}^k} \\
&= \max_{0 \leq E_{cu}^{L+1} \leq E_{\text{CUs}}} \max_{\sum_{k=1}^{L} E_{cu}^k = E_{\text{CUs}} - E_{cu}^{L+1}} \frac{a_0 + \sum_{k=1}^{L} a_k E_{cu}^k + a_{L+1} E_{cu}^{L+1}}{b_0 + \sum_{k=1}^{L} b_k E_{cu}^k + b_{L+1} E_{cu}^{L+1}} \\
&= \max_{0 \leq E_{cu}^{L+1} \leq E_{\text{CUs}}} \max_{k=1,\ldots,L} \frac{a_0 + a_k (E_{\text{CUs}} - E_{cu}^{L+1}) + a_{L+1} E_{cu}^{L+1}}{b_0 + b_k (E_{\text{CUs}} - E_{cu}^{L+1}) + b_{L+1} E_{cu}^{L+1}}.
\end{aligned} \tag{36}$$

We switch the maximum operations on the right-hand side to have

$$\begin{aligned}
&\max_{\sum_{k=1}^{L+1} E_{cu}^k = E_{\text{CUs}}} \frac{a_0 + \sum_{k=1}^{K+1} a_k E_{cu}^k}{b_0 + \sum_{k=1}^{K+1} b_k E_{cu}^k} \\
&= \max_{k=1,\ldots,L} \max_{0 \leq E_{cu}^{L+1} \leq E_{\text{CUs}}} \frac{a_0 + a_k (E_{\text{CUs}} - E_{cu}^{L+1}) + a_{L+1} E_{cu}^{L+1}}{b_0 + b_k (E_{\text{CUs}} - E_{cu}^{L+1}) + b_{L+1} E_{cu}^{L+1}}.
\end{aligned} \tag{37}$$

Due to the monotonicity of (32), we can easily get

$$\begin{aligned}
&\max_{\sum_{k=1}^{L+1} E_{cu}^k = E_{\text{CUs}}} \frac{a_0 + \sum_{k=1}^{K+1} a_k E_{cu}^k}{b_0 + \sum_{k=1}^{K+1} b_k E_{cu}^k} \\
&= \max_{k=1,\ldots,L} \max \left(\frac{a_0 + a_k E_{\text{CUs}}}{b_0 + b_k E_{\text{CUs}}}, \frac{a_0 + a_{L+1} E_{\text{CUs}}}{b_0 + b_{L+1} E_{\text{CUs}}} \right) \\
&= \max_{k=1,\ldots,L+1} \frac{a_0 + a_k E_{\text{CUs}}}{b_0 + b_k E_{\text{CUs}}}.
\end{aligned} \tag{38}$$

Therefore, (31) also holds for $K = L + 1$, which proves (20a) by mathematical induction.

Abbreviations

NSCRS: Non-selfish symbiotic cognitive relaying scheme; PU: Primary user; CUs: Cognitive users; CSI: Channel state information; WSN: Wireless sensor network; EE: Energy efficiency; AF: Amplify-and-forward; DF: Decoded-and-forward; NAF: Non-orthogonal AF; AP: Access point; CCR: Conventional cognitive radio scheme; TDMA: Time division multiple address; AN: Artificial noise; SNR: Signal-to-noise ratio; AWGN: Additive white Gaussian noise; EPA: Equal energy allocation algorithm; OPA: Optimal energy and time allocation algorithm with full CSI; PPA: Partial CSI feedback based suboptimal energy and time allocation algorithm.

Acknowledgements

The authors thank the person who provided meticulous and valuable suggestions for improving the paper.

Authors' contributions

PL and PG proposed the overall research direction and ideas. LH and PG designed the system model and the resource allocation algorithm. LH and XG drafted the article and designed the simulations. HL read the relevant literature and revised the manuscript. The authors read and approved the final manuscript.

Funding

This work was supported in part by the National Natural Science foundation of China under Grant 62073039 and National Key Research and Development Program of China under Grant 2018YFC0823003.

Data availibility

Data sharing is not applicable to this article as no datasets are generated or analyzed during the current study.

Competing interests

The authors declare that they have no competing interests.

Received: 31 July 2020 Accepted: 15 January 2021
Published online: 08 March 2021

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