Optimal Time Allocation in Relay Assisted Backscatter Communication Systems

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***Abstract*—In this paper, we consider a relay assisted backscatter communication (RaBackCom) system, where a user backscatters incident signals from a carrier emitter (CE) to a relay and a receiver simultaneously, and then the relay forwards the user's information to the receiver for throughput improvement. We consider two cases that the relay is with/without an embedded energy source. Specifically, if the relay does not have an energy source, it first harvests energy from the signals from the CE and then uses its harvested energy for information forwarding. For both cases, we formulate time allocation problems on the user's information backscattering, the user's information forwarding, or the relay's energy harvesting to maximize the system throughput, and then derive closed-form solutions. Simulation results demonstrate the advantages of the proposed relay cooperation scheme with the optimal time allocation in terms of system throughput.**

I. Introduction

With the development of Internet of Things (IoT), massive wireless devices are deployed throughout our lives. However, the lifetime of these devices is limited since they are typically powered by their embedded batteries [1]. To prolong the devices' lifetime, wireless power transfer (WPT) has been proposed, where the devices harvest energy from the signals radiated by a wireless energy source [2]. Specifically, a typical application of WPT for IoT is wireless powered communication network (WPCN) [3]. In a WPCN, the devices transmit their information actively based on the harvested energy such that the oscillators are required to generate carrier signals and analog-to-digital converters (ADCs) are used for digital modulation. Hence, the circuit power consumption of these devices is not low enough for the long-lifetime requirement for IoT.

Recently, backscatter communication (BackCom) is emerging as a new communication mode [4]–[9]. For BackCom, a real-world application is RF Identification (RFID), where a device (tag) does not require any active RF components to transmit data and the data transmission is operated by reflecting and modulating the incident signals via mismatching the device's antenna impedance [4]. Hence, the circuit power consumption of a device in BackCom mode is orders-of-magnitude less than that in a traditional WPCN. In [5], the authors studied various collision resolution techniques in a large-scale BackCom network. In [6] and [7], the authors investigated the physical layer security of BackCom systems and proposed the noise-injection schemes to guarantee the system security. In [8], the authors introduced BackCom to cognitive radio networks, where the secondary user working in BackCom shares the spectrum with the primary communication system. In [9], the duty cycle was introduced to RF-powered communication networks with BackCom to avoid the situation that the instantaneous received power cannot operate the device.

Most of the works in the field of BackCom systems consider the scenarios that the user backscatters information to the receiver directly. However, the system throughput is typically limited due to the channel fading between the carrier emitter (CE) and the user and between the user and the information receiver. The cooperative transmission technique has been extensively applied in wireless communication systems to increase system capacity. In a cooperative network, the relay node is usually used to forward information transmission [10]. Inspired by this, in this paper, we employ a relay to improve the BackCom system throughput. We study a time-switching relay assisted BackCom (RaBackCom) system, which is shown in Fig. 1. In the considered system, there is a CE, a user, a receiver and a relay. The user backscatters the continuous carrier wave (CW) from the CE to both the relay and the receiver simultaneously, and then the relay forwards the received signal from the user to the receiver. We consider two cases: 1) the relay is with an embedded energy source; 2) the relay is without an embedded energy source. For both cases, the relay uses its embedded energy or the harvested energy from the CE for information forwarding. Under this setup, we study the throughput maximization problems by optimizing the time allocation and derive the closed-form solutions for the two cases, respectively. Simulation results are finally presented to verify the superiority of the proposed relay cooperation scheme.

II. System model

As illustrated in Fig. 1, we study a RaBackCom system, where each terminal has one single antenna. The system is studied based on a transmission block with duration of T. Denote the distances between the CE and the user, between the CE and the relay, between the CE and the receiver, between the user and the receiver, between the user and the relay, and between the relay and the receiver as $d_{0,1}$, $d_{0,2}$, $d_{0,3}$, d_1, d_2 and d_3. To make the relay assist the information transmission between the user and the receiver, i.e., the relay first decodes the information backscattered by the user and then forwards

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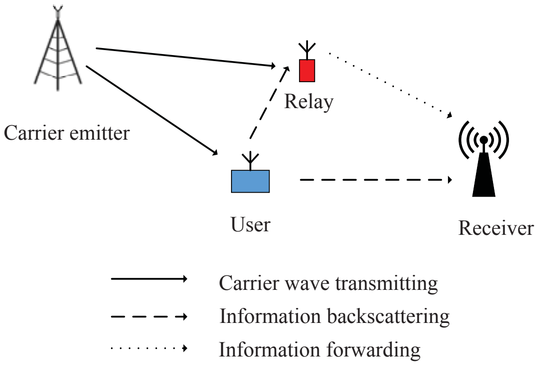
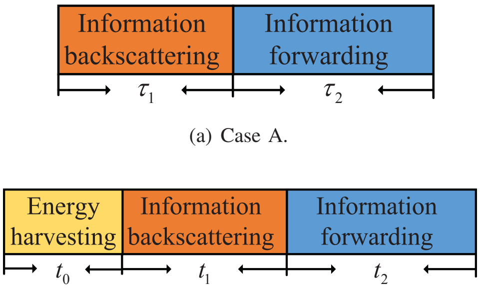


Fig. 1. A RaBackCom system.



(a) Case A.

(b) Case B.

Fig. 2. Block structure.

the decoded information to the receiver, we assume that $d_1 > d_2$ and $d_1 > d_3$. Denote the channel gains between the CE and the user, between the CE and the relay, between the CE and the receiver, between the user and the receiver, between the user and the relay, and between the relay and the receiver as $h_{0,1}$, $h_{0,2}$, $h_{0,3}$, h_1, h_2, and h_3, which are modelled as quasi-static flat-fading and remain constant during each transmission block, but may vary from one block to another. Following [3], we only consider the distance-dependent signal attenuation such that we have $h_1 < h_2$ and $h_1 < h_3$.

We assume the CE transmits the continuous CW with power P and denote its transmitted signal as s, where $\mathbb{E}[|s|^2] = P$. The user backscatters information based on the incident signal from the CE. We consider two cases for the relay, i.e., the relay is with an embedded energy source and the relay is without an embedded energy source. To simplify the aftermentioned descriptions, we denote the cases that the relay is with/without an embedded energy source as Case A and Case B, respectively.

A. Relay with embedded energy source

If the relay has an embedded energy source, it does not need to harvest energy from the CE. The structure of a transmission block is illustrated in Fig. 2 (a). During τ_1, the CE transmits the CW signal and the received signal at the user is given by $\sqrt{h_{0,1}}s$ without considering the noise following [11]. Denote the reflection coefficient at the user as α, where $0 \le \alpha \le 1$. For simplicity, we assume that $\alpha = 1$, i.e., all the received signal at the user will be backscattered[1]. Following the definition in [8], the user's own signal is denoted as c, where $\mathbb{E}[|c|^2] = 1$. The backscattered signal at the user, denoted by x, is thus expressed as

$$x = \alpha\sqrt{h_{0,1}}sc = \sqrt{h_{0,1}}sc, \tag{1}$$

and the received signals at the receiver and the relay, denoted as y_1 and y_2, are respectively given by

$$y_1 = \sqrt{h_1}\sqrt{h_{0,1}}sc + \sqrt{h_{0,3}}s + n_1, \tag{2}$$

$$y_2 = \sqrt{h_2}\sqrt{h_{0,1}}sc + \sqrt{h_{0,2}}s + n_2. \tag{3}$$

where $n_i, i = 1, 2$, is the Gaussian noise satisfying $n_i \sim \mathcal{CN}(0, \sigma_i^2)$, $\sqrt{h_{0,3}}s$ and $\sqrt{h_{0,2}}s$ are the interference signals from the CE at the receiver and the relay, respectively. We assume that successive interference cancellation (SIC) is adopted at both the receiver and the relay following [8]. Hence, both the receiver and the relay can first decode the interference signals and then subtract them from the received signals. Denote the signal-noise-ratio (SNR) at the receiver and the relay during τ_1 as γ_1 and γ_2, respectively, which are given by $\gamma_1 = \frac{Ph_{0,1}h_1}{\sigma_1^2}$ and $\gamma_2 = \frac{Ph_{0,1}h_2}{\sigma_2^2}$.

Denote the relay's energy for forwarding the user's information as E, which is exhausted during τ_2. Hence, the average transmit power at the relay is given by $P_r = \frac{E}{\tau_2}$. Denote the forwarded signal at the relay as $\hat{x}$, where $\mathbb{E}[|\hat{x}|^2] = P_r$. The received signal at the receiver from the relay is thus expressed as

$$y_3 = \sqrt{h_3}\hat{x} + n_1. \tag{4}$$

Denote the instantaneous transmission rates from the user to the receiver, from the user to the relay, from the relay to the receiver as R_1, R_2 and R_3, respectively, which are expressed as

$$R_1 = \tau_1 \log_2(1 + \gamma_1), \tag{5}$$

$$R_2 = \tau_1 \log_2(1 + \gamma_2), \tag{6}$$

$$R_3 = \tau_2 \log_2(1 + \frac{\gamma_3}{\tau_2}), \tag{7}$$

where $\gamma_3 = \frac{h_3 E}{\sigma_1^2}$. From [3], [12], the instantaneous transmission rate of the user, denoted by R, is given by

$$R = \min\{R_1 + R_3, R_2\}. \tag{8}$$

B. Relay without embedded energy source

If the relay does not have an embedded energy source, it needs to harvest energy from the CE. The block structure of this case is given in Fig. 2 (b). Different from Case A, an energy harvesting time for the relay is required here. During t_0, only the relay is activated to harvest energy from the CE[2], where the harvested energy is given by

$$\hat{E} = \eta P h_{0,2} t_0,$$

[1] In this paper, we assume that the main energy consumption of the user and the relay is for information transmission and does not consider other circuit energy consumption for simplicity.

[2] The user can also be activated to backscatter information to the receiver during t_0. However, at this stage, we assume the user stays in the idle state.

where η is the energy harvesting efficiency. During t_1 and t_2, the system works as that we describe during τ_1 and τ_2 in Section II-A. Hence, the average transmit power for the relay during t_2, denoted by $\hat{P}_r$, is given by $\hat{P}_r = \frac{\eta P h_{0,2} t_0}{t_2}$.

Denote the instantaneous transmission rates from the user to the receiver, from the user to the relay, from the relay to the receiver for Case B as $\hat{R}_1$, $\hat{R}_2$ and $\hat{R}_3$. Similar as the analysis for Case A, we have

$$\hat{R}_1 = t_1 \log_2(1+\gamma_1), \tag{9}$$

$$\hat{R}_2 = t_1 \log_2(1+\gamma_2), \tag{10}$$

$$\hat{R}_3 = t_2 \log_2(1+\hat{\gamma}_3 \frac{t_0}{t_2}), \tag{11}$$

where $\hat{\gamma}_3 = \frac{\eta P h_{0,2} h_3}{\sigma_1^2}$. The instantaneous transmission rate of the user for Case B, denoted by $\hat{R}$, is formulated as

$$\hat{R} = \min\{\hat{R}_1 + \hat{R}_3, \hat{R}_2\}. \tag{12}$$

III. Optimal time allocation

In this section, we study the throughput maximization problems by finding the optimal time allocation scheme for both Case A and Case B.

A. Case A

We formulate the optimization problem for Case A as follows.

$$\begin{aligned} \max_{\boldsymbol{\tau}} \quad & R \\ \text{s.t.} \quad & \text{C1:} \ \ \tau_1 + \tau_2 \le T, \\ & \text{C2:} \ \ \tau_1, \tau_2 \ge 0, \end{aligned} \tag{\textbf{P1}}$$

where $\boldsymbol{\tau} = [\tau_1, \tau_2]$. Constraint C1 indicates that the summation of the user's backscattering time and the relay's forwarding time cannot exceed the duration of a transmission block, and constraint C2 limits that the optimization variables are non-negative. Denote the optimal solution for Problem P1 as $\boldsymbol{\tau^*} = [\tau_1^*, \tau_2^*]$. Before solving Problem P1, we have the following lemmas.

Lemma 1: $R_3(\tau_2)$ is an increasing function with respect to τ_2, and $R_1(\tau_1)$ and $R_2(\tau_1)$ are both increasing functions with respect to τ_1.

Lemma 2: In the optimal condition for Problem P1, we have

$$\text{C3}: \quad \tau_1^* + \tau_2^* = T, \tag{13}$$

$$\text{C4}: \quad R_1(\tau_1^*) + R_3(\tau_2^*) \le R_2(\tau_1^*). \tag{14}$$

Proof 1: Please refer to Appendix A.

According to Lemma 2, we have

$$\begin{aligned} \max_{\boldsymbol{\tau}} \quad & R_1(\tau_1) + R_3(\tau_2) \\ \text{s.t.} \quad & \text{C2, C3, C4.} \end{aligned} \tag{\textbf{P2}}$$

To obtain the optimal solution for Problem P2, we consider the following two subcases. First, we consider the condition that $R_1(\tau_1^*) + R_3(\tau_2^*) = R_2(\tau_1^*)$, and derive the optimal solution for Problem P2 in the following proposition.

Proposition 1: If $R_1(\tau_1^*) + R_3(\tau_2^*) = R_2(\tau_1^*)$, the optimal solution for Problem P2 satisfies

$$\tau_1^* = T - \tau_2^*, \tag{15}$$

where $\tau_2^* > 0$ is the unique solution of $\tau_2 \log_2(1 + \frac{\gamma_3}{\tau_2}) + \tau_2 \log_2(1+\gamma_2) - \tau_2 \log_2(1+\gamma_1) = T[\log_2(1+\gamma_2) - \log_2(1+\gamma_1)]$, which can be easily obtained by the bisection method.

Then, we consider the condition that $R_1(\tau_1^*) + R_3(\tau_2^*) < R_2(\tau_1^*)$. For this condition, we have Proposition 2.

Proposition 2: The optimal solution for Problem P2 satisfies

$$\tau_1^* = T - \tau_2^*, \tag{16}$$

where $\tau_2^* > 0$ is the unique solution of $\log_2(1 + \frac{\gamma_3}{\tau_2}) - \frac{\frac{\gamma_3}{\tau_2}}{\ln 2(1+\frac{\gamma_3}{\tau_2})} = \log_2(1+\gamma_1)$, which can also be obtained by the bisection method.

From Proposition 1 and Proposition 2, we can conclude that both τ_1^* and τ_2^* are non-negative. That is to say, for Case A, the relay is always involved to forward the user's information transmission.

B. Case B

For Case B, the optimization problem is given as follows.

$$\begin{aligned} \max_{\boldsymbol{t}} \quad & \hat{R} \\ \text{s.t.} \quad & \text{C5:} \ \ t_0 + t_1 + t_2 \le T, \\ & \text{C6:} \ \ t_0, t_1, t_2 \ge 0, \end{aligned} \tag{\textbf{P3}}$$

where $\boldsymbol{t} = [t_0, t_1, t_2]$. Denote the optimal solution for Problem P3 as $\boldsymbol{t}^* = [t_0^*, t_1^*, t_2^*]$.

Similar as Lemma 2, we also have the following conditions for Problem P3

$$\text{C7}: \quad t_0^* + t_1^* + t_2^* = T, \tag{17}$$

$$\text{C8}: \quad \hat{R}_1(t_1^*) + \hat{R}_3(t_0^*, t_2^*) \le \hat{R}_2(t_1^*). \tag{18}$$

From (17) and (18), we have

$$\begin{aligned} \max_{\boldsymbol{t}} \quad & \hat{R}_1(t_1) + \hat{R}_3(t_0, t_2) \\ \text{s.t.} \quad & \text{C6, C7, C8.} \end{aligned} \tag{\textbf{P4}}$$

It can be proved that Problem P4 is a convex optimization problem, which can be solved by the interior-point method [13]. However, this method needs iterations to find the optimal solution. To avoid the high-complexity iterations, we exploit the special structure of Problem P4 to obtain the optimal solution, for which Problem P4 is further decomposed into two sub-problems. First, given t_1, we find the optimal relationship between t_0 and t_2 by solving Problem P5.

$$\begin{aligned} \max_{t_0, t_2} \quad & \hat{R}_3(t_0, t_2) \\ \text{s.t.} \quad & t_0 + t_2 = T - t_1, \\ & \hat{R}_3(t_0, t_2) \le \hat{R}_2(t_1) - \hat{R}_1(t_1), \\ & t_0, \ t_2 \ge 0. \end{aligned} \tag{\textbf{P5}}$$

The Lagrangian of Problem P5 is given by

$$\mathcal{L}(t_0,t_2,\lambda_1,\lambda_2) = \hat{R}_3(t_0,t_2) - \lambda_1(t_0+t_2-T+t_1) - \lambda_2(\hat{R}_3(t_0,t_2) - \hat{R}_2(t_1) + \hat{R}_1(t_1)), \quad (19)$$

where λ_1 and λ_2 are the Lagrangian multipliers, and the corresponding KKT conditions are given by

$$\frac{\partial L}{\partial t_0} = (1-\lambda_2)\frac{\hat{\gamma}_3}{\ln 2(1+\hat{\gamma}_3\frac{t_0}{t_2})} - \lambda_1 = 0, \quad (20)$$

$$\frac{\partial L}{\partial t_2} = (1-\lambda_2)\left[\log_2(1+\hat{\gamma}_3\frac{t_0}{t_2}) - \frac{\hat{\gamma}_3\frac{t_0}{t_2}}{\ln 2(1+\hat{\gamma}_3\frac{t_0}{t_2})}\right] - \lambda_1 = 0. \quad (21)$$

Combining with (20) and (21), we have the following equation

$$f(z) = \hat{\gamma}_3, \quad (22)$$

where $f(z) = z\ln z - z + 1$, $z = 1+\hat{\gamma}_3\frac{t_0}{t_2}$. From [14], we know that $f(z)$ is an increasing function with respect to z ($z>1$), and there is a unique solution $z^*>1$ satisfying (22). Hence, we derive t_0 and t_2 with given t_1, which are given by

$$t_0 = \frac{(z^*-1)(T-t_1)}{z^*-1+\hat{\gamma}_3},$$
$$t_2 = \frac{\hat{\gamma}_3(T-t_1)}{z^*-1+\hat{\gamma}_3}.$$

With the above result, we further derive t_1 by solving the following problem.

$$\max_{t_1} \quad t_1\log_2(1+\gamma_1) + \frac{\hat{\gamma}_3(T-t_1)}{z^*-1+\hat{\gamma}_3}\log_2(z^*)$$
$$\text{s.t.} \quad 0 \le t_1 \le T, \quad \textbf{(P6)}$$
$$\frac{\hat{\gamma}_3(T-t_1)}{z^*-1+\hat{\gamma}_3}\log_2(z^*) \le a t_1,$$

where $a = \log_2(1+\gamma_2) - \log_2(1+\gamma_1)$.

By solving Problem P6, we have the following proposition.

Proposition 3: By solving Problem P6, the optimal solution is given by

$$\text{If } \log_2(1+\gamma_1) \ge \frac{\hat{\gamma}_3\log_2(z^*)}{\hat{\gamma}_3+z^*-1}, \quad t_1^* = T, \quad (23)$$

$$\text{if } \log_2(1+\gamma_1) < \frac{\hat{\gamma}_3\log_2(z^*)}{\hat{\gamma}_3+z^*-1}, \quad t_1^* = \frac{b}{a+b}T, \quad (24)$$

where $b = \frac{\hat{\gamma}_3\log_2(z^*)}{\hat{\gamma}_3+z^*-1}$. If $\log_2(1+\gamma_1) \ge \frac{\hat{\gamma}_3\log_2(z^*)}{\hat{\gamma}_3+z^*-1}$, it indicates that the system throughput maximum is obtained without the aid of the relay; If $\log_2(1+\gamma_1) < \frac{\hat{\gamma}_3\log_2(z^*)}{\hat{\gamma}_3+z^*-1}$, the relay is employed to maximize the system throughput, and $t_0^* = \frac{(z^*-1)(T-t_1^*)}{z^*-1+\hat{\gamma}_3}$, $t_2^* = \frac{\hat{\gamma}_3(T-t_1^*)}{z^*-1+\hat{\gamma}_3}$.

IV. Numerical Results

In this section, numerical results are provided to evaluate the performance of RaBackCom systems. The simulation parameters are given as follows unless stated otherwise. We set the transmit power of the CE as $P = 30$ dBm, the relay's embedded energy as 100 μJ, the noise power as $\sigma_1^2 = \sigma_2^2 = -70$ dBm, the relay's energy harvesting efficiency as $\eta = 0.8$, the transmission block duration as $T = 1$ s. The channel power gains are modelled as $h_{0,i} = 10^{-3}\theta_{0,i}d_{0,i}^{-\alpha}$ and $h_i = 10^{-3}\theta_i d_i^{-\alpha}$, $i = 1,2,3$, where $\theta_{0,i}$ and θ_i characterize the channel short-term fading and are set as $\theta_{0,i} = \theta_i = 1$ since we only consider the long-term fading, and the path-loss exponent is set as $\alpha = 3$. We further set $d_{0,1} = d_{0,2} = 5$ m, $d_1 = 2$ m, $d_2 = 1.6$ m, and $d_3 = 0.7$ m. The scheme that BackCom without relay assistance is served as a benchmark.

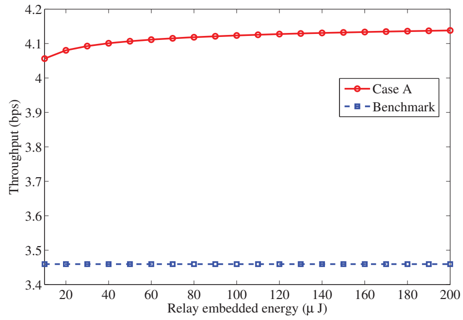


Fig. 3. Throughput vs. embedded energy.

Fig. 3 shows the system throughput versus the relay's embedded energy. It is obvious that the throughput of Case A is larger than that of the benchmark. As the embedded energy increases, the throughput increases slowly. It is because for Case A, the time is mostly used for the user's information backscattering. Fig. 4 investigates the system throughput versus the distance between the relay and the receiver. As the distance increases, the throughput reduces due to the decrease of h_3. Other observations are similar as Fig. 3.

Figs. 5 and 6 investigate the performance of Case B. Fig. 5 depicts the effect of CW signal's power on the system throughput. We observe that the throughputs of both Case B and the benchmark are increasing functions with the transmit power. For Case B, even a fraction of time is used for the relay's energy harvesting, Case B still achieves a larger throughput. Fig. 6 shows the throughput versus the distance between the relay and the receiver. When the distance is small, the performance of Case B is superior to that of the benchmark. When the distance exceeds a threshold ($d_3 = 1$ m), the relay is not required to forward the user's information transmission. This observation is coincident with our analysis in Proposition 3.

V. Conclusion

In this paper, we have considered a relay cooperation scheme in backscatter communication systems, where the relay is employed to forward the user's information to the receiver for the system throughput improvement. We have considered two cases that the relay is with/without an embedded energy source. If the relay has an energy source, it uses its own energy to forward the user's information. If not, the relay first harvests energy from the CW signal and then uses the harvested energy for information forwarding. For both cases,

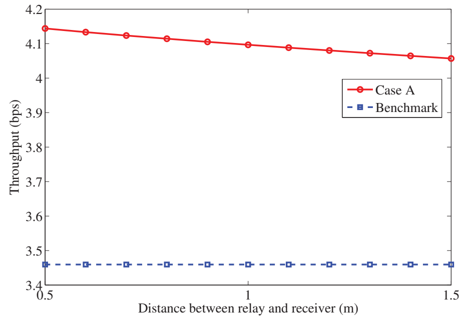


Fig. 4. Throughput vs. distance between relay and receiver for Case A.

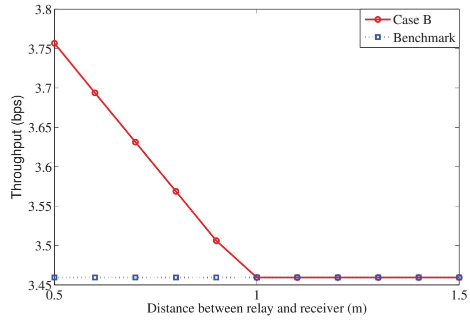


Fig. 6. Throughput vs. distance between relay and receiver for Case B.

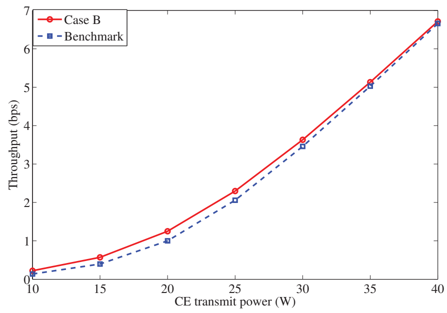


Fig. 5. Throughput vs. CE transmit power.

optimization problems for maximizing the system throughput have been formulated and closed-form solutions have been given, respectively. In the further work, we will extend the system model with multiple users or relays for a more practical IoT environment.

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APPENDIX A
PROOF OF LEMMA 2

Denote the optimal solution for Problem P1 as $\{\hat{\tau}_1, \hat{\tau}_2\}$, which satisfies $\hat{\tau}_1 + \hat{\tau}_2 < T$. Then, by contradiction, we show that $\{\hat{\tau}_1, \hat{\tau}_2\}$ is not the optimal solution. We consider that there exists $\{\tau_1^*, \tau_2^*\}$ satisfying

$$\tau_1^* + \tau_2^* = T, \quad \tau_1^* > \hat{\tau}_1, \quad \text{and} \quad \tau_2^* = \hat{\tau}_2.$$

From Lemma 1, we derive that $R_1(\tau_1^*) + R_3(\tau_2^*) > R_1(\hat{\tau}_1) + R_3(\hat{\tau}_2)$ and $R_2(\tau_1^*) > R_2(\hat{\tau}_1)$. It indicates that $\{\hat{\tau}_1, \hat{\tau}_2\}$ is not the optimal solution.

We further prove $R_1(\tau_1) + R_3(\tau_2) \leq R_2(\tau_1)$ in the optimal condition by contradiction. Denote the optimal solution for Problem P1 as $\{\tilde{\tau}_1, \tilde{\tau}_2\}$, where $\tilde{\tau}_1 + \tilde{\tau}_2 = T$. If $R_1(\tilde{\tau}_1) + R_3(\tilde{\tau}_2) > R_2(\tilde{\tau}_1)$, we can increase $\tilde{\tau}_1$ to τ_1^* and reduce $\tilde{\tau}_2$ to τ_2^* to guarantee that $R_1(\tau_1^*) + R_3(\tau_2^*) = R_2(\tau_1^*) > R_2(\tilde{\tau}_1)$ according to Lemma 1, where $\tau_1^* + \tau_2^* = T$. This contradicts with the assumption that $\{\tilde{\tau}_1, \tilde{\tau}_2\}$ is the optimal solution.

Therefore, we prove Lemma 2.

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