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Research Article

Energy Efficiency Maximization in the Wireless-Powered Backscatter Communication Networks with DF Relaying

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This paper focuses on the design of an optimal resource allocation scheme to maximize the energy efficiency (EE) in the wireless-powered backscatter communication networks (WPBCN) with decode and forward (DF) relaying. The two different devices are supported to operate in different modes, the harvest-then-transmit (HTT) mode and backscatter communication (BackCom) mode, respectively. In particular, we formulate an optimization problem to maximize system EE by jointly optimizing the transmit power of hybrid access point (H-AP) and the system time resource allocation. To deal with the nonconvex problem, we investigate the characteristics of the EE expression and a variable substitution approach. Then, the optimal power allocation scheme and iterative optimization algorithm were derived for achieving maximum EE. Extensive simulation results have demonstrated that the system EE can be improved about 10% because the proposed scheme provides more flexibility to utilize the resource efficiently by employing the proposed scheme.

1. Introduction

With the development of the Internet of Things (IoT), numerous wireless devices (WDs) have been deployed widely in the world to provide ubiquitous connectivity, which improves human being's life greatly in all aspects [1, 2]. However, the sustainable energy supply is a major challenge for the evolvable IoT networks. Fortunately, a new technology named as wireless power transfer (WPT) has been deemed as an attractive promising approach to power WDs conveniently and steadily [3–8]. Wireless-powered communication network (WPCN) is a novel communication solution for IoT that using WPT techniques solves the problem of sustainable energy supply for the tiny WDs. Consequently, WPCN has been widely studied in recent years, especially in [5–9]. A well-known protocol for WPCN is named as "harvest-then-transmit (HTT)" protocol proposed in [8]. Following the HTT protocol, hybrid access point (H-AP) first broadcasts the wireless energy to its served users for energy harvesting, and then, users transmit their information actively to H-AP by utilizing the harvested energy.

Recently, ambient backscatter communication (Back-Com) [10] has been emerging as a promising technology for low-energy communication systems that was designed to communicate with WDs nearby without resorting to any existing energy supply or storage device. Different from the devices using the HTT mode, the BackCom devices transmit information by modulating and reflecting the instantaneous incident signals passively [11, 12]. Hence, the active RF components are not required at all, which can significantly decrease the circuit energy consumption and meet the low-power requirement of IoT devices. Furthermore, the dedicated energy harvesting (EH) time is also not necessary, and then, the information transmission time can be extended.

Essentially, there exist some different tradeoffs between EH time and data transmission time for HTT protocol and BackCom. They may complement each other for increasing the data rates and energy utilization while they are used in IoT. Hence, applying BackCom in WPCNs and wireless-powered backscatter communication networks (WPBCNs) is a very efficient way to exploit the advantages of the HTT mode and the BackCom mode, which have gained extensive attention in academic field, especially in [12–16]. The authors in [12] presented an optimal time resource allocation method to achieve the maximal throughput for WPBCNs. The literatures [13–16] played an emphasis on optimizing the EE performance of WPBCNs.

It is to be noted that EE is a crucial performance metric in IoT to achieve a better tradeoff between data rates and the overall energy consumption. Due to the characteristics of WPT, the energy cost of WPCNs, especially the energy consumption of the dedicated energy source devices, has drawn a great deal of attention [14, 15]. In [17], the authors proposed an EE resource allocation scheme which employed a Dinkelbach-based iterative algorithm to obtain the optimal time allocation, reflection coefficient, and transmit power of the dedicated RF energy source in BackCom networks. The literature [18] utilized energy beamforming communication and ambient BackCom to overcome the energy problem of network, and a EE cooperative communication scheme was presented. The EE maximum problem was investigated in cooperative sensor networks with bidirectional wireless information and power transfer [19]. By studying the derivative properties of the objective function, the authors derived the optimal power allocation and time allocation. The authors in [20] studied the EE performances for an unmanned aerial vehicle- (UAV-) assisted backscatter communication network. They maximized the EE of the network by jointly optimizing the UAV trajectory, the backscatter device scheduling, and the carrier emitter transmit power. The literature [14] studied the EE of WPBCNs which consist of two types of WDs that operate in different modes, the HTT mode and BackCom mode, respectively. The authors in [14] study the network which includes two different types WDs. One device named as HD, operating in the HTT mode, transmits its information directly to the access point (AP), and the other device named as BD, operating in the BackCom mode, backscatters its information directly to AP. By jointly optimizing the energy beamforming vector, power allocation, and time allocation, the system maximum EE is achieved. Obviously, the researchers have done many works in improving the EE of WPCNs and a lot of valuable achievements have been obtained. However, the EE optimization of WPBCNs that consists of two types of WDs has not been sufficiently exploited by the existing works.

The authors in [12] proposed a new network structure in which HTT mode is adopted in the last hop and BackCom mode is used in the other hops. They assumed that the devices could only consume the energy harvested within the current time block. Therefore, based on the above assumption, the nodes do not harvest the energy after they finish the information forwarding in one time block, which leads to the reduction of harvested energy and the inefficient

energy utilization. Both in [19, 21], the authors think that the devices can store the harvested energy in their battery and do not consume all the energy harvested in the current time block. Especially in [19], the remote device is designed to harvest the energy from the relay during the phase of relay transmitting information to the base station. Inspired by the literatures [19, 21], we develop a new network model and the corresponding communication protocol which improve the EE and throughput of new model.

In this paper, we investigate a new WPBCN with DF relaying (WPB-R-CN) which is more suitable to the realistic IoT application scenario. WPB-R-CN consists of one hybrid access point (H-AP), one relay, and one backscatter user (SU) which is shown in Figure 1. Following the literature [12], SU operates in BackCom mode and relay transmits the information by operating in HTT mode. Different from [12], SU is required to harvest energy from RF signal transmitted by a relay device during the phase of relay transmitting information to H-AP. The energy harvested during this time by SU will be stored in its battery for use in the next time block. Obviously, the proposed new model can improve system EE further.

Obviously, WPB-R-CN is a new network model which is different with the existing models, such as the models of literatures [12, 14], which are more similar to our proposed model. In [12, 14], BackCom mode and HTT mode are used simultaneously in the models. However, in [14], the device named as HD, operating in the HTT mode, transmits its information directly to access point (AP) and the other device named as BD, operating in the BackCom mode, backscatters its information directly to AP. The authors in [14] only study one-hop link performane for two different types WDs. Different from the model of [14], the authors in [12] study multihop hybrid backscatter communication network. However, the other nodes do not harvest the energy transmitted by the node operating in HTT mode which leads to the reduction of harvested energy and the inefficient energy utilization. Therefore, the model we studied in this paper is a new one. No existing algorithms can achieve the maximum EE of WPB-R-CN.

We aim at WPB-R-CN EE maximization by optimizing its resource allocation and H-AP transmit power. To obtain the optimal parameters, we formulate a nonconvex system EE maximization problem. To make the optimization problem tractable, we investigate the characteristics of the EE expression. Then, the optimal power allocation scheme and iterative optimization algorithm were derived for solving the nonconvex optimal problem and achieving maximum EE. Our contribution can provide a useful insight for optimizing system performance in both system throughput and EE in WPBCN.

The main contributions of our work are summarized as follows:

(i) We propose a new WPB-R-CN network model which consists of one hybrid access point (H-AP), one relay, and one backscatter user (SU). To improve the system EE performance, SU required to harvest energy from RF signal transmitted by
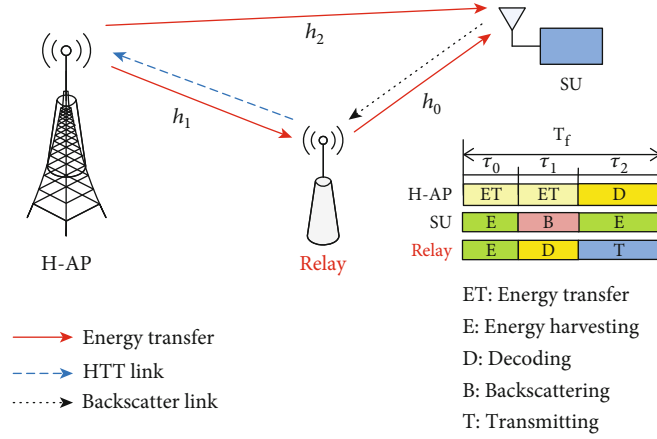
FIGURE 1: System model.

relay during the phase of relay transmitting information to H-AP

(ii) We develop a new protocol for the WPB-R-CN network to achieve the maximum EE. In the new protocol, SU harvests wireless energy from the relay during relay transmitting the data to H-AP and stores its harvested energy in a battery. And the stored energy can be scheduled across different transmission blocks

(iii) We formulate a system EE maximization problem and obtain the joint power allocation scheme for the proposed model. By investigating the characteristics of the EE expression, the optimal power allocation scheme and iterative optimization algorithm were derived for achieving maximum EE

(iv) We investigate the performances of the optimal power allocation scheme and the proposed iterative optimization algorithm. Comparing their performances with the other two schemes, our proposed scheme is proved to be efficient in improving system EE performance

The remainder of the paper is organized as follows. System model and communication protocol are described in Section 2. The problem of jointly optimizing H-AP transmit power and time resource allocation scheme is formulated to maximize the system EE in Section 3. Section 4 gives the optimal time allocation and power allocation schemes for maximizing the system EE. Simulation experiments are conducted to verify the effectiveness of the proposed strategies in Section 5. Finally, we conclude the paper in Section 6.

2. System Model and Communication Protocol

2.1. System Model.
We consider a WPB-R-CN illustrated in Figure 1, which consists of one H-AP, one relay, and one SU. Each device is equipped with one antenna. H-AP is assumed to have sustainable power supply acting as a wireless power provider and information receiver. Relay and

SU operate in the HTT mode and the BackCom mode, respectively. They do not have embedded energy supplies. Both relay and SU can harvest the energy from RF signal using their EH circuit and store the energy into a rechargeable battery. The stored energy can be consumed while relay and SU transmit their information. Moreover, by using the existing energy in SU battery, the information transmission can be initialized before energy harvesting and SU can consume all the harvested energy during the frame [19]. Each channel among nodes is assumed to be undergoing independent identically distributed (i.i.d) quasistatic block fading [22]. And the channels are reciprocal in two directions [19, 22]. Assume that no direct link exists between nodes H-AP and SU due to severe path loss and/or shadowing. Therefore, relay node has the obligation to relay the data of SU to H-AP.

Let h_0, h_1, h_2 denote the channel response of the relay–SU link, the H-AP–relay link, and the H-AP–SU link, respectively. Similarly, d_0, d_1, d_2 are the distance of relay and SU, H-AP and relay, and H-AP and SU. Let n_1, n_2, n_3 denote the additive white Gaussian noise at the receiver of SU, relay, and H-AP, respectively, $n_i \sim \mathscr{CN}(0, \sigma^2), i \in \{1, 2, 3\}$. Without loss of generality, relay is closer to H-AP than SU in the system which means $d_1 < d_2$, resulting in $|h_1|^2 > |h_2|^2$. The duration of each frame T_f is one second, and the system bandwidth is B Hz. P_{cr} is the circuit power consumed while the H-AP and relay work as the receiver. P_{ct} is denoted as the circuit power consumed while SU and relay work as the transmitter.

2.2. Proposed New Communication Protocol.
As shown in Figure 2, one time-frame duration T_f is divided into three time phases that are denoted by τ_0, τ_1, and τ_2, respectively. During the first time phase τ_0, H-AP transfers its wireless energy to relay and SU by transmitting the modulated signal $s(t) = \sqrt{P_H} x(t)$, where P_H denotes the transmit power of H-AP and $x(t)$ is a known signal with $\mathbb{E}[|x(t)|^2] = 1$. Correspondingly, both relay and SU work as the energy harvester and harvest the energy from the ambient RF signal using their EH circuit and store the energy into a rechargeable
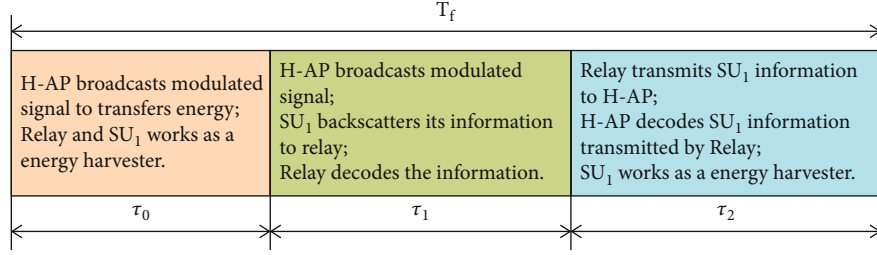
FIGURE 2: Framework of the communication protocol.

battery. The harvested energy E_{R_0} by relay and the harvested energy E_{U_0} by SU are expressed as

$$E_{R_0} = \eta P_H |h_1|^2 \tau_0, \qquad (1)$$

$$E_{U_0} = \eta P_H |h_2|^2 \tau_0, \qquad (2)$$

where $\eta \in (0, 1]$ denotes the energy harvesting efficiency. The harvested energy of relay is split into two parts. One part energy is used to maintain the circuit consumption of the relay during the time τ_1, and the other part is used to transmit information during the time τ_2. The harvested energy of SU is used to maintain its circuit consumption while SU backscatters the information during the time τ_1.

During the second time phase τ_1, H-AP continues to transmit the modulated signal $s(t)$. SU enters the active state to backscatter its information to relay by utilizing incident signals from H-AP, and relay also enters the active state to decode the information of SU. The received signal $y_1(t)$ by SU is given by

$$y_1(t) = \sqrt{P_H} h_2 x(t) + n_1(t). \qquad (3)$$

Then, SU modulates its own signal $c_1(t)$ on the received signal $y_1(t)$ and $c_1(t)$ satisfies $\mathbb{E}[|c_1(t)|^2] = 1$. Therefore, the backscattered signal $y_2(t)$ by SU is written as

$$y_2(t) = \sqrt{P_H} h_2 x(t) c_1(t) + n_1(t) c_1(t). \qquad (4)$$

The signal received by relay is denoted as $y_3(t)$ which is expressed as

$$y_3(t) = h_0 y_2(t) + h_1 s(t) + n_2(t) = \sqrt{P_H} h_2 h_0 x(t) c_1(t) \\ + h_0 n_1(t) c_1(t) + \sqrt{P_H} h_1 x(t) + n_2(t). \qquad (5)$$

Obviously, The first term of $y_3(t)$ is the received desired signal by relay. The second term of $y_3(t)$ is the noise caused by backscattering process. The third term of $y_3(t)$ is the interference from the H-AP, the power of which is typically larger than that of the desired signal. Following the literatures [23, 24], successive interference cancellation (SIC) technique is used to remove it from the $y_3(t)$ since relay has known the information $s(t)$ well. Thus, the signal-

noise-ratio (SNR) at relay during the second time phase τ_1 is given by

$$\gamma_1 = \frac{P_H |h_0|^2 |h_2|^2}{(|h_0|^2 + 1)\sigma^2}. \qquad (6)$$

While $|h_0|^2 < <1$, then equation (6) can be written as

$$\gamma_1 = \frac{P_H |h_0|^2 |h_2|^2}{\sigma^2}. \qquad (7)$$

During the third time phase τ_2, H-AP stops transmitting the modulated signal $s(t)$ and acts as a information receiver. Relay operates in HTT mode and transmits the information decoded during the time τ_1. SU enters sleep state and acts as energy harvester. It harvests the RF energy transmitted by relay. Let $\mathscr{P}_R$ denote the transmit power of relay which is written as

$$\mathscr{P}_R = \frac{E_{R_0} - P_{cr} \tau_1 - P_{ct} \tau_2}{\tau_2}. \qquad (8)$$

Relay transmits the information $c_2(t)$ to H-AP, and $c_2(t)$ satisfies $\mathbb{E}[|c_2(t)|^2] = 1$. The received signal of H-AP $y_4(t)$ and SNR γ_2 at H-AP is, respectively, given by

$$y_4(t) = \sqrt{\mathscr{P}_R} h_1 c_2(t) + n_2(t), \\ \gamma_2 = \frac{\mathscr{P}_R |h_1|^2}{\sigma^2}. \qquad (9)$$

The harvested energy E_{U_1} by SU is expressed as

$$E_{U_1} = \eta \mathscr{P}_R |h_0|^2 \tau_2. \qquad (10)$$

Thus, the total energy harvested E_U by SU is written as

$$E_U = E_{U_0} + E_{U_1} = \eta P_H |h_2|^2 \tau_0 + \eta \mathscr{P}_R |h_0|^2 \tau_2. \qquad (11)$$

Consequently, the SU–relay link and relay–H-AP link throughput are, respectively, calculated as

$$\mathscr{R}_1 = \tau_1 B \log_2 (1 + \gamma_1) = \tau_1 B \log_2 \left(1 + \frac{P_H |h_0|^2 |h_2|^2}{\sigma^2} \right), \qquad (12)$$

$$\mathcal{R}_2 = \tau_2 B \log_2(1 + \gamma_2) = \tau_2 B \log_2\left(1 + \frac{\mathcal{P}_R |h_1|^2}{\sigma^2}\right). \quad (13)$$

Following the literature [19], the system throughput $\mathcal{R}$ is given by

$$\mathcal{R} = \min\{\mathcal{R}_1, \mathcal{R}_2\}. \quad (14)$$

Obviously, since both SU and relay are powered by harvested energy, only H-AP device consumes the energy in the system. Therefore, the total energy consumption of the whole system is also the energy consumption of H-AP which consists of two parts: the energy consumed in H-AP transmitting RF signal phase and the energy consumed in H-AP decoding information phase. Then, the total energy consumption of the whole system is written as

$$E_c = \left(\frac{P_H}{\zeta}\right)(\tau_0 + \tau_1) + P_{cr}\tau_2, \quad (15)$$

where $\zeta \in (0, 1]$ is the power amplifier efficiency.

3. Problem Formulation and Analysis

In this section, we formulate an optimization problem to maximize the system EE by jointly optimizing time resource allocation and H-AP transmit power. The system EE $\psi(P_H, \tau_0, \tau_1, \tau_2)$ is defined as the ratio of the achievable system throughput to the total energy consumption [14, 16], which is given by

$$\psi(P_H, \tau_0, \tau_1, \tau_2) = \frac{\mathcal{R}}{E_c} = \frac{\min\{\mathcal{R}_1, \mathcal{R}_2\}}{(P_H/\zeta)(\tau_0 + \tau_1) + P_{cr}\tau_2}. \quad (16)$$

Then, the optimization problem is formulated as

$$\begin{aligned} \mathbf{P1}: \max_{P_H, \tau_0, \tau_1, \tau_2} \quad & \frac{\min\{\mathcal{R}_1, \mathcal{R}_2\}}{(P_H/\zeta)(\tau_0 + \tau_1) + P_{cr}\tau_2} \\ \text{s.t.} \quad & C1: \tau_0 + \tau_1 + \tau_2 = T_f \\ & C2: \tau_0, \tau_1, \tau_2 \geq 0 \\ & C3: 0 \leq P_H \leq P_{\max} \\ & C4: E_U \geq P_{ct}\tau_1 \\ & C5: E_{R_0} \geq P_{cr}\tau_1 \end{aligned} \quad (17)$$

In problem P1, C1 indicates that the summation of three time variables equals to the duration of one frame T_f. C2 limits that each time variables must be nonnegative. C3 constrains the transmit power range of H-AP. C4 and C5 guarantee that the total energy consumed does not exceed the total energy harvested for SU and relay, respectively. Notice that the WPB-R-CN is a new network which is distinguished from the conventional relaying and the main difference can be found in Section 2. These differences make the formulated EE problem noticeably different from that of the conventional relaying network.

Obviously, the above-formulated EE optimization problem is appealing in practice. For one thing, the time resource allocation can be exploited to satisfy the maximum system throughput requirement. For another, the EE can be further improved by optimizing the transmit power of H-AP. However, problem P1 cannot be solved directly for the following two main challenges. First, both the nominator and denominator of problem P1 include the variables $\{\tau_0, \tau_1, \tau_2\}, P_H$. Second, the optimization variables $\{\tau_0, \tau_1, \tau_2\}, P_H$ are coupled in both objective function and the constrains C4 and C5. Consequently, P1 is a nonconvex problem which cannot be solved directly. In general, there are no standard methods to solve the nonconvex optimization problems efficiently. Note that when P_H remains unchanged, the bigger nominator of objective function leads to the bigger EE. Then, the original problem P1 can be written as

$$\begin{aligned} \mathbf{P2}: \max_{P_H, \tau_0, \tau_1, \tau_2} \quad & \frac{\max\{\min\{\mathcal{R}_1, \mathcal{R}_2\}\}}{(P_H/\zeta)(\tau_0 + \tau_1) + P_{cr}\tau_2} \\ \text{s.t.} \quad & C1 - C5 \end{aligned} \quad (18)$$

Obviously, the problem P2 is also nonconvex optimization problem which is too difficult to obtain a globally optimal solution.

4. Energy Efficiency Maximization Resource Allocation

To solve problem P2 for obtaining its optimal solution $\{\tau_0^*, \tau_1^*, \tau_2^*, P_H^*\}$, we decompose the problem P2 into two subproblems to make it more tractable according to reference [19].

4.1. Optimal Resource Allocation Scheme. First, we formulate one subproblem to achieve the maximum system throughput by optimizing the resource allocation while P_H is considered as remaining unchanged. The optimal resource allocation is denoted as $\{\tau_0^*, \tau_1^*, \tau_2^*\}$. Let $\mathcal{R}^*$ denote the system throughput which corresponds to the optimal resource allocation $\{\tau_0^*, \tau_1^*, \tau_2^*\}$. It means that $\mathcal{R}^* > \mathcal{R}^+, \forall \{\tau_0^+, \tau_1^+, \tau_2^+\} \neq \{\tau_0^*, \tau_1^*, \tau_2^*\}$ when P_H remains unchanged, where $\mathcal{R}^+$ denotes the system throughput which corresponds to the resource allocation $\{\tau_0^+, \tau_1^+, \tau_2^+\}$.

Therefore, the first subproblem denoted as P2a is formulated as

$$\begin{aligned} \mathbf{P2a}: \max_{\tau_0, \tau_1, \tau_2} \quad & \{\min\{\mathcal{R}_1, \mathcal{R}_2\}\} \\ \text{s.t.} \quad & C1 - C5 \end{aligned} \quad (19)$$

Accordingly, P2a is still a nonconvex problem because there are coupling relationships among different optimization variables. In order to solve it, we present the following lemmas.

Lemma 1. $\mathcal{R}_1 = \mathcal{R}_2$ *is a necessary but insufficient condition for problem P2a obtaining the optimal solution.*

Proof. It is assumed that $\mathscr{R}_1 > \mathscr{R}_2$. Then, $\mathscr{R} = \mathscr{R}_2$ is the maximum system throughput. In order to cut down the SU–relay link throughput $\mathscr{R}_1$, we reduce SU backscattering time τ_1 to $\tau_{1'}$ for achieving $\mathscr{R}_1' = \mathscr{R}_2$. Let $\tau_1 = \tau_{1'} + \Delta$. Thus, we divide Δ into three parts $\{\Delta_{0'}, \Delta_{1'}, \Delta_{2'}\}$ in the ratio of $\tau_0 : \tau_{1'} : \tau_2$ and let $\tau_{0'} = \tau_0 + \Delta_{0'}$, $\tau_{1''} = \tau_{1'} + \Delta_{1'}$, and $\tau_{2'} = \tau_2 + \Delta_{2'}$. Obviously, the achieved system throughput $\mathscr{R}'$ is greater than $\mathscr{R}$ which is result from the new resource allocation scheme $\{\tau_{0'}, \tau_{1''}, \tau_{2'}\}$, which contradicts with the assumption. Then, Lemma 1 is proved. □

We apply Lemma 1 to the problem P2a. Then, the new optimization problem P3 is formulated as

$$\text{P3}: \max_{\tau_0, \tau_1, \tau_2} \quad \{\mathscr{R}_1 = \mathscr{R}_2\} \tag{20}$$
$$\text{s.t.} \quad \text{C1} - \text{C5}$$

Similar to problem P2a, problem P3 is also a nonconvex problem. To tackle this problem, we first divide the problem P3 into two subproblems and solve two subproblems sequently. Finally, We use the optimal solutions of the two subproblems to obtain the optimal solution of problem P3 by iterative optimization and proportional compression algorithm.

At first, we relax the variable τ_2 and make $\tau_2 = 0$. Correspondingly, the constrain C1 becomes the new constrain $\tau_0 + \tau_1 = T_f$. Let $\tau_0 = \alpha T_f$ and $\tau_1 = (1 - \alpha) T_f$, where $0 < \alpha < 1$ is the factor of SU transmission time. The first subproblem P3a is formulated as

$$\text{P3a}: \max_{\alpha} \mathscr{R}_1 \tag{21}$$
$$\text{s.t.} \quad \text{C3} - \text{C5}, \text{C6}: 0 < \alpha < 1$$

According to the references [4, 17, 22], $P_{cr} \leq P_{ct}$ is always satisfied in WPCN. Obviously, $E_{R_0} > E_U$ is always satisfied according to the system model. Thus, the constrain C5 can be satisfied while the constrain C4 is satisfied. Based on the above conclusion, we formulate problem P4 as follows:

$$\text{P4}: \max_{\alpha} \mathscr{R}_1 \tag{22}$$
$$\text{s.t.} \quad \text{C3}, \text{C4}, \text{C6}$$

Obviously, P4 is a more tractable problem. By use of the optimization method in [12, 17], P4 can obtain the maximum throughput while the constrain C4 satisfies $E_U = P_{ct} \tau_1$. Substituting $\tau_0 = \alpha T_f$, $\tau_1 = (1 - \alpha) T_f$ and equation (2) into $E_U = P_{ct}\tau_1$, the following equation can be obtained shown as follows:

$$\eta P_H |h_2|^2 \alpha T_f = P_{ct}(1 - \alpha) T_f. \tag{23}$$

The optimal solution α^* can be easily calculated from equation (16) which is given by

$$\alpha^* = \frac{P_{ct}}{\eta P_H |h_2|^2 + P_{ct}}. \tag{24}$$

Substituting the optimal solution α^* into the objective function, the maximum throughput $\widehat{R}_1$ of problem P3a is achieved which is written as

$$\widehat{R}_1 = \frac{\eta P_H |h_2|^2}{\eta P_H |h_2|^2 + P_{ct}} T_f B \log_2 \left(1 + \frac{P_H |h_0|^2 |h_2|^2}{\sigma^2} \right). \tag{25}$$

Secondly, we relax the variable τ_1 to satisfy $\tau_1 = 0$ and relax the variable T_f to satisfy $T_f = T_R$, where $0 < T_R < T_f$ denotes the transmission cycle time of relay. Additionally, to simplify the optimization process, we make $\tau_0 = \beta T_R$ and $\tau_2 = (1 - \beta) T_R$, where $0 < \beta < 1$ is the factor of relay transmission cycle time. Thus, another subproblem P3b of problem P3 is formulated as

$$\text{P3b}: \max_{\beta} \mathscr{R}_2 \tag{26}$$
$$\text{s.t.} \quad \text{C3}, \text{C7}: 0 < \beta < 1$$

Substituting $\tau_0 = \beta T_R$, $\tau_2 = (1 - \beta) T_R$ and equation (7) into equation (12), $\mathscr{R}_2$ can be written as

$$\mathscr{R}_2 = (1 - \beta) T_R B \log_2 \left(1 + \frac{\eta P_H |h_1|^4 (\beta/(1 - \beta) 1 - \beta) - P_{ct} |h_1|^2}{\sigma^2} \right). \tag{27}$$

Let $c = (\eta P_H |h_1|^4)/\sigma^2$ and $b = 1 - (P_{ct} |h_1|^2)/\sigma^2$. Then, the objective function $\mathscr{R}_2$ can be rewritten as

$$\mathscr{R}_2 = (1 - \beta) T_R B \log_2 \left(c \frac{\beta}{1 - \beta} + b \right). \tag{28}$$

Lemma 2. *The optimization problem P3b is convex, and the optimal parameter $\beta^* = (x^* - b)/(x^* - b + c)$ and x^* is the solution of equation $cx \ln x - x + b - c = 0$.*

Proof. See the appendix.

Substituting the optimal solution β^* into the objective function of P3b, the maximum throughput $\widehat{R}_2$ of problem P3b is achieved which is given by

$$\widehat{R}_2 = (1 - \beta^*) T_R B \log_2 \left(c \frac{\beta^*}{1 - \beta^*} + b \right). \tag{29}$$

In order to solve problem P3, we make $\widehat{R}_2 = \widehat{R}_1$ to obtain T_R which is expressed as

$$T_R = \frac{\widehat{R}_1}{(1 - \beta^*) B \log_2(c(\beta^*/(1 - \beta^*) 1 - \beta^*) + b)}. \tag{30}$$

1: Initialize the parameter ε

2: Divide the problem P3 into two subproblems by relaxing variable τ_2 and τ_1, respectively.

3: Solve problem P3a to obtain α^* and solve problem P3b to obtain β^*.

4: Calculate T_R by use of (29).

5: Let $\tau_{01} = \alpha^* T_f$, $\tau_{11} = (1 - \alpha^*) T_f$, $\tau_{02} = \beta^* T_R$ and $\tau_{22} = (1 - \beta^*) T_R$

6: **if** $\tau_{01} > \tau_{02}$ **then**

7:      Let $\tau_0 = \tau_{01}$, $\tau_1 = \tau_{11}$ and $\tau_2 = \tau_{22}$

8:      Calculate $\mathcal{P}_R$ and $\mathcal{R}_1$

9:      Update $\tau_2 = \mathcal{R}_1 / B \log_2(1 + (\mathcal{P}_R |h_1|^2 / \sigma^2))$

10:      **while** $|\tau_{22} - \tau_2| > \varepsilon$ **do**

11:          $\tau_{22} = \tau_2$

12:          Calculate $\hat{\tau}_{01} = \tau_{01} - (\mathcal{P}_R |h_0|^2 / P_H |h_1|^2) \tau_{22}$

13:          Let $\tau_0 = \max\{\hat{\tau}_{01}, \tau_{02}\}$

14:          Update $\mathcal{P}_R$

15:          Calculate $\tau_2 = \mathcal{R}_1 / B \log_2(1 + (\mathcal{P}_R |h_1|^2 / \sigma^2))$

16:      **end while**

17: **else**

18:      Let $\tau_0 = \tau_{02}$, $\tau_1 = \tau_{11}$ and $\tau_2 = \tau_{22}$

19: **end if**

20: Then $\tau_0^* = \tau_0 T_f / \tau_0 + \tau_1 + \tau_2$, $\tau_1^* = \tau_1 T_f / \tau_0 + \tau_1 + \tau_2$, $\tau_2^* = \tau_2 T_f / \tau_0 + \tau_1 + \tau_2$.

ALGORITHM 1: Iterative optimization algorithm for solving problem P3.

According to our model, we can easily get $0 < T_R < T_f$ for the cause of $|h_1|^2 > |h_2|^2$. To find the optimal solution $\{\tau_0^*, \tau_1^*, \tau_2^*\}$, we define $\tau_{01} = \alpha^* T_f$, $\tau_{11} = (1 - \alpha^*) T_f$, $\tau_{02} = \beta^* T_R$, and $\tau_{22} = (1 - \beta^*) T_R$. Obviously, we select $\tau_{00} = \max\{\tau_{01}, \tau_{02}\}$ which can satisfy $\mathcal{R}_1 = \mathcal{R}_2$. Then, we devise a iterative optimization algorithm to obtain the optimal solution $\{\tau_0^*, \tau_1^*, \tau_2^*\}$ of problem P3 which is given in Algorithm 1 with an error ε. □

4.2. Optimal Transmit Power Allocation Scheme. The optimal power allocation scheme will be aimed at maximizing the energy efficiency in this subsection while the optimal resource allocation solution is obtained. Then, another subproblem P5 of problem P2 is formulated as

$$\text{P5}: \max_{P_H} \psi(P_H)$$

$$= \frac{\tau_1^* B \log_2\left(1 + \left((P_H |h_0|^2 |h_2|^2) P_H |h_0|^2 |h_2|^2 / \sigma^2\right)\right)}{(P_H / \zeta)(\tau_0^* + \tau_1^*) + P_{cr} \tau_2^*}$$

$$\text{s.t.} \quad \text{C3} \tag{31}$$

Let $\lambda = \sigma^2 / |h_0|^2 |h_2|^2$ and $\varphi = 1/\zeta(\tau_0^* + \tau_1^*)$. By taking the derivative of $\psi(P_H)$ with respect to P_H, we get

$$\frac{\partial \psi(P_H)}{\partial P_H} = \frac{((\tau_1^* B \lambda(P_H \varphi + P_{cr} \tau_2^*)) \tau_1^* B \lambda(P_H \varphi + P_{cr} \tau_2^*)/(\ln 2(1 + P_H \lambda)) \ln 2(1 + P_H \lambda)) - \tau_1^* B \log_2(1 + P_H \lambda) \varphi}{(P_H \varphi + P_{cr} \tau_2^*)^2}. \tag{32}$$

In equation (30), the denominator $(P_H \varphi + P_{cr} \tau_2^*)^2$ is greater than zero. Therefore, the sign of $(\partial \psi(P_H))/\partial P_H$ depends on its numerator. We define the numerator as a new function $g(P_H)$ which is given by

$$g(P_H) = \frac{\tau_1^* B \lambda(P_H \varphi + P_{cr} \tau_2^*)}{\ln 2(1 + P_H \lambda)} - \tau_1^* B \log_2(1 + P_H \lambda) \varphi. \tag{33}$$

Similarly, the derivative of $g(P_H)$ with respect to P_H can

be written as

$$\frac{\partial g(P_H)}{\partial P_H} = \frac{-\tau_1^* B \lambda^2 (P_H \varphi + P_{cr} \tau_2^*) \ln 2}{(\ln 2(1 + P_H \lambda))^2}. \tag{34}$$

It is evident that $(\partial g(P_H))/\partial P_H$ is less than zero, which means that $g(P_H)$ is a monotone decreasing function of P_H while $0 < P_H < P_{\max}$. In addition, $g(0)$ is greater than zero. Then, when $g(P_{\max}) \geq 0$, the optimal solution $P_H^* = P_{\max}$. The reason is that $(\partial \psi(P_H))/\partial P_H$ is always greater than zero while $0 < P_H < P_{\max}$. It means that $\psi(P_H)$ is a monotone increasing function while $0 < P_H < P_{\max}$. Therefore, the

```
 1: Let P_1 = 0, P_2 = P_max and δ > 0
 2: Calculate v = g(P_max) based on Eq.(32).
 3: if v < 0 then
 4:    while |P_2 − P_1| > δ do
 5:        Let P_H^+ = P_1 + P_2/2
 6:        Calculate u = g(P_H^+)
 7:        if u ≥ 0 then
 8:            Let P_1 = P_1 + P_2/2
 9:        else
10:            Let P_2 = P_1 + P_2/2
11:        end if
12:    end while
13:    P_H^* = P_H^+
14: else
15:    P_H^* = P_max.
16: end if
```

ALGORITHM 2: Power allocation algorithm.

maximum energy efficient can be obtained while $P_H^* = P_{\max}$. Otherwise, there exists P_H^+ satisfying $(\partial \psi(P_H))/\partial P_H = 0$. And the energy efficient $\psi(P_H)$ is a monotone increasing function while $0 < P_H < P_H^+$ and $\psi(P_H)$ is a monotone decreasing function while $P_H^+ < P_H < P_{\max}$. Therefore, we can solve the equation $g(P_H^*) = 0$ to obtain the optimal solution P_H^*. Thus, the optimal solution P_H^* is given by

$$P_H^* = \begin{cases} P_{\max} & g(P_{\max}) \geq 0 \\ P_H^+ & g(P_{\max}) < 0 \end{cases}, \tag{35}$$

where P_H^+ is the unique solution satisfying $g(P_H^+) = 0$.

To solve the optimal solution P_H^*, we devise a power allocation algorithm which is described in Algorithm 2 with the given error δ.

5. Simulation Results

In this section, the performance of WPB-R-CN is evaluated by the system-level simulation. The following parameters are used for simulation unless stated otherwise. The simulation duration is ten time frames, and the channel model between arbitrary nodes is modeled as $|h_i|^2 = |g_i|^2 d_i^{-3}$ [22], where $g_i \sim \mathcal{CN}(0, 1)$ denotes the channel coefficient between two nodes and is set as $g_i = 1$ for simplicity [14]; d_i is the distance between adjacent nodes. System bandwidth is set $B = 100$ Hz. The distance between relay and SU is set $d_0 = 20$ m, the distance between H-AP and relay is set $d_1 = 14$ m, and the distance between H-AP and SU is set $d_2 = 30$ m. $P_{\max} = 30$ dBm [14], $\sigma^2 = -70$ dBm, $\eta = 0.6$ [12], $T_f = 1.0$ s, $P_{ct} = -16.5$ dBm [12], and $P_{cr} = -20.5$ dBm [12].

Assume that $\{\tau_0^*, \tau_1^*, \tau_2^*, P_H^*\}$ is an optimal solution for achieving maximum EE of the system. According to Algorithm 1, if the energy E_{U_0} harvested by SU during the time τ_0^* is greater than the energy consumed by SU maintaining the circuit normal operation during the time τ_1^*, SU does not require to harvest the energy from the relay during the

time τ_2^*. Therefore, it does not need to execute iteration. This scenario is not considered in this section. We mainly play an emphasis on the other scenario that includes $E_{U_0} < P_{ct}\tau_1^*$ and the energy E_{R_0} harvested by relay during the time τ_0^* being enough to transmit the required data to H-AP. Therefore, SU needs to harvest the energy from the relay during the time τ_2^* to store it into the rechargeable battery for use in the next frame.

Figure 3 depicts the EE of the proposed Algorithm 1 versus the number of iterations under different H-AP transmit powers P_H. It can be seen that Algorithm 1 converges after only three iterations, which demonstrate the efficiency of Algorithm 1. Simultaneously, Figure 3 shows that system EE increases while H-AP transmit power P_H increases from 19 dBm to 23 dBm. It shows that the optimal H-AP transmit power P_H^* is greater than 23 dBm.

Figure 4 shows the system EE performance versus H-AP maximum transmit power $P_{\max}$. Four different schemes have been simulated to verify the predominance of the proposed scheme. "Proposed scheme with iteration" denotes as "the proposed Algorithm 1" and the optimal H-AP transmit power P_H^* is obtained by use of Algorithm 2. "Proposed scheme without iteration" denotes as the "scheme 2" that the optimal τ_0^* equals to the maximal value of τ_{01} and τ_{02} in the proposed Algorithm 1, and the optimal H-AP transmit power P_H^* is obtained by the use of Algorithm 2. "Throughput maximization" denotes "scheme 3" that $\{\tau_0^*, \tau_1^*, \tau_2^*\}$ are solved by the use of the proposed Algorithm 1, and P_H^* is set to $P_{\max}$ for achieving the maximal system throughput. To show the superiority of the framework design and proposed scheme, we have simulated the performance of the existing scheme proposed in reference [12], which is denoted as "scheme 4." In "scheme 4," we aim at the maximum EE by solving for the optimal H-AP transmitting power. It can be seen from Figure 4 that the system EE of four schemes is increasing with the increasing $P_{\max}$ while $P_{\max} \leq P_H^*$. "The proposed Algorithm 1," "scheme 3," and "scheme 4" behave exactly the same in system EE when $P_{\max} \leq P_H^*$. However, the system EE of "scheme 3" decreases sharply and the other two schemes keep unchangeable while $P_{\max} \geq P_H^*$. We conclude that the throughput maximization scheme may achieve the lower EE than "the proposed Algorithm 1" due to the fact that the optimal resource allocation for throughput maximization is not energy efficient. It illustrates the importance of maximizing the EE. It also can be observed that "the proposed Algorithm 1" always achieves the better system EE than that of the other three schemes, because SU can harvest energy from the relay during the time τ_2^* and the τ_0^* is reduced by the iteration process.

In addition, we have also simulated the system throughput performance of four different schemes shown in Figure 5, which shows the system throughput performance versus H-AP maximum transmit power $P_{\max}$. "The proposed Algorithm 1," "scheme 2," and "scheme 4" behave similarly in the system throughput. Their system throughput is increasing when $P_{\max} \leq P_H^*$ and kept unchanged when $P_{\max} \geq P_H^*$, whereas the system throughput of "scheme 3" always increases with the increasing $P_{\max}$. The reason is that
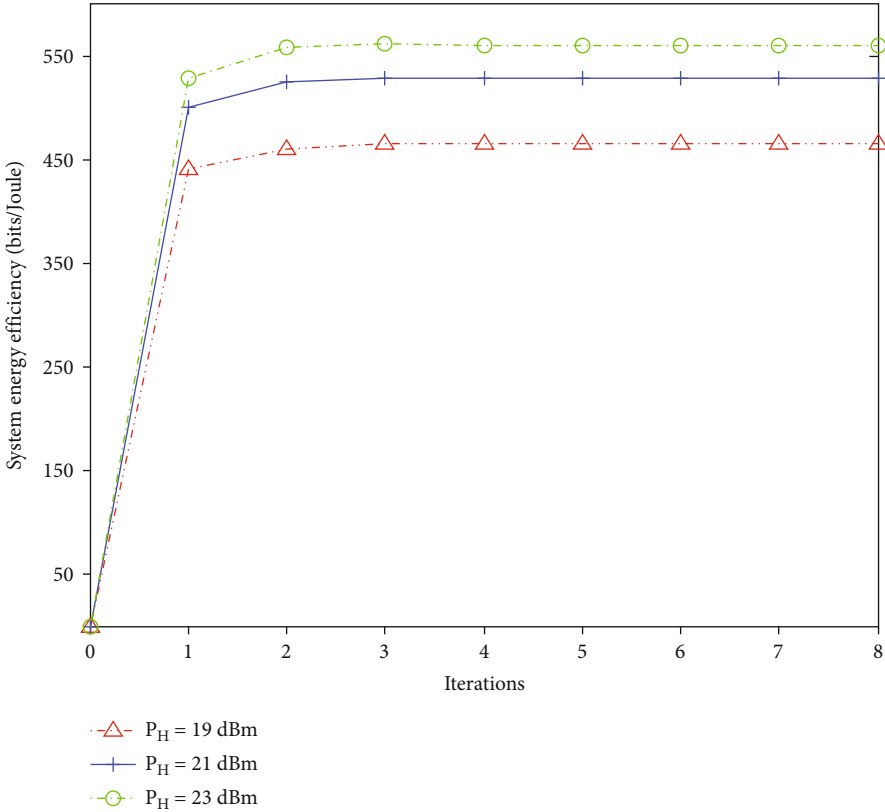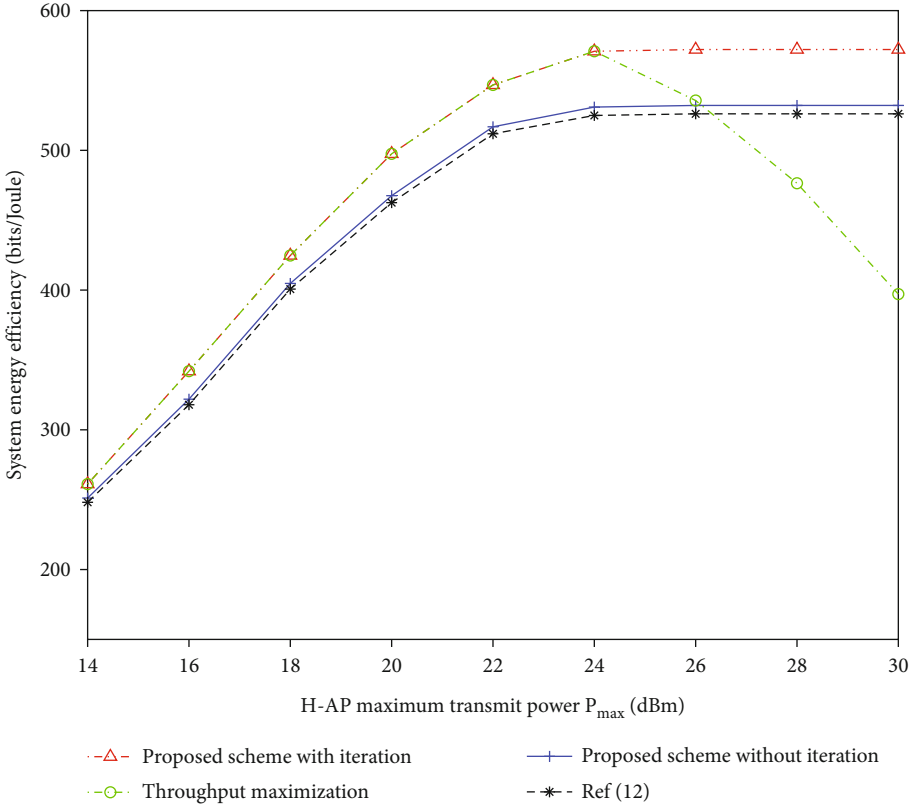
FIGURE 3: The convergence of Algorithm 1.

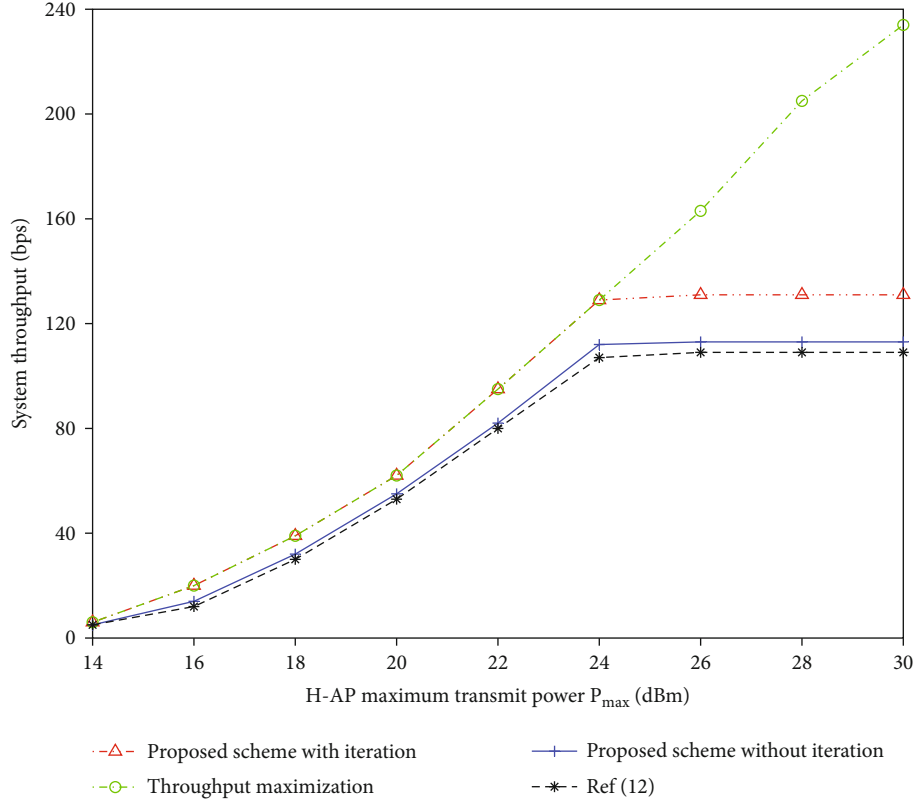FIGURE 4: System EE versus H-AP maximum transmit power P_{max}.

FIGURE 5: System throughout versus H-AP maximum transmit power $P_{\max}$.

"the proposed Algorithm 1," "scheme 2," and "scheme 4" are aimed at the maximum system EE. When $P_{\max} \geq P_H^*$, the algorithms always select $P_H = P_H^*$ as the optimal transmit power. However, "scheme 3" always sets $P_H = P_{\max}$ to achieve the maximum system throughput. Equations (11), (12), and (13) show that the system throughput is increasing function with the variant P_H. Therefore, When $P_{\max} \geq P_H^*$, H-AP transmit power is kept unchanged in Algorithm 1" and "scheme 2" and increasing in "scheme 3," which leads to the different throughput performances.

Simultaneously, Figures 4 and 5 tell us that our proposed scheme can always achieve the better performance both in EE performance and throughput performance. The reason is that the optimal parameters are obtained by searching algorithm while our scheme adopts more accurate iterative optimization method. Therefore, the proposed scheme can achieve the better performance compared with the scheme in reference [12]. Simulation results demonstrate that the proposed algorithm is efficient and achieves the more system EE due to adopting the proposed new communication protocol. Figures 4 and 5 illustrate the importance of considering the EE. Another observation is that our proposed scheme can achieve the highest EE among these schemes since the proposed scheme provides more flexibility to utilize the resource efficiently.

6. Conclusion

In this article, a new WPBCN with DF relaying has been studied which is more suitable to the realistic IoT applica-

tion scenario. In order to achieve high system EE in this network, a new communication protocol was developed, in which SU harvests wireless energy from the relay during relay transmitting the data to H-AP and stores its harvested energy in a battery. And the stored energy can be scheduled across different transmission blocks. To maximize the system EE, we obtained the joint power allocation scheme for the proposed model. Then, by investigating the derivative of the EE expression, the optimal power allocation scheme and iterative optimization algorithm were derived for achieving maximum EE. Extensive simulation results have demonstrated that the system EE can be improved about 10% because the proposed scheme provides more flexibility to utilize the resource efficiently by employing the proposed scheme. Our contribution can provide a useful insight for optimizing system performance in both system throughput and EE in WPBCN.

Appendix

A. Convex Proof of Lemma 2

By taking the derivative of $\mathscr{R}_2$ with respect to β, we get

$$\frac{\partial \mathscr{R}_2}{\partial \beta} = \frac{T_R B}{\ln 2} \left(-\ln \left(c \frac{\beta}{1-\beta} + b \right) + \frac{1}{c\beta + b(1-\beta)} \right). \quad \text{(A.1)}$$

Then, the second-order derivative of $\mathscr{R}_2$ with respect to β is expressed as

$$\frac{\partial^2 \mathscr{R}_2}{\partial^2 \beta} = \frac{T_R B}{\ln 2(c\beta + b(1-\beta))} \left(-\frac{c}{1-\beta} - b(1-\beta) - \frac{c-b}{c\beta + b(1-\beta)} \right). \tag{A.2}$$

Since always hold with $0 < \beta < 1$, we conclude that P3b is a convex problem. The optimal solution β^* is obtained while $\partial \mathscr{R}_2 / \partial \beta = 0$. Then, we get the following equation:

$$\ln \left(c\frac{\beta}{1-\beta} + b \right) = \frac{1}{c\beta + b(1-\beta)}. \tag{A.3}$$

Let $x = c(\beta/(1-\beta)1 - \beta) + b$ with $x > 1$. Then, we can get $\beta = (x-b)/(x-b+c)$. Substituting these into the above equation, we get the following equation:

$$\ln (x) = \frac{x-b+c}{cx}. \tag{A.4}$$

$cx \ln x - x + b - c = 0$ and x^* is the solution. Define $f(x) = cx \ln x - x + b - c$. It is easy to prove that $f(x)$ is a monotone-increasing function of x if $x > 1$. Therefore, we observe that x^* is unique. Thus, the optimal solution $\beta^* = (x^* - b)/(x^* - b + c)$ and x^* is the solution of equation (33).

Data Availability

All the data used to support the findings of this study are included within the article.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

Acknowledgments

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