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Wireless Powered Opportunistic Cooperative Backscatter Communications: To Relay or Not?

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***Abstract*—In this article, we propose a wireless powered opportunistic cooperative backscatter communication network, where an Internet of Things (IoT) node conveys information to its associated receiver via backscatter communications with the help of a hybrid access point (HAP) in each transmission block. The HAP provides energy signals for the IoT node in the first half transmission block, and continues to do or relays the IoT node's signal to the receiver via decode-and-forward protocol in the second half transmission block. We investigate under which condition the HAP serves as the relay node in the second half transmission block in terms of the achievable throughput. To this end, a mixed integer non-convex optimization is formulated to maximize the throughput of the IoT node by optimizing the power reflection coefficient (PRC) of the IoT node and the operation mode of the HAP during the second half transmission block, while meeting the energy-causality constraint of the IoT node. We derive the closed-form expressions for the optimal PRC and operation mode, based on which a scheme is proposed to determine the optimal operation mode of the HAP. Simulations validate the derived results and study the impacts of various parameters on the optimal operation mode and throughput.**

***Index Terms*—Cooperative backscatter communication network, relay, throughput.**

I. Introduction

The limited life span of massive smart devices has been a major obstacle for realizing pervasive development of Internet of Things (IoT), and this calls for energy self-sustainability technologies. One particular promising technology is wireless powered backscatter communication (WPBC) [1], where the IoT nodes are allowed to modulate and reflect the incident signals transmitted by the dedicated energy source, i.e., power beacon (PB), by adjusting the antenna load impedance instead of generating radio frequency (RF) signals by itself, while to harvest energy to support its circuit operation. However, due to the free of power-consuming active components, the performance of the WPBC is limited and such a technology is appropriate for low-data/short-range communications [1].

There are two typical solutions for solving the above problem. One way is the hybrid WPBC and active communications (AC), where the IoT nodes convey information to the receiver via hybrid backscatter communications (BC) and AC, subject to the energy-causality constraint of each IoT node. Such a hybrid communication fully exploits the complementary of BC and AC in terms of the throughput and power consumption, and thus achieves a better performance than WPBC, as verified by [2]–[4]. The other is the relay-assisted WPBC, where the relay node is deployed to re-encode and forward the backscattered signal of IoT nodes via AC [5]–[8]. In [5] and [6], the authors formulated two problems to maximize the throughput of the IoT node by optimizing the time for WPBC and AC under two scenarios with energy-constrained relay and the non-energy-constrained relay, respectively. Subsequently, the authors in [7] extended the single relay link into the multiple links scenario, where all the relays are energy-constrained and the links between the IoT node and the destination are assumed to be blocked. Under this setting, the time for energy harvesting (EH), AC, and WPBC is optimized to maximize the sum throughput of all the IoT nodes. The above works [5]–[7] have not considered the energy consumption and harvesting of the IoT node and such a gap was filled in [8].

Although various contributions have been made to improve the performance of WPBC, there is still a room for improvement. In particular, for the hybrid WPBC-AC [2]–[4]/energy-constrained relay-assisted WPBC [5]–[8], due to the low efficiency of EH, the IoT node/energy-constrained relay has to allocate a long period for EH and leaves a short period for AC in each transmission block, thus the performance promotion is limited. While for the non-energy-constrained relay-assisted WPBC [5], [6], [8], it deploys non-energy-constrained relays that are either connected to the grid or frequently replaced by the new battery, leading to a high cost. Besides, in [5], [6], [8], the authors considered the maximum ratio combining (MRC) at the receiver and the unequal transmission time for the IoT node-relay (receiver) link and the relay-receiver link, resulting in unequal time of the received signals at the receiver. Although this can be addressed by complex signal processing technologies, e.g., the linear mapping scheme [9], such an approach has not been considered in [5], [6], [8] and the extra cost may be high if used.

In this article, we propose a wireless powered opportunistic cooperative backscatter communication network, where a hybrid access point (HAP) serves as the PB in the first half transmission block and opportunistically functions as the decode-and-forward (DF) relay or PB in the second half transmission block. The main advantages of the proposed networks are three-fold. First, in hybrid WPBC-AC [2]–[4]/energy-constrained relay-assisted WPBC [5]–[8], the performance of AC is constrained by the harvested energy, while it can be avoided in the proposed network. Second, our proposed network enjoys a lower hardware cost than the relay-assisted WPBC [5]–[8] as the dedicated relay is not required. Third, thanks to the equal time allocation in the proposed network,

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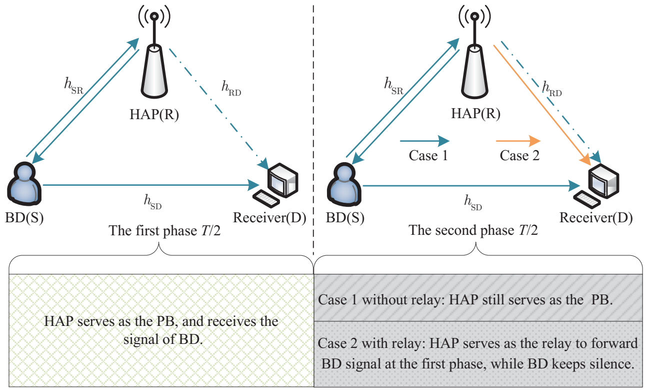

Fig. 1: System model and time scheduling structure.

the received signals at the receiver can be easily processed via MRC, thus avoiding the complex signal processing. To maximize the throughput of the proposed network, we formulate a mixed integer non-convex optimization problem to jointly optimize the power reflection coefficient (PRC) of the IoT node and the binary operation mode of the HAP during the second half transmission block, i.e., PB or relay. Closed-form expressions for the optimal PRC and operation mode are derived, based on which a scheme is proposed to determine which role the HAP should function in the second half transmission block. Simulations are provided to verify the derived results and reveal the impacts of system parameters on the optimal operation mode and throughput.

II. System Model

As depicted in Fig. 1, we consider a wireless powered opportunistic cooperative backscatter communications network with one HAP (also termed as R), one the IoT node (also termed as S) and one receiver (also termed as D). We assume that both the IoT node and receiver are equipped with a single antenna, while the HAP[1] is with two antennas so as to broadcast energy signals and receive the reflected signal from the IoT node simultaneously. In this network, the HAP is deployed nearly the IoT node to provide energy signals on demand to the IoT node in the first half transmission block and go on to do or forward the signal backscattered by the IoT node to the receiver in the second half transmission block. We consider a quasi-static channel fading, i.e., the channel power gains of all links keep unchanged within each transmission block T. Denote the channel power gains of the S$-$R link, the R$-$D link, and the S$-$D link as $h_{\rm SR}$, $h_{\rm RD}$ and $h_{\rm SD}$, respectively.

In the first half transmission block, the HAP broadcasts the energy signal, then the signal received by the IoT node is given by [5]–[7]

$$z_{\rm B} = \sqrt{P_0}\sqrt{h_{\rm SR}}s, \tag{1}$$

where P_0 represents the transmit power of the HAP, and s denotes the broadcasted signals of the HAP and follows the standard circularly symmetric complex Gaussian distribution, i.e., $s \sim \mathcal{CN}(0,1)$. Note that the noise of the IoT node can be neglected since there are only passive components on its integrated circuit.

By performing BC, the received signal $z_{\rm B}$ is split into two parts via a PRC β, $(0 \le \beta \le 1)$, i.e., a $\sqrt{\beta}$ portion of received signal, $\sqrt{\beta P_0 h_{\rm SR}}s$, is used as the carrier to modulate information and reflect to the receiver, and the remaining one, $\sqrt{(1-\beta)P_0 h_{\rm SR}}s$, is fed into the energy harvester. Thus, the backscattered signal and the harvested energy of the IoT node can be written as, respectively,

$$z_{\rm B'} = z_{\rm B}\sqrt{\beta}c = \sqrt{P_0\beta h_{\rm SR}}sc, \tag{2}$$

$$E_{\rm har1} = \frac{T}{2}\eta(1-\beta)P_0 h_{\rm SR}, \tag{3}$$

where η is the EH efficiency.

The received signals at the receiver and the HAP are, respectively, denoted as

$$z_{\rm D1} = \sqrt{P_0\beta h_{\rm SR}h_{\rm SD}}sc + \sqrt{P_0 h_{\rm RD}}s + n_2, \tag{4}$$

$$z_{\rm R} = \sqrt{P_0\beta h_{\rm SR}h_{\rm SR}}sc + \sqrt{P_0 h_{\rm LI}}s + n_1, \tag{5}$$

where n_1 and n_2 are the additive white complex Gaussian noise with mean zero and variance σ^2, respectively, and $h_{\rm LI}$ denotes the residual loop interference channel gain at the HAP.

Eqs. (4) and (5) indicate that there exists co-channel interference caused by the energy signal. Since the energy signal can be predefined and known by the HAP and the receiver, the co-channel interference can be removed via successive interference cancellation (SIC) before decoding c at the HAP and the receiver [5]–[7]. Accordingly, the instantaneous signal-plus-noise ratios (SNR) of both the S$-$D and S$-$R links can be expressed as, respectively,

$$\gamma_{\rm SD} = \frac{\beta P_0 h_{\rm SR}h_{\rm SD}}{\sigma^2}, \tag{6}$$

$$\gamma_{\rm SR} = \frac{\beta P_0 h_{\rm SR}^2}{\sigma^2}. \tag{7}$$

In the second half transmission block, there are two operation modes for the HAP, i.e., providing energy signals or forwarding the IoT node's signal. If the HAP serves as the DF relay, the IoT node keeps silent and the received signal at the receiver can be written as

$$z_{\rm D2} = c\sqrt{P_0}\sqrt{h_{\rm RD}} + n_3, \tag{8}$$

where n_3 represents the additive white complex Gaussian noise with zero mean and variance σ^2.

Based on eq. (8), the SNR of R$-$D link is calculated as

$$\gamma_{\rm RD} = \frac{P_0 h_{\rm RD}}{\sigma^2}. \tag{9}$$

In this case, there are two different links transmitting the signal of the IoT node in one transmission block: a direct link from the IoT node to the receiver during the first half transmission block and a relay link from the HAP to the receiver during the second half transmission block. By implementing

[1]Such a configuration is usually considered in monostatic backscatter communication, i.e., one for transmitting energy signal, and the other for receiving backscattered signal.

the MRC scheme, the overall SNR of the receiver can be expressed as [10]

$$\gamma^{\mathrm{e}} = \max\left\{\gamma_{\mathrm{SD},} \min\left(\gamma_{\mathrm{SR}}, \gamma_{\mathrm{SD}} + \gamma_{\mathrm{RD}}\right)\right\}. \tag{10}$$

As a result, the achievable throughput of the IoT node can be expressed as

$$R1 = \frac{T}{2} W \log_2\left(1 + \gamma^{\mathrm{e}}\right), \tag{11}$$

where W denotes the channel bandwidth in hertz(Hz).

If the HAP continues to broadcast energy signals, the received signal and the corresponding SNR at the receiver are the same as (2) and (6). Accordingly, the achievable throughput and the harvest energy of the IoT node in one transmission block can be expressed as

$$R2 = TW \log_2\left(1 + \gamma_{\mathrm{SD}}\right), \tag{12}$$

$$E_{\mathrm{har2}} = T\eta\left(1 - \beta\right) P_0 h_{\mathrm{SR}}. \tag{13}$$

Based on (11) and (12), the achievable throughput of the IoT node is given as

$$R{=}TW\left\{\frac{x}{2}\log_2\left\{1 + \gamma^{\mathrm{e}}\right\} + \left(1 - x\right)\log_2\left(1 + \gamma_{\mathrm{SD}}\right)\right\}, \tag{14}$$

where $x \in \{0, 1\}$ is the binary variable indicating the operation mode of the HAP during the second half transmission block. Specifically, $x = 1$ corresponds to the case where the HAP serves as the relay, and $x = 0$ indicates that the HAP always functions as the PB in the whole transmission block.

Remark. Compared with the case without relay, the case with relay enjoys a larger SNR but at a cost of reducing transmission time. This indicates that the operation mode of the HAP has a significant impact on the throughput of the IoT node. Thus, to maximize the throughput of the IoT node, it is required to study under which condition the HAP should function as the relay, and this will be studied in Section III.

III. Problem Formulation and Solution

In this Section, we formulate a mixed integer non-convex optimization problem to maximize the IoT node's throughput by optimizing the PRC of the IoT node and the operation mode of the HAP, subject to the energy-causality constraint of the IoT node, given by

$$\begin{aligned} (\mathrm{P1}): \max_{x,\beta}\ & \tfrac{x}{2} TW \log_2\left\{1 + \gamma^{\mathrm{e}}\right\} \\ & + \left(1 - x\right) TW \log_2\left(1 + \gamma_{\mathrm{SD}}\right) \\ \text{s.t.}\ \ & \mathrm{C1}:\ 0 \le \beta \le 1, \\ & \mathrm{C2}:\ \tfrac{T}{1+x} P_{\mathrm{c}} \le \tfrac{T}{1+x}\eta\left(1 - \beta\right) P_0 h_{\mathrm{SR}}, \\ & \mathrm{C3}:\ x \in \{0, 1\}, \end{aligned} \tag{15}$$

where P_{c} denotes the circuit power consumption to perform BC at the IoT node, constraint C1 sets the value range of the PRC of the IoT node, and constraint C2 is the energy-causality constraint, i.e., the consumed energy of the IoT node should not exceed its harvested energy.

To make (P1) more tractable, Lemma 1 is provided.

Lemma 1. The PRC maximizing the throughput is $1 - \frac{P_{\mathrm{c}}}{\eta P_0 h_{\mathrm{SR}}}$, i.e., $\beta^* = 1 - \frac{P_{\mathrm{c}}}{\eta P_0 h_{\mathrm{SR}}}$.

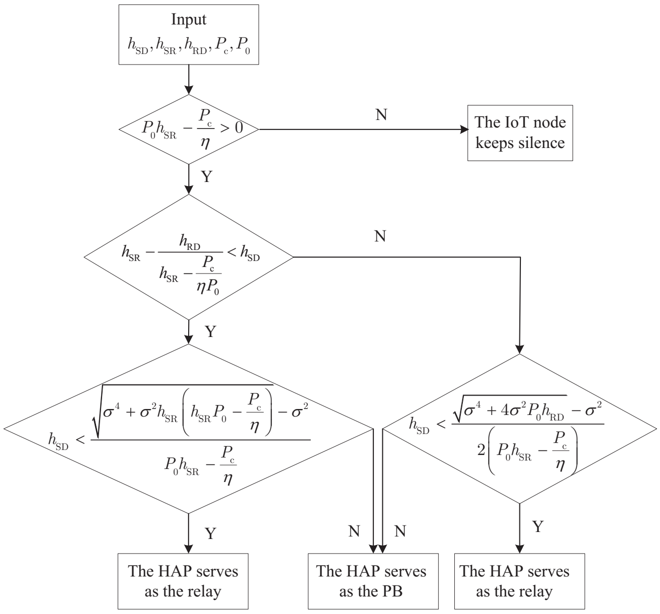

Fig. 2: Flow chart.

Proof: Since the objective function of (P1) increases with the PRC, the optimal PRC equals the maximum one within its feasible range. From C1 and C2, we have $0 < \beta \le 1 - \frac{P_{\mathrm{c}}}{\eta P_0 h_{\mathrm{SR}}}$, and thus Lemma 1 is proved. ■

Based on Lemma 1, (P1) is converted to

$$\begin{aligned} (\mathrm{P2}): \max_{x}\ & \tfrac{x}{2} TW \log_2\left\{1 + \gamma^{\mathrm{e}\prime}\right\} \\ & + \left(1 - x\right) TW \log_2\left(1 + \gamma'_{\mathrm{SD}}\right) \\ \text{s.t.}\ \ & \mathrm{C1}:\ x \in \{0, 1\}, \end{aligned} \tag{16}$$

where

$$\gamma^{\mathrm{e}\prime} = \max\left\{\gamma'_{\mathrm{SD},} \min\left(\gamma'_{\mathrm{SR}}, \gamma'_{\mathrm{SD}} + \gamma_{\mathrm{RD}}\right)\right\}, \tag{17}$$

$$\gamma'_{\mathrm{SR}}{=}\frac{\left(\eta P_0 h_{\mathrm{SR}}{-}P_{\mathrm{c}}\right) h_{\mathrm{SR}}}{\eta\sigma^2}, \gamma'_{\mathrm{SD}}{=}\frac{\left(\eta P_0 h_{\mathrm{SR}}{-}P_{\mathrm{c}}\right) h_{\mathrm{SD}}}{\eta\sigma^2}. \tag{18}$$

Problem (P2) is still non-convex and cannot be directly solved by the convex tools. However, there is only one binary variable needed to be optimized, and this motivates us to solve (P2) by comparing the throughput achieved by the relay with that without relay. Particularly, when $x = 1$, the throughput of (P2) is reduced to $R1' = \frac{T}{2} W \log_2\left(1 + \gamma^{\mathrm{e}\prime}\right)$; when $x = 0$, the throughput of (P2) is calculated as $R2' = TW \log_2\left(1 + \gamma'_{\mathrm{SD}}\right)$. Then the optimal x can be determined by comparing $R1'$ with $R2'$ and the result can be summarized in Lemma 2.

Lemma 2. The optimal x of (P2) problem is

$$x^* = \begin{cases} 1, & \text{Case 1 or 2} \\ 0, & \text{Otherwise} \end{cases}, \tag{19}$$

where

$$\left\{\begin{aligned} & \text{Case 1}:\ h_{\mathrm{SR}} - \frac{h_{\mathrm{RD}}}{h_{\mathrm{SR}} - \frac{P_{\mathrm{c}}}{\eta P_0}} < h_{\mathrm{SD}} \\ & \quad \& \ h_{\mathrm{SD}} < \frac{\sqrt{\sigma^4 + \sigma^2 h_{\mathrm{SR}}\left(h_{\mathrm{SR}} P_0 - \frac{P_{\mathrm{c}}}{\eta}\right)} - \sigma^2}{P_0 h_{\mathrm{SR}} - \frac{P_{\mathrm{c}}}{\eta}} \\ & \text{Case 2}:\ h_{\mathrm{SR}} - \frac{h_{\mathrm{RD}}}{h_{\mathrm{SR}} - \frac{P_{\mathrm{c}}}{\eta P_0}} > h_{\mathrm{SD}} \\ & \quad \& \ h_{\mathrm{SD}} < \frac{\sqrt{\sigma^4 + 4\sigma^2 P_0 h_{\mathrm{RD}}} - \sigma^2}{2\left(P_0 h_{\mathrm{SR}} - \frac{P_{\mathrm{c}}}{\eta}\right)} \end{aligned}\right. .$$

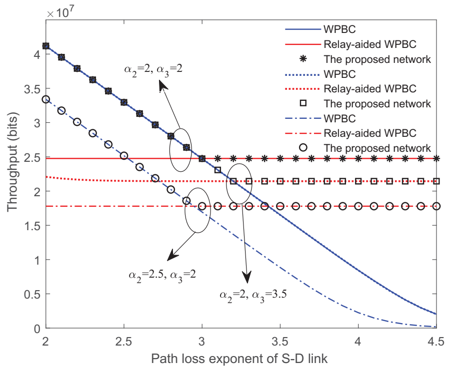

Fig. 3: Throughput versus path loss exponent of the S−D link.

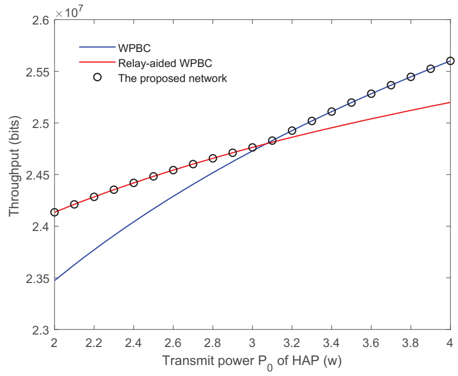

Fig. 4: Throughput versus the transmit power of HAP.

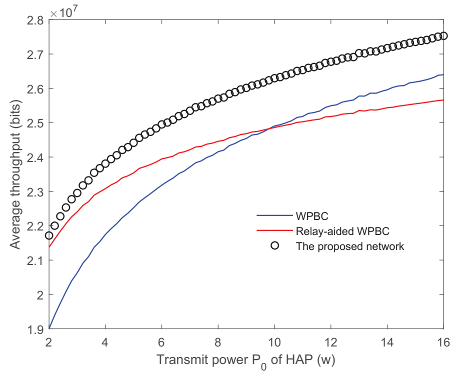

Fig. 5: Average throughput versus the transmit power of HAP.

Proof: Please see Appendix A. ■

Using Lemma 2, we propose a scheme to determine the mode selection of the HAP as summarized in Fig. 2.

IV. Simulations

In this Section, we compare the performance of the proposed network with WPBC and relay-aided WPBC. The channel gains are modeled as $h_{\rm SD} = \xi_{\rm SD} d_{\rm SD}^{-\alpha_1}$, $h_{\rm SR} = \xi_{\rm SR} d_{\rm SR}^{-\alpha_2}$ and $h_{\rm RD} = \xi_{\rm RD} d_{\rm RD}^{-\alpha_3}$, where ξ_i and d_i are the power gain of the small-scale fading and the distance for the i link $i \in \{\rm SD, SR, RD\}$, and α_1, α_2 and α_3 denote the path loss exponents of the S−D, S−R and R−D links, respectively. The basic simulation parameters are set as $T = 2$s, $W = 1000$kHz, $\sigma^2 = -174$dBm/Hz, $P_0 = 3$watt, $\eta = 0.3$, $P_c = 0.01$mW, $\alpha_2 = 2$ and $\alpha_3 = 2$. Besides, the coordinates of the IoT node, the receiver and the HAP are set as [0,0], [300,0] and [50,50], respectively.

Fig. 3 presents the relationship between the throughput and the path loss exponent of S−D link. In the proposed network, the optimal PRC and the optimal operation mode are adopted, while for WPBC and relay-aided WPBC, only the optimal PRC is used. If the HAP in the proposed network serves as the relay (PB) in the second half transmission block, our proposed network is reduced to the relay-aided WPBC (WPBC). In order to model various channel conditions for the proposed network, we assume that the power gain of the small-scale fading for all links is one and the path loss exponent of S−D link, i.e., α_1, varies from 2 to 4.5. One can see that our proposed network always achieves a higher throughput than the WPBC and the relay-aided WPBC, as the HAP can adjust its operation modes according to channel conditions. This validates the correctness of the derived result in Lemma 2. One can also see that with the increase of the path loss exponent of S−D link, the probability that the HAP functions as the relay increases. This observation can be explained as follows. When the channel condition of the direct link is very poor, the relay link will contribute more throughput than the the direct link, as expected in Lemma 2. As we can see from Lemma 2, decreasing $h_{\rm SD}$ increases the probability that the optimal x is 1. Besides, by comparing the curves obtained by different α_2 and α_3, we can observe that for maximizing the throughput, increasing α_2 or α_3 decreases the probability that the HAP functions as the relay.

Fig. 4 studies the impact of the transmit power of the HAP on the throughput, where the power gain of the small-scale fading is assumed to be one. As we can see from Fig. 3, the proposed network always yields the best performance and can be reduced to the WPBC and relay-aided WPBC based on channel conditions, which verifies the correctness of Lemma 2 again. In addition, we observe that to maximize the throughput, increasing the transmit power of the HAP will increase the probability that the HAP functions as the PB in the whole transmission block. This is because a large transmit power can boost the SNR of the direct link.

In Fig. 5, we compare the average throughput of our proposed network, WPBC and relay-aided WPBC under different transmit power of the HAP. One observation is that the average throughput of the proposed network is always higher than the other. This is because the proposed scheme can switch freely between the other two modes compared with the WPBC or relay-aided WPBC under random channel conditions.

V. Conclusions

In this article, we have proposed a wireless powered opportunistic cooperative backscatter communication network, and have studied the problem that under which conditions the HAP serves as the relay in the second half transmission block for maximizing the throughput of the IoT node. Specifically,

Table I

The value of $\gamma^{e'}$	Conditions
$\gamma'_{\rm SD}$	$\gamma'_{\rm SR} < \gamma'_{\rm SD} + \gamma_{\rm RD}$ and $\gamma'_{\rm SD} > \gamma'_{\rm SR}$
$\gamma'_{\rm SR}$	$\gamma'_{\rm SR} < \gamma'_{\rm SD} + \gamma_{\rm RD}$ and $\gamma'_{\rm SD} < \gamma'_{\rm SR}$
$\gamma'_{\rm SD} + \gamma_{\rm RD}$	$\gamma'_{\rm SR} > \gamma'_{\rm SD} + \gamma_{\rm RD}$

we have formulated a non-convex throughput maximization optimization problem by jointly optimizing the PRC of the IoT node and the operation mode of the HAP, and have derived the optimal PRC and the optimal operation mode of the HAP in the closed forms. Simulation results have validated the correctness of our derived results and have revealed the influence of the path loss exponent and the transmit power on the achievable throughput.

Appendix A

Due to the max and min functions included in $\gamma^{e'}$, we compare $R1'$ with $R2'$ from the following three cases, as shown in Table 1.

Case 1 with $\gamma^{e'} = \gamma'_{\rm SD}$: in this case, it is easy to know $R1' > R2'$, which means that for maximizing the throughput of the IoT node, the HAP should function as the PB in the whole transmission block. In what follow, we derive under what condition $\gamma^{e'} = \gamma'_{\rm SD}$ holds. According to Table I, if $\gamma^{e'} = \gamma'_{\rm SD}$, then $\gamma'_{\rm SR} < \gamma'_{\rm SD} + \gamma_{\rm RD}$ and $\gamma'_{\rm SD} > \gamma'_{\rm SR}$ should be satisfied. The first inequality can be rewritten as

$$\begin{aligned} &\gamma'_{\rm SR} < \gamma'_{\rm SD} + \gamma_{\rm RD} \\ &\Rightarrow \left(1 - \frac{P_{\rm c}}{\eta P_0 h_{\rm SR}}\right)(h_{\rm SR}^2 - h_{\rm SR}h_{\rm SD}) < h_{\rm RD} \\ &\Rightarrow h_{\rm SR} - \frac{h_{\rm RD}}{h_{\rm SR} - \frac{P_{\rm c}}{\eta P_0}} < h_{\rm SD}. \end{aligned} \tag{A.1}$$

The second inequality $\gamma'_{\rm SD} > \gamma'_{\rm SR}$ is equivalent to $\frac{\beta^* P_0 h_{\rm SR} h_{\rm SD}}{\sigma^2} > \frac{\beta^* P_0 h_{\rm SR}^2}{\sigma^2}$, indicating that $h_{\rm SR} - h_{\rm SD} < 0$ holds in this case.

Case 2 with $\gamma^{e'} = \gamma'_{\rm SR}$: in this case, $\gamma'_{\rm SR} < \gamma'_{\rm SD} + \gamma_{\rm RD}$ and $\gamma'_{\rm SD} < \gamma'_{\rm SR}$ need to be satisfied. Using a similar approach with Case 1, $h_{\rm SR} - \frac{h_{\rm RD}}{h_{\rm SR} - \frac{P_{\rm c}}{\eta P_0}} < h_{\rm SD}$ and $h_{\rm SR} - h_{\rm SD} > 0$ should be satisfied.

In what follows, we investigate under what condition $R1' > R2'$ holds, yielding

$$\begin{aligned} &R1' > R2' \\ &\Rightarrow \beta^* < \frac{\sigma^2 (h_{\rm SR} - 2h_{\rm SD})}{P_0 h_{\rm SD}^2 h_{\rm SR}} \\ &\Rightarrow 1 - \frac{P_{\rm c}}{\eta P_0 h_{\rm SR}} < \frac{\sigma^2 (h_{\rm SR} - 2h_{\rm SD})}{P_0 h_{\rm SD}^2 h_{\rm SR}} \\ &\Rightarrow \left(\frac{P_{\rm c}}{\eta} - P_0 h_{\rm SR}\right) h_{\rm SD}^2 - 2\sigma^2 h_{\rm SD} + \sigma^2 h_{\rm SR} > 0 \\ &\Rightarrow h_{\rm SD} < \frac{\sqrt{\sigma^4 + \sigma^2 h_{\rm SR}\left(h_{\rm SR}P_0 - \frac{P_{\rm c}}{\eta}\right)} - \sigma^2}{P_0 h_{\rm SR} - \frac{P_{\rm c}}{\eta}}. \end{aligned} \tag{A.2}$$

Using the facts that $\beta^* < \frac{\sigma^2(h_{\rm SR} - 2h_{\rm SD})}{P_0 h_{\rm SD}^2 h_{\rm SR}}$ holds for $R1' > R2'$ and that the PRC should be larger than zero, it is inferred that the denominator on the right side of the inequality should satisfy $h_{\rm SR} - 2h_{\rm SD} > 0$. We also note that if $h_{\rm SD} < \frac{\sqrt{\sigma^4 + \sigma^2 h_{\rm SR}\left(h_{\rm SR}P_0 - \frac{P_{\rm c}}{\eta}\right)} - \sigma^2}{P_0 h_{\rm SR} - \frac{P_{\rm c}}{\eta}}$, $h_{\rm SR} - 2h_{\rm SD} > 0$ is satisfied. Thus, we can confirm that for maximizing the throughput, the HAP should serve as the relay when $h_{\rm SR} - \frac{h_{\rm RD}}{h_{\rm SR} - \frac{P_{\rm c}}{\eta P_0}} < h_{\rm SD}$ and $h_{\rm SD} < \frac{\sqrt{\sigma^4 + \sigma^2 h_{\rm SR}\left(h_{\rm SR}P_0 - \frac{P_{\rm c}}{\eta}\right)} - \sigma^2}{P_0 h_{\rm SR} - \frac{P_{\rm c}}{\eta}}$.

Case 3 with $\gamma^{e'} = \gamma'_{\rm SD} + \gamma_{\rm RD}$: in this case, $\gamma'_{\rm SR} > \gamma'_{\rm SD} + \gamma_{\rm RD}$ needs to be satisfied. Similarly as above, we have $h_{\rm SR} - \frac{h_{\rm RD}}{h_{\rm SR} - \frac{P_{\rm c}}{\eta P_0}} > h_{\rm SD}$. Then we investigate under what condition $R1' > R2'$ holds, yielding

$$\begin{aligned} &R1' > R2' \\ &\Rightarrow 1 + \frac{\beta^* P_0 h_{\rm SR} h_{\rm SD}}{\sigma^2} + \frac{P_0 h_{\rm RD}}{\sigma^2} > \left(1 + \frac{\beta^* P_0 h_{\rm SR} h_{\rm SD}}{\sigma^2}\right)^2 \\ &\Rightarrow (\beta^*)^2 P_0 h_{\rm SR}^2 h_{\rm SD}^2 + \sigma^2 \beta^* h_{\rm SR} h_{\rm SD} - \sigma^2 h_{\rm RD} < 0 \\ &\Rightarrow h_{\rm SD} < \frac{\sqrt{\sigma^4 + 4\sigma^2 P_0 h_{\rm RD}} - \sigma^2}{2\beta^* P_0 h_{\rm SR}} \\ &\Rightarrow h_{\rm SD} < \frac{\sqrt{\sigma^4 + 4\sigma^2 P_0 h_{\rm RD}} - \sigma^2}{2\left(P_0 h_{\rm SR} - \frac{P_{\rm c}}{\eta}\right)}. \end{aligned} \tag{A.3}$$

Therefore, when $h_{\rm SR} - \frac{h_{\rm RD}}{h_{\rm SR} - \frac{P_{\rm c}}{\eta P_0}} > h_{\rm SD}$ and $h_{\rm SD} < \frac{\sqrt{\sigma^4 + 4\sigma^2 P_0 h_{\rm RD}} - \sigma^2}{2\left(P_0 h_{\rm SR} - \frac{P_{\rm c}}{\eta}\right)}$ are satisfied, the best choice of the HAP is to serve as the relay in the second half transmission block.

Based on the above discussion and some mathematical manipulations, Lemma 2 is proven.

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