

## Research Article

# Fairness-Aware Resource Allocation in Full-Duplex Backscatter-Assisted Wireless Powered Communication Networks

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In this paper, we introduce a full-duplex backscatter-assisted wireless powered communication network (FDBA-WPCN) with a full-duplex access point (FAP) and multiple energy harvesting wireless devices (WDs). The communication mode is a combination of backscatter communication (BC) and harvest-then-transmit (HTT). The entire time period of network is divided into energy harvesting/backscattering (EHB) period and information transmission (IT) period. In the EHB period, each WD either reflects information to the FAP by backscatter or harvests energy to prepare for the IT period. In the IT period, the WDs use their harvested energy to transmit information to FAP in time division multiple access (TDMA). However, under the setting, WDs with different distances from FAP will encounter unfairness in throughput due to the round-trip path loss in backscatter and the doubly near-far problem in HTT. To overcome the drawback, an optimization problem is considered to maximize the sum throughput under the condition of ensuring throughput fairness. By using convex optimization techniques, we obtain the optimal time allocation and the maximum same throughput of each WD. Comparing to the other two benchmark schemes, the simulation results prove the superiority of our proposed method.

## 1. Introduction

With the rapid evolution of the Internet of Things (IoT) and the proposal of green communication, energy harvesting (EH) technology for power-constrained wireless devices (WDs) has aroused great concerns in academia and industry. EH replaces traditional battery-powered or wired power supply methods and enables WDs to achieve contact-less and sustainable power supply. It can not only extend the life of the WDs but also reduce green gas emissions [1, 2]. Currently, traditional natural EH (such as solar EH and wind EH) cannot achieve stable power supply due to severe environmental constraints. In contrast, radio frequency energy harvesting (RF-EH) technology is more stable and controllable because it is less affected by the environment [3], which has attracted more attention from scholars.

RF-EH is the WD harvest energy from the radio frequency (RF) signal radiated by the energy source (ES). As the main technology of wireless energy transfer (WET), it is usually used in conjunction with wireless information trans-

mission (WIT). The most typical application is wireless powered communication networks (WPCNs). WPCNs were first studied in [4], where the author proposes a typical transmission protocol, named harvest-then-transmit (HTT). In the protocol, there are multiple WDs and a half-duplex (HD) hybrid access point (HAP) that gathers an ES and an information receiver (IR). The WDs first harvest energy from the RF signal broadcast by the HAP and then use the harvested energy to actively transmit information to the HAP in time division multiple access (TDMA). However, WDs may require a long time to harvest enough energy for WIT in this process, which can reduce the time for information transmission (IT). It will lead to a decrease in system throughput. In order to solve this problem, many experts have turned their attention to backscatter communication (BC) in recent years [5–7].

The backscatter communication system is different from the traditional wireless communication system. In this system, the backscatter transmitter does not actively generate the RF signal, but reflects the RF signal radiated by the RF

source to transmit its own information. Specifically, the BC transmitter transmits bit data by adjusting the matching degree between the antenna impedance and the load impedance. When the antenna impedance matches the load impedance, the antenna will be in absorbing state to collect the incident signal, which means that the BC transmitter indicates the information bit “0” to its corresponding receiver. Otherwise, the antenna will be in the reflection state to reflect the incident signal, which means the transmission information bit is “1.” The whole process is called load modulation. Here, WDs are equivalent to BC transmitter, and HAP is equivalent to RF signal source and receiver.

Since the BC transmitter itself does not process the signal, the energy consumption generated by it is very low, and passive communication can be achieved almost without harvesting energy. Therefore, the dedicated time for harvesting energy can be ignored. It is a promising method to improve the system performance by introducing backscatter into the traditional WPCN. However, if ES and IR are both placed on the same device, WDs at different distances will be affected to different degrees by the round-trip path loss of BC [8] and the doubly near-far problem of HTT. For example, the users, who are far away from HAP, will spend more time harvesting energy but have very little channel capacity. As a result, there is an unfair transmission rate between WDs. In summary, this paper will study the maximization of throughput in full-duplex (FD) backscatter-assisted WPCN (FDBA-WPCN) under the guarantee of fairness.

*1.1. Related Work.* According to [4], we learned that the classic WPCN has the problems of the unfair transmission rate and insufficient resource utilization. Therefore, some scholars have launched a series of studies on these two aspects. For example, [9] extended HAP from HD mode to FD mode on the basis of [4] and maximized system throughput through time and power allocation optimization. Further, [10] not only exploited FD HAP but also adopted relay-assisted communication to improve system performance. In addition, energy beamforming is designed to transmit energy by employing multiple antennas in [11]. However, users of the above schemes all need to harvest energy before transmitting data, which leads to the failure of urgent information transmission. To overcome this drawback, backscatter was introduced to assist HTT communication. A new cooperation mechanism on backscattering and HTT is introduced for wireless sensor networks in [12]. Each sensor allocates a portion of the energy harvesting time for backscattering, which significantly improves the time utilization rate and obtains higher throughput. Moreover, a mode selection strategy is proposed in [13], in which users can choose backscatter mode or HTT mode according to the actual situation and current channel state. Finally, the sum throughput of multiusers is maximized by the optimal model permutation and time allocation. Similarly, [14] studies the throughput maximization in the cases of infinite and finite battery capacity with two users, which can work in the backscatter mode and the HTT mode, respectively. There are also some literatures applying the fusion of backscatter and HTT to the cognitive radio environment [15, 16], but these studies

have not analyzed the unfairness between different users. To solve the doubly near-far problem in HTT, the remote energy-limited relay in the dual-hop WPCN is scheduled with more time to forward data [17]. Only using the HTT is not efficient; so, [18] studies fairness enhancement of a two-user WPCN in which part of the far user’s information is transmitted by HTT, and the other part is reflected to the nearby user by backscatter. But in this way, users who are relays need to consume part of their own energy and time for forwarding.

*1.2. Contribution.* Motivated by the advantages of the above research, this paper investigates an FDBA-WPCN with an FD access point (FAP) and multiple WDs, where each WD is equipped with HTT module and BC module. Due to the introduction of BC, this system is relatively suitable for low-power networks, such as tracking devices, medical telemetry, and low-cost sensor networks [19, 20]. In this network, when the FAP broadcasts RF signals to surrounding WDs, the WDs either reflect the data to the FAP by backscatter or harvest energy from the signal to prepare for subsequent WIT. FAP is equivalent to a FD HAP, which can save more deployment costs, comparing to separately distributed ES and IR. But in this case, WDs will suffer from the round-trip path loss in backscatter and the doubly near-far problem in HTT. The goal of this paper is to maximize the throughput of each WD under the guarantee of fairness. Unlike [17], the proposed scheme integrates the BC mode and the HTT mode, and the constructed optimization function is more complicated and difficult to solve. The main contributions of this paper are summarized as follows.

- (i) We first propose a new scheme that combines BC mode and HTT mode. In this scheme, each WD can allocate a portion of the original energy harvesting time in HTT to backscatter. By ingeniously integrating backscatter into the HTT mode, the energy harvesting period in HTT is modified as the energy harvesting/backscatter (EHB) period. In this period, WDs perform backscattering in a time division multiple access (TDMA) manner. When one of the WD backscatters, the other WDs harvest energy. And then the WDs use the harvested energy to transmit information in TDMA. Under the setting, the time can be utilized more efficiently, and thus the system throughput will be increased. In addition, the combination of BC mode and HTT mode will drive to more complex WDs. There are two independent circuit modules inside all WDs, namely, the BC module and the HTT module. Each WD can adaptively allocate time to call a certain module in real time according to its own channel state information (CSI).
- (ii) In the above scheme, we propose an optimal problem of maximizing throughput and ensuring fairness simultaneously. As far as we know, there is no work to study fairness enhancement in our proposed multi-WD case. By applying convex optimization techniques, we can get each WD’s optimal time

allocations of backscattering, harvesting energy and information transmission to maximize the same throughput that the WDs can achieve

- (iii) Through simulation results, we compare system performance between the proposed scheme and the benchmark schemes. The results show that the throughput maximization scheme of backscatter-assisted transmission produces serious throughput unfairness, while the fairness enhancement scheme that only uses HTT makes the average throughput very small. In comparison, the proposed scheme can provide better performance, which can guarantee high fairness and improve average throughput

## 2. System Model

**2.1. Model Framework.** As shown in Figure 1, we envision a FDDBA-WPCN, which is composed of one two-antenna FAP and  $K$  single-antenna WDs denoted by  $WD_i$ ,  $i = 1, 2, \dots, K$ . FAP works in FD mode with perfect successive interference cancellation (SIC) technology, in which one antenna is used to transmit RF signals, while the other antenna is used to receive signals from WDs. In this network, it is assumed that FAP has a fixed energy supply, and WDs have no embedded energy supply. Therefore, all WDs need to harvest energy from the signals broadcast by FAP and then transmit information to the FAP using the obtained energy. Moreover, such signals can also be used for backscatter communication by adjusting WDs' antenna load impedance. Thus, when the FAP broadcasts signals to the surroundings, the WDs could either harvest energy or reflect information to the FAP by backscatter. We define the channel power gain from FAP to  $WD_i$  as  $H_i$ ,  $i = 1, 2, \dots, K$ , and the channel power gain from  $WD_i$  to FAP as  $G_i$ ,  $i = 1, 2, \dots, K$ . In this model,  $H_i$  and  $G_i$  are considered to be quasistatic flat fading, which stays the same in a time slot, but changes in different time slots. It is further assumed that  $H_i$  and  $G_i$  are completely known at FAP. In practice, error on these two parameters will exist, with imperfect channel gain knowledge. However, there are already mature mechanisms for estimating and eliminating the error of these two parameters, for example, the finite-length minimum mean-square error decision-feedback equalizer (MMSE-DFE) and MMSE Tomlinson-Harashima (MMSE-TH) precoder. In addition, many existing related research literature also assume that  $H_i$  and  $G_i$  are completely known, such as literature [4, 9]. Therefore, we assume that these two parameters are known.

The time design of the FDDBA-WPCN system is illuminated in Figure 2, which is mainly divided into two periods. One period is the energy harvesting/backscatter (EHB) period, and the other is the information transmission (IT) period. For convenience, the assumption for the entire time frame is 1. For the EHB period which is defined as  $t_0$ , the period is divided into multiple subslots, the number of which corresponds to the number of WDs, denoted as  $\beta_i$ ,  $i = 1, 2, \dots, K$ .  $\beta_i$  is utilized for backscatter of  $WD_i$ , and the remaining part denoted as  $t_0 - \beta_i$  is used for energy harvesting. Then, in the IT period, the WDs transmit data to the FAP in TDMA using

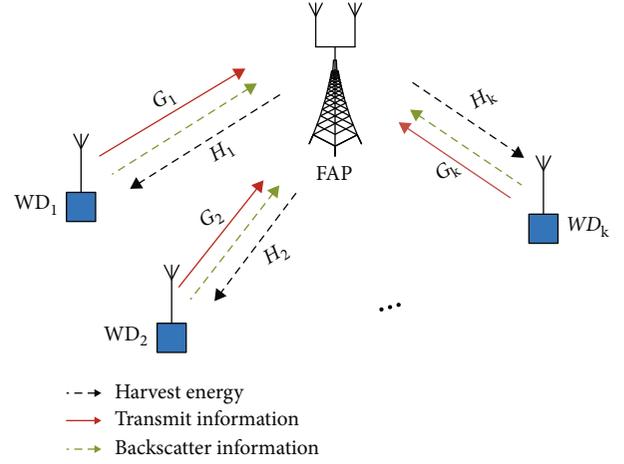


FIGURE 1: Multi-WD full-duplex backscatter-assisted wireless powered communication networks (FDDBA-WPCN).

the previously harvested energy, denoted as  $\alpha_i$ ,  $i = 1, 2, \dots, K$ . Finally, the time constraints are obtained:  $t_0 + \sum_{i=1}^K \alpha_i \leq 1$ ,  $\sum_{i=1}^K \beta_i = t_0$ .

**2.2. Problem Formulation.** In the EHB period, it is assumed that the unmodulated baseband signal broadcast by FAP is defined as  $c(t)$ , where  $c(t)$  is a circularly symmetric complex Gaussian (CSCG) random signal with  $|c(t)|^2 = P_T$ .  $P_T$  represents the transmit power of FAP. Then, the backscattered emission wave of  $WD_i$  obtained by load modulation is given by

$$x(t) = \sqrt{sH_i}c(t), \quad (1)$$

where  $s \in (0, 1)$  denotes the backscatter coefficient of  $WD_i$ . Furthermore, the processed received signal at FAP is expressed as

$$y(t) = \sqrt{sH_iG_i}c(t) + N(t), \quad (2)$$

where  $N(t)$  represents the additive Gaussian white noise (AGWN) that follows the zero-mean CSCG distribution  $\mathcal{C}(0, \sigma^2)$  at the receiving antenna of the FAP, and noise power is  $\sigma^2$ . Therefore, the throughput of  $WD_i$  by backscattering is obtained as

$$R_i^B = \beta_i \log \left( 1 + \frac{sH_iG_iP_T}{\sigma^2} \right), \quad i = 1, 2, \dots, K. \quad (3)$$

Moreover, note that WDs can also harvest energy from the signal broadcast by FAP during  $(t_0 - \beta_i)$ ; so, the harvested energy by  $WD_i$  can be shown as

$$E_{H,i} = \varepsilon_k P_T H_i (t_0 - \beta_i), \quad i = 1, 2, \dots, K, \quad (4)$$

where  $\varepsilon_i \in (0, 1)$  is the harvesting efficiency of energy, and assume that all obtained energy is exhausted during  $\alpha_i$  of the IT period to avoid energy waste. Hence, the average transmit power of  $WD_i$  is imposed by

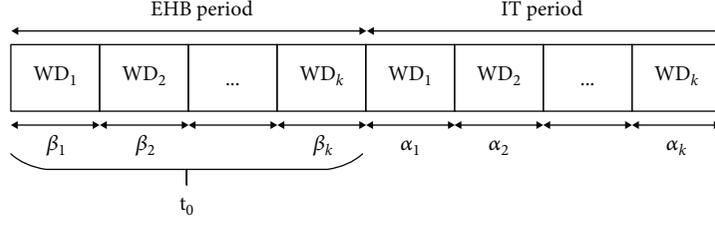


FIGURE 2: Time design of the FDMA-WPCN system.

$$P_i^{\text{WD}} = \frac{E_i^H}{\alpha_i} = \frac{\varepsilon_i P_T H_i (t_0 - \beta_i)}{\alpha_i}, i = 1, 2, \dots, K. \quad (5)$$

The throughput of  $\text{WD}_i$  in the IT period is as follows:

$$R_i^H = \alpha_i \log \left( 1 + \frac{\varepsilon_i P_T H_i G_i t_0 - \beta_i}{\sigma^2 \alpha_i} \right), i = 1, 2, \dots, K. \quad (6)$$

To sum up, the total throughput of each WD is given by

$$R_i^T = R_i^B + R_i^H = \beta_i B_i + \alpha_i \log \left( 1 + \gamma_i \frac{t_0 - \beta_i}{\alpha_i} \right), i = 1, 2, \dots, K, \quad (7)$$

where  $B_i = \log(1 + (\text{s}H_i G_i P_T / \sigma^2))$  and  $\gamma_i = \varepsilon_i P_T H_i G_i / \sigma^2$ .

In the paper, we aim to solve the unfairness between WDs caused by round-trip path loss and the doubly near-far problem. Thus, a minimum throughput maximization problem was proposed to enhance the fairness of the system. The formula is as follows:

$$\begin{aligned} \text{(P1):} \quad & \max_{t_0, \{\alpha_i\}, \{\beta_i\}} \min (R_1^T, R_2^T, \dots, R_K^T), \\ \text{s.t.} \quad & t_0 + \sum_{i=1}^K \alpha_i \leq 1, \\ & \sum_{i=1}^K \beta_i = t_0, \\ & 0 \leq t_0 \leq 1, \\ & 0 \leq \beta_i \leq t_0, \\ & 0 \leq \alpha_i \leq 1 - t_0, i = 1, 2, \dots, K. \end{aligned} \quad (8)$$

### 3. Optimal Solution of Proposed Problem

It can be observed that the above minimum throughput maximization problem is a nonconvex optimization problem. In this section, we first convert the problem to a convex optimization problem by introducing an extra variable  $Q$  and then use Karush-Kuhn-Tucker (KKT) conditions and construct Lagrange duality function to find the optimal time schedule, which ensures the equal throughput to all WDs and then maximizes the sum throughput.

**3.1. Nonconvex Optimization Conversion.** Since P1 is a nonconvex problem that is difficult to solve, it is transformed into the equivalent problem P2 as follows:

$$\text{(P2):} \quad \max_{t_0, \{\alpha_i\}, \{\beta_i\}, Q} Q, \quad (9)$$

$$\text{s.t.} \quad Q - \left( \beta_i B_i + \alpha_i \log \left( 1 + \gamma_i \frac{t_0 - \beta_i}{\alpha_i} \right) \right) \leq 0, \forall i, \quad (10)$$

$$t_0 + \sum_{i=1}^K \alpha_i \leq 1, \quad (11)$$

$$\sum_{i=1}^K \beta_i = t_0, \quad (12)$$

$$0 \leq t_0 \leq 1, \quad (13)$$

$$0 \leq \beta_i \leq t_0, \quad (14)$$

$$0 \leq \alpha_i \leq 1 - t_0, i = 1, 2, \dots, K, \quad (14)$$

with an extra variable  $Q \in R$  ( $R$  means real number set) and a set of new inequalities that the throughput of every WD is not less than  $Q$  as constraints.

**Proposition 1.** *P2 is a convex optimization problem.*

*Proof.* In P2, the objective function is a linear function, and the constraints from (11)-(14) are all affine. If these  $K$  new inequality constraints are convex in  $(t_0, \{\alpha_i\}, \{\beta_i\}, Q)$ , it can be concluded that P2 is a convex optimization problem.

Carefully, it is found that each new constraint function consists of linear function  $(Q - \beta_i B_i)$  and  $\alpha_i \log(1 + \gamma_i(t_0 - \beta_i/\alpha_i))$  which is the perspective function of  $\log(1 + \gamma_i(t_0 - \beta_i))$ . Since the perspective operation retains the concavity, if  $\log(1 + \gamma_i(t_0 - \beta_i))$  is shown to be a concave function, the concavity of  $\alpha_i \log(1 + \gamma_i(t_0 - \beta_i/\alpha_i))$  can be proved so that  $(-\alpha_i \log(1 + \gamma_i(t_0 - \beta_i/\alpha_i)))$  is convex. Then, the constraints (10) are proved to be convex because each of them is a nonnegative weighted sum of convex functions. In other words, as long as  $\log(1 + \gamma_i(t_0 - \beta_i))$  is shown as a concave function, the proposition can be proved.

Thus, we need to prove that  $\log(1 + \gamma_i(t_0 - \beta_i))$  is a concave function with respect to  $(t_0, \beta_i)$  next. Firstly, let

$$\Gamma(t_0, \beta_i) = \log(1 + \gamma_i(t_0 - \beta_i)), \quad (15)$$

and drive the Hessian of  $\Gamma(t_0, \beta_i)$  as

$$H_s^i = \begin{bmatrix} \frac{\partial \Gamma}{\partial t_0^2} & \frac{\partial \Gamma}{\partial t_0 \partial \beta_i} \\ \frac{\partial \Gamma}{\partial \beta_i \partial t_0} & \frac{\partial \Gamma}{\partial \beta_i^2} \end{bmatrix} = \begin{bmatrix} -\frac{\gamma_i^2}{(1 + \gamma_i(t_0 - \beta_i))^2} & \frac{\gamma_i^2}{(1 + \gamma_i(t_0 - \beta_i))^2} \\ \frac{\gamma_i^2}{(1 + \gamma_i(t_0 - \beta_i))^2} & -\frac{\gamma_i^2}{(1 + \gamma_i(t_0 - \beta_i))^2} \end{bmatrix}. \quad (16)$$

Given an arbitrary nonzero real column vector  $\mathbf{X} = [x_1, x_2]^T$ , we have

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Initialize  $t_0 = 0, Q^{opt} = 0$ .
while  $t_0 \in [0, 1]$  do
  Initialize  $\lambda \geq 0, \mu \geq 0, \nu$ .
  repeat
    Initialize  $\beta$ .
    repeat
      Update  $\alpha$  using (24),
      Update  $\beta$  using (23),
    until  $\alpha, \beta$  all converge.
    Update  $\lambda, \mu, \nu$  using (26), (27) and (28), respectively.
  until  $\lambda, \mu, \nu$  all converge.
  Compute  $g_{\min} = g(\lambda, \mu, \nu)$  according to (21) and (22) and let  $Q = g_{\min}$ .
  if  $Q > Q^{opt}$  then
     $t_0^{opt} \leftarrow t_0, \alpha^{opt} \leftarrow \alpha, \beta^{opt} \leftarrow \beta, Q^{opt} \leftarrow Q$ .
  else
     $t_0 \leftarrow t_0 + \Delta$ .
  end if
end while
 $t_0^* = t_0^{opt}, \alpha^* = \alpha^{opt}, \beta^* = \beta^{opt}, Q^* = Q^{opt}$ .

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ALGORITHM 1: Algorithm to solve problem P2.

$$X^T H_s^i X = -\frac{\gamma_i^2 (x_1 - x_2)^2}{(1 + \gamma_i (t_0 - \beta_i))^2} \leq 0. \quad (17)$$

Therefore,  $H_s^i$  is a seminegative definite matrix, and  $\Gamma(t_0, \beta_i)$  is a concave function in  $(t_0, \beta_i)$ . So far, it can be confirmed that (P2) is indeed a convex optimization problem.

*Remark 2.* P2 is designed to gradually solve the unfairness in throughput of WDs caused by difference channel conditions. Assuming that the EHB period  $t_0$  is fixed, according to the time allocation strategy of this period, it can be known that the more time the  $WD_i$  uses to harvest energy (the more throughput of HTT), the less time the backscattering (the less throughput of backscatter) will consume, and vice versa. So when the throughput of different WDs is not equal, we can balance HTT mode and backscatter mode of WDs by continuously adjusting energy harvesting, backscatter, and information transmission time  $(t_0, \beta, \alpha)$ . Ultimately, the optimal time allocation  $(t_0^*, \beta^*, \alpha^*)$  will allocate the optimal same throughput to all WDs, i.e.,  $R_1^{T*} = R_2^{T*} = \dots = R_K^{T*} = Q^*$ .

**3.2. Optimal Solution.** In order to facilitate the solution, it is assumed that the value of  $t_0$  is given. Then, P2 becomes a problem with unknown variables  $(\alpha, \beta, Q)$ ,  $\alpha = [\alpha_1, \alpha_2, \dots, \alpha_K]$ ,  $\beta = [\beta_1, \beta_2, \dots, \beta_K]$ . According to [21], the Lagrange duality method can be used to efficiently get the optimal solution of P2. The Lagrangian function of P2 can be expressed as

$$L(\alpha, \beta, Q, \lambda, \mu, \nu) = Q - \sum_{i=1}^K \lambda_i \left( Q - \left( \beta_i B_i + \alpha_i \log \left( 1 + \gamma_i \frac{t_0 - \beta_i}{\alpha_i} \right) \right) \right) - \mu \left( t_0 + \sum_{i=1}^K \alpha_i - 1 \right) + \nu \left( \sum_{i=1}^K \beta_i - t_0 \right), \quad (18)$$

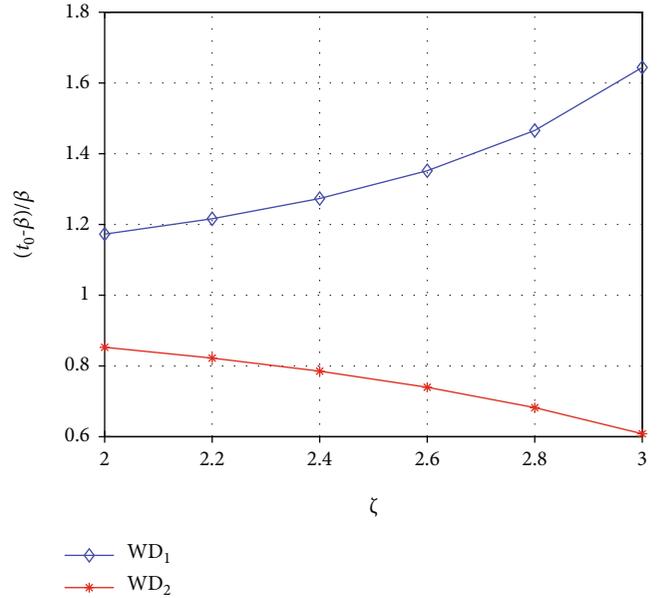


FIGURE 3: Energy harvesting and backscatter time allocation ratio of two WDs.

where  $\lambda = \{\lambda_i\}_{i=1}^K$ ,  $\lambda_i$ , is the Lagrange multiplier associated with the  $i_{th}$  inequality constraint of (10),  $\mu$  and  $\nu$  are the Lagrange multipliers associated with the inequality constraint (11) and the equality constraint (12), respectively. Then, the dual function of P2 is formulated as

$$g(\lambda, \mu, \nu) = \begin{pmatrix} \max_{\alpha, \beta, Q} L(\alpha, \beta, Q, \lambda, \mu, \nu) \\ s.t. (13) \end{pmatrix}. \quad (19)$$

Here, the dual function yields higher bounds on the

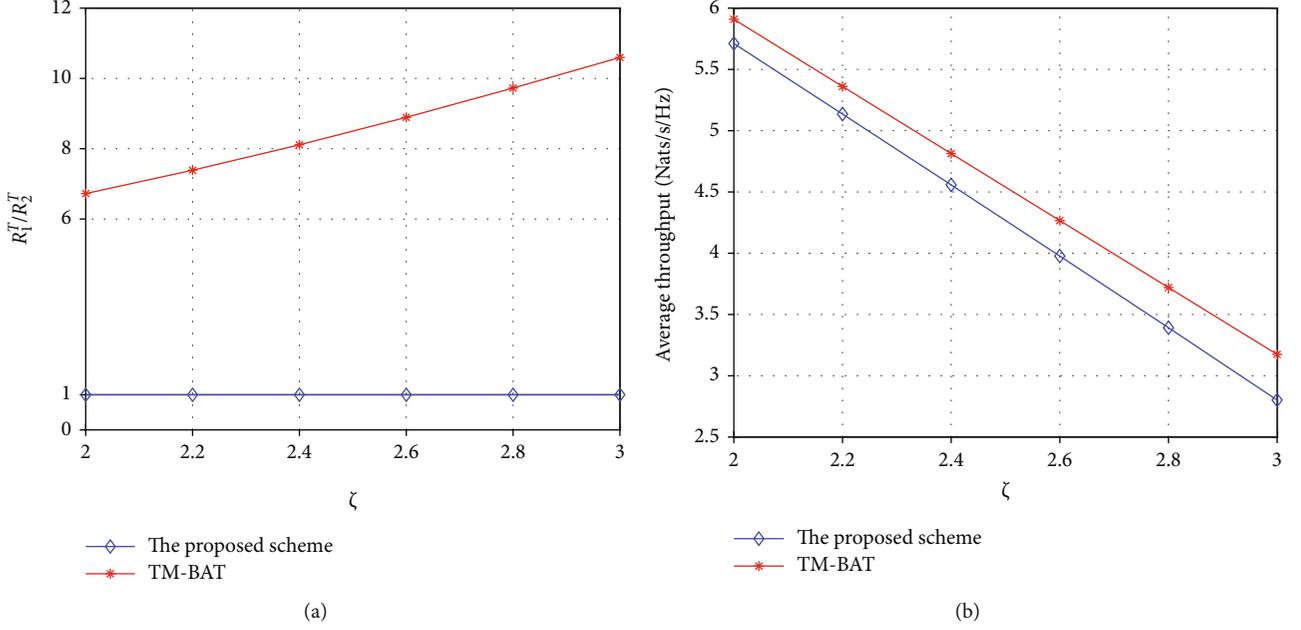


FIGURE 4: Comparison between the TM-BAT and the proposed scheme of two WDs.

optimal value  $Q^*$  of the problem P2, and there is the following proposition.

**Theorem 3.** P2 is infeasible if and only if there exists any  $\lambda \geq 0$  ( $\geq$  indicates that all values in the vector satisfy the inequality), any  $\mu \geq 0$ , and any  $v$  such that

$$g(\lambda, \mu, v) \geq Q^*. \quad (20)$$

For simplicity, please refer to Appendix A for specific proofs.

This shows that  $g(\lambda, \mu, v)$  has a lower boundary. Then, (19) is further derived as

$$g(\lambda, \mu, v) = \begin{cases} \max_{\alpha, \beta} L(\alpha, \beta, \lambda, \mu, v) & 1 - \sum_{i=1}^K \lambda_i = 0 \\ +\infty & \text{otherwise} \\ \text{s.t.} & (13) \end{cases}. \quad (21)$$

Because there is a boundary for the linear function  $((1 - \sum_{i=1}^K \lambda_i)Q)$  of (18), only when the coefficient of this term is 0. Otherwise, there must be  $Q$ , so that  $g(\lambda, \mu, v) = +\infty$ . Therefore, the variable  $Q$  is eliminated and  $0 \leq \lambda \leq 1$ . Finally, the dual problem of P2 is expressed by

$$\min_{0 \leq \lambda \leq 1, \mu \geq 0, v} g(\lambda, \mu, v). \quad (22)$$

It is easy to see from (10) and (11) that there exists  $(\beta, \alpha, t_0)$ , making P2's series of inequality constraints strictly held. Thus, the strong duality holds for this problem according to the Slater condition [21]. This demonstrates that the minimum of the dual problem is equivalent to the maximum of

the primal problem, i.e.,  $g_{\min} = Q^*$ . So, we can solve the primal problem by gaining the minimum of the dual problem.

**Corollary 4.** For given  $t_0$  and the multipliers, the optimal backscattering and information transmission time of P2 from (18) to (21) are obtained as

$$\beta_i^* = \min \left\{ \max \left\{ t_0 - \alpha_i^* \left( \frac{\lambda_i}{B_i \lambda_i + v} - \frac{1}{\gamma_i} \right), 0 \right\}, t_0 \right\}, \forall i, \quad (23)$$

$$\alpha_i^* = \min \left\{ \gamma_i \frac{t_0 - \beta_i^*}{q_i^* - 1}, 1 - t_0 \right\}, \forall i, \quad (24)$$

where  $q_i^*$ ,  $i = 1, 2, \dots, K$  is the solution of

$$\log(q_i) + \frac{1}{q_i} - 1 = \frac{\mu}{\lambda_i}. \quad (25)$$

*Proof.* Please refer to Appendix B.

With Corollary 4, we can easily compute  $\beta^*$  and  $\alpha^*$  as follows. Set an initial value for  $\beta_i$  and then bring into equation (23) to calculate  $\alpha_i$  and then calculate  $\beta_i$  from  $\alpha_i$  according to (22), so iterate until convergence is achieved. With the found  $\beta^*$  and  $\alpha^*$ ,  $\lambda$ ,  $\mu$ , and  $v$  can be updated by using subgradient based algorithms, given by

$$\lambda_i^{n+1} = \min \left\{ \max \left\{ 0, \lambda_i^n - \rho_{\lambda_i}^n \psi_{\lambda_i}^n \right\}, 1 \right\}, \quad (26)$$

$$\mu^{n+1} = \max \left\{ 0, \mu^n - \rho_{\mu}^n \psi_{\mu}^n \right\}, \quad (27)$$

$$v^{n+1} = v^n - \rho_v^n \psi_v^n, \quad (28)$$

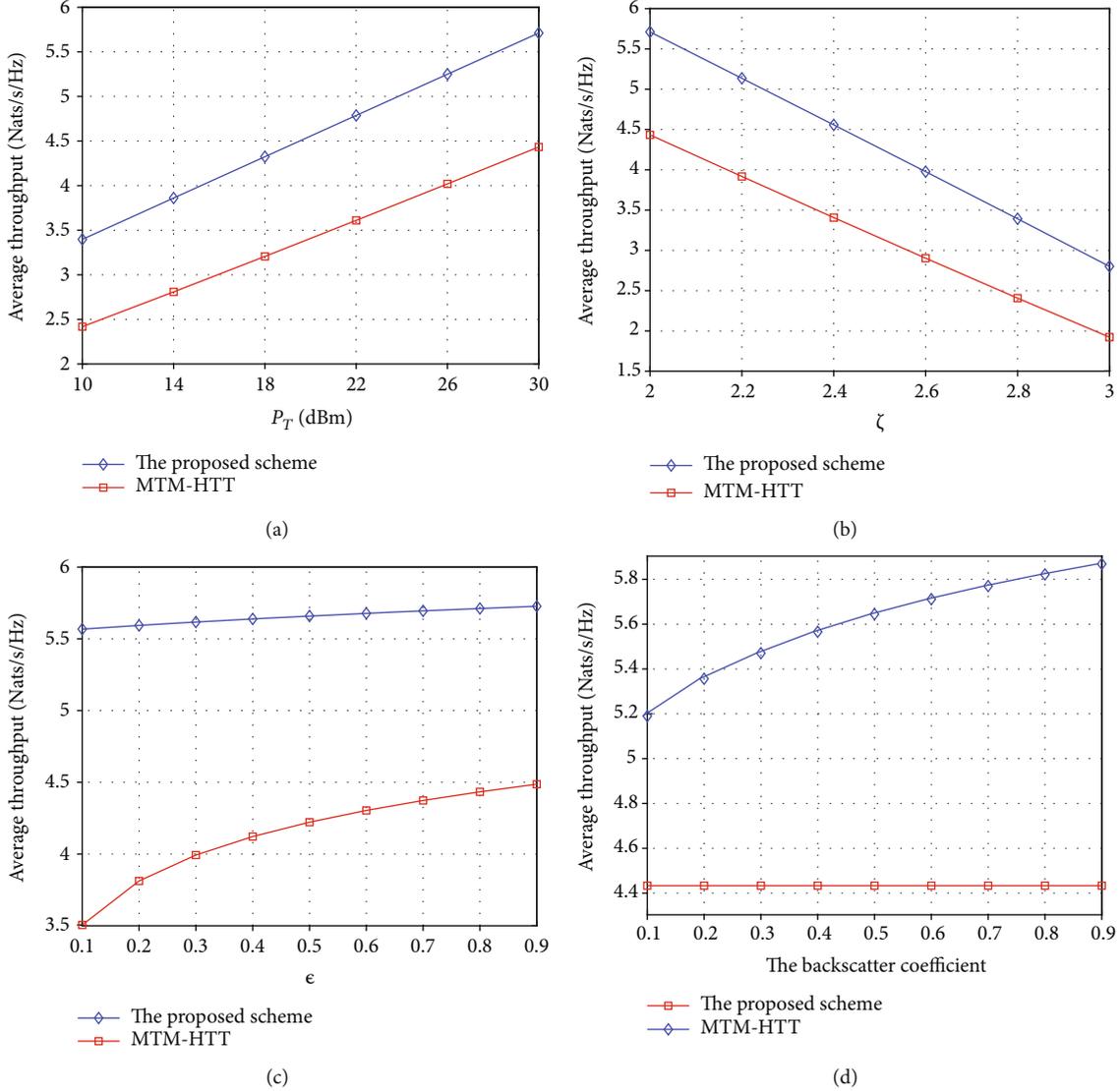


FIGURE 5: The average throughput comparisons of the MTM-HTT and the proposed scheme with respect to different parameters.

where  $\psi_{\lambda_i}^n = \beta_i^* B_i + \alpha_i^* \log(1 + \gamma_i(t_0 - \beta_i^*/\alpha_i^*))$ ,  $\psi_{\mu}^n = 1 - t_0 - \sum_{i=1}^K \alpha_i^*$ , and  $\psi_v^n = \sum_{i=1}^K \beta_i^* - t_0$  are the subgradients of  $g(\lambda, \mu, v)$ .  $\rho_{\lambda_i}^n$ ,  $\rho_{\mu}^n$ , and  $\rho_v^n$  are the step sizes for updating  $\lambda_i$ ,  $\mu$ , and  $v$  at  $n_{th}$  iteration, respectively, until  $\lambda$ ,  $\mu$ , and  $v$  converge to  $\lambda^*$ ,  $\mu^*$ , and  $v^*$ , respectively, and the minimum of problem (22)  $g_{\min}$  is obtained. And then the optimal solution of the primal problem is found. To summarize, an algorithm for solving problem P2 is given in Algorithm 1.

#### 4. Numerical Results

In this section, numerical results are presented to evaluate the superiority of the proposed scheme for FDBA-WPCN. The simulation environment is as follows unless otherwise specified. The transmission power of FAP is set as  $P_T = 30 \text{ dBm}$  without loss of generality. The channel power gains for the uplink and downlink are modeled as  $G_i = d_i^{-\zeta_1}$  and  $H_i =$

$d_i^{-\zeta_2}$ , where  $d_i$  represents the distance between FAP and  $W D_i$ , and  $\zeta_1$  and  $\zeta_2$  are the path-loss exponents that are set as  $\zeta_1 = \zeta_2 = \zeta = 2$ . The distance between FAP and  $W D_i$  is assumed as  $(10 + (10/K) \times i)m$ , which shows that the distances of different branches are different. Furthermore,  $\epsilon_i = 0.8$ ,  $s = 0.6$ , and the noise power spectral density at the FAP is assumed to be  $-70 \text{ dBm/Hz}$ . The throughput maximization of backscatter assisted transmission (TM-BAT) and the minimum throughput maximization of harvest-then-transmit (MTM-HTT) are served as benchmark schemes. There are two benchmark schemes in this paper. Among them, TM-BAT represents a scheme that has both backscatter and HTT functions but does not consider fairness. MTM-HTT represents a scheme that considers fairness but only has the HTT mode.

We first consider the case that the number of WDs is  $K = 2$ . Figure 3 plots the energy harvesting and backscatter time allocation ratio  $((t_0 - \beta)/\beta)$  of each WD versus  $\zeta$ . It

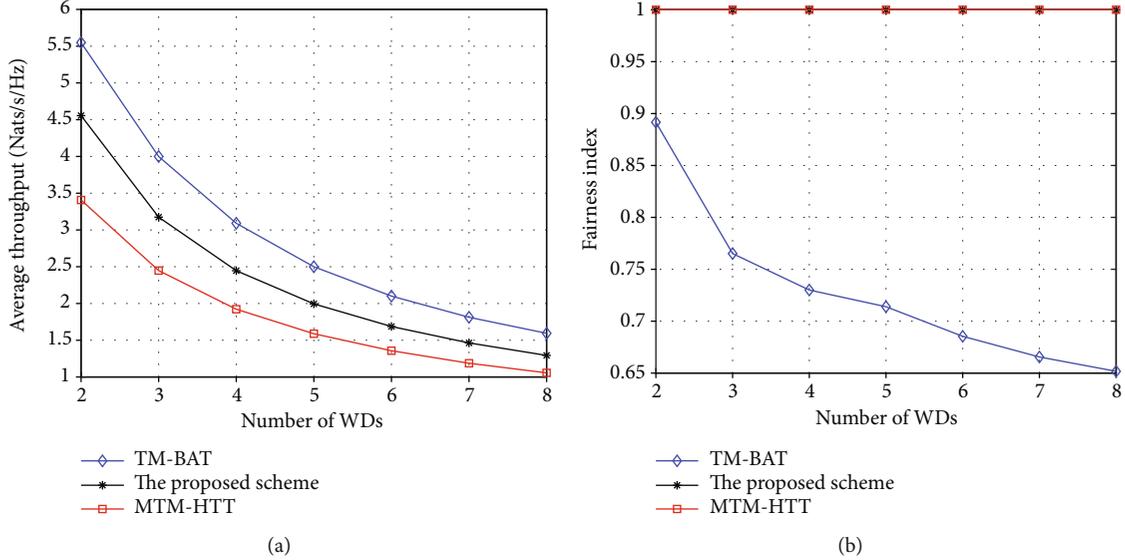


FIGURE 6: Average throughput and fairness index versus the number of WDs.

can be seen that  $(t_0 - \beta)/\beta$  of  $WD_1$  increases, and  $(t_0 - \beta)/\beta$  of  $WD_2$  decreases with  $\zeta$  increasing. In addition, the time ratio of  $WD_1$  is always greater than 1, and the time ratio of  $WD_2$  is always less than 1. The specific reasons are as follows. As  $\zeta$  increases, the channel gap between  $WD_2$  and  $WD_1$  will become larger because the longer distance between  $WD_2$  and FAP causes the channel of  $WD_2$  to degrade faster. Hence,  $WD_1$  spends more time harvesting energy for later information transmission. Because  $WD_1$  is close to FAP, it is more conducive to energy harvesting.  $WD_2$  takes more time for backscattering, because backscatter is more beneficial to obtain more throughput for  $WD_2$ . And as the channel gap increases,  $WD_1$  takes more and more time to harvest energy, while  $WD_2$  takes more and more time to backscatter. To summarize, the advantages of backscattering and HTT are taken to enhance fairness and maximize the throughput of each WD.

Figure 4 aims to display the performance of TM-BAT and the proposed scheme as  $\zeta$  increases. Figure 4(a) depicts throughput unfairness in the TM-BAT and throughput fairness in the proposed scheme. As  $\zeta$  increases, the throughput ratio of  $WD_1$  and  $WD_2$  in the TM-BAT increases, but the ratio in the proposed scheme is always 1. This demonstrates that in the TM-BAT, more resources are allocated to the WD with good channel conditions ( $WD_1$ ) due to the fact that  $WD_2$  suffers from the round-trip path loss [14] and the doubly near-far problem. However, the proposed scheme can always maintain the same throughput of each WD through the reasonable time allocation in Figure 3. Both TM-BAT and the proposed scheme combine the HTT mode and the backscatter mode, but these two schemes have different goals. TM-BAT only seeks to maximize the total throughput, which causes large unfairness in throughput among WDs. And this unfair phenomenon becomes more serious as  $\zeta$  increases. The proposed scheme tends to maintain a high level of fairness by sacrificing some throughput. But from Figure 4(b), the average throughput of the proposed scheme is only

slightly lower than that of TM-BAT. So by comparing with the MT-BAT, these two graphs show the performance advantage of the proposed scheme.

Next, Figure 5 compares the average throughput of the MTM-HTT and the proposed scheme with respect to (a) the transmission power, (b) the path-loss exponent, (c) energy harvesting efficiency, and (d) the backscatter coefficient, respectively. Both the MTM-HTT and the proposed scheme maintain the same throughput for every WD. Figure 5(a) and 5(d) illuminate that as  $P_T$  and the backscatter coefficient increase, the average throughput difference between the proposed scheme and the MTM-HTT is gradually increasing, which is gradually reduced in Figures 5(c) and 5(d). The reason for the increase is that  $P_T$  affects both backscattering and HTT, and the backscattering coefficient only affects backscattering, so the throughput of the proposed scheme grows faster. The reason for the decrease is that the increase of  $\epsilon$  is more conducive in harvesting energy, and the increase of  $\zeta$  will make the proposed scheme decline faster due to the round-trip path loss in backscatter and the doubly near-far problem in HTT. However, it can be observed from Figure 5 that the proposed scheme can always provide higher throughput for each WD in different parameters. Therefore, the proposed scheme can achieve better performance than the MTM-HTT scheme in throughput.

Finally, we promote the two-WD scenario to a multi-WD scenario by changing the number of WDs from 2 to 8. Other parameter settings are the same as before. Figure 6(a) investigates that as the number of WDs increases, the average throughput allocated to each user decreases in the three schemes. It can be seen that the proposed scheme outperforms MTM-HTT and worsens to TM-BAT in throughput. Figure 6(b) studies fairness index of different schemes versus the number of WDs. The formula for the fairness index is set as  $F = (\sum_{i=1}^K R_i)^2 / K \sum_{i=1}^K R_i^2$  [18], where  $R_i$  is the throughput of the  $i_{th}$  WD. As can be seen from the figure, MTM-HTT and

the proposed scheme have equal fairness index and higher than that of TM-BAT. In addition, as the number of WDs increases, the fairness index of TM-BAT becomes smaller and smaller. This shows that the bigger the number of users is, the more unfair the resource allocation of TM-BAT will be. Combining the two figures, it can be seen that the proposed solution not only solves the unfairness problem in TM-BAT but can also provide higher throughput than MTM-HTT under the condition of equal fairness level. In general, the proposed scheme can achieve better performance under the condition of fair transmission. We can see from Figure 6(a) of 8 WDs that the gap between the average throughput of the proposed solution and the benchmark schemes is getting smaller and smaller, as the number of wireless devices increases. When the number of wireless devices is large enough, the throughput of these three schemes will be equal. However, it can be seen from Figure 6(b) that as the number of wireless devices increases, the fairness of the TM-BAT scheme will become worse and worse. Therefore, the proposed scheme can be applied to multiuser scenarios. For the convenience of presentation, only 8 WDs are selected in this paper.

## 5. Conclusion

This study considered fairness enhancement and throughput improvement in multi-WD FD WPCN assisted by backscatter. When the FAP emits a radio frequency signal, the WD either reflects the data to the FAP by backscatter or harvests energy to prepare for information transmission, which greatly improves time utilization. However, WD farther away from FAP will encounter the round-trip path loss of backscattering and the doubly near-far problem of HTT. This paper proposes the minimum throughput maximization problem, so that WDs at different distances have equal throughput. In order to solve this problem, the algorithm in the paper is used to reasonably arrange the time of backscattering, energy harvesting, and information transmission and make the throughput of each WD as high as possible. By comparing with TM-BAT, it is highlighted that the proposed scheme can guarantee good fairness when the throughput is not much different from that of TM-BAT. By comparing with MTM-HTT, it is highlighted that the proposed scheme can provide higher common throughput. Finally, the simulation numerical results reveal that the proposed scheme can not only ensure high fairness, but can also achieve high throughput compared to the two benchmark schemes.

## Appendix

### A. Proof of Theorem 1

Firstly we prove the sufficiency of proposition 1, that is, if P2 is feasible, then for any  $\lambda \geq 0$ , any  $\mu \geq 0$ , and any  $v$ , we have  $g(\lambda, \mu, v) \geq Q^*$ . Suppose  $(\beta, \alpha, t_0)$  is a feasible point for the problem P2, i.e., which is satisfying the conditions (18) and

(19). Then, for any  $\lambda \geq 0$ , any  $\mu \geq 0$ , and any  $v$ , we have

$$g(\lambda, \mu, v) = \max_{\alpha, \beta, Q} L(\alpha, \beta, Q, \lambda, \mu, v) \geq Q^* - \sum_{i=1}^K \lambda_i \cdot \left( Q - \left( \beta_i B_i + \alpha_i \log \left( 1 + \gamma_i \frac{t_0 - \beta_i}{\alpha_i} \right) \right) \right) - \mu \left( t_0 + \sum_{i=1}^K \alpha_i - 1 \right) + v \left( \sum_{i=1}^K \beta_i - t_0 \right) \geq Q^*. \quad (\text{A.1})$$

Since the third term and each term in the sum is positive, the fourth term is zero. The sufficiency is thus proved.

Next, we prove the necessity of Proposition 1 by contradiction. Suppose that if P2 is infeasible, then there exist  $\lambda > 0$ ,  $\mu > 0$  and  $v$  so that  $g(\lambda, \mu, v) \geq Q^*$ . However, since P2 is assumed to be infeasible, there exist  $\lambda > 0$ ,  $\mu > 0$ , and  $v$  so that  $-\sum_{i=1}^K \lambda_i (Q - (\beta_i B_i + \alpha_i \log(1 + \gamma_i(t_0 - \beta_i/\alpha_i)))) - \mu(t_0 + \sum_{i=1}^K \alpha_i - 1) + v(\sum_{i=1}^K \beta_i - t_0) < 0$ , resulting in  $g(\lambda, \mu, v) < Q^*$ . This contradicts  $g(\lambda, \mu, v) \geq Q^*$ . Thus, the necessity is proved.

### B. Proof of Corollary 1

Through the Lagrange multiplier method, the problem P2 is approximately transformed into an unconstrained optimization problem. Thus, we can directly calculate  $\{\beta_i^*\}$  and  $\{\alpha_i^*\}$  by partial derivatives. Firstly, it is obtained by  $\partial L / \partial \beta_i = 0$  as

$$B_i \lambda_i - \frac{\lambda_i \gamma_i}{1 + \gamma_i(t_0 - \beta_i/\alpha_i)} + v = 0, \quad (\text{B.1})$$

where  $t_0$ ,  $\lambda_i$ , and  $\alpha_i$  are given. Then, taking the constraint (14) into account, we derive  $\beta_i^*$  as given in (22). Similarly,  $\alpha_i$  is obtained as

$$B_i \lambda_i - \frac{\lambda_i \gamma_i}{1 + \gamma_i(t_0 - \beta_i/\alpha_i)} + v = 0, \quad (\text{B.2})$$

where let  $q_i = 1 + \gamma_i(t_0 - \beta_i/\alpha_i)$ . Then, the above formula is simplified to (24) and  $\alpha_i = \gamma_i(t_0 - \beta_i)/q_i - 1$ . Note that  $\gamma_i(t_0 - \beta_i)/q_i - 1 \geq 0$ , because  $\beta_i \leq t_0$  and  $q_i \geq 1$  according to (24) for  $\lambda_i, \mu \geq 0$ . Therefore, we derive  $\alpha_i^*$  as given in (22) for a given  $\beta_i^*$ . This thus completes the proof of Corollary 1.

### Data Availability

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

### Conflicts of Interest

The authors declare that they have no conflicts of interest.

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