Hindawi
Wireless Communications and Mobile Computing
Volume 2018, Article ID 7606513, 11 pages
https://doi.org/10.1155/2018/7606513

Research Article

Mobile Fog Computing-Assisted Resource Allocation for Two-Hop SWIPT OFDM Networks

Xiaofei Di,[1] Yu Zhang,[2,3] Tong Liu,[4] Shaoli Kang,[5] and Yue Zhao[6]

[1] *School of Communication Engineering, Hangzhou Dianzi University, Hangzhou 310018, China*
[2] *State Grid Energy Research Institute Co., Ltd., Beijing 102209, China*
[3] *School of Computer and Communication Engineering, University of Science and Technology Beijing, Beijing 100083, China*
[4] *Beijing Computing Center, Beike Industry Park, Beijing 100094, China*
[5] *China Academy of Telecommunications Technology, Beijing 100191, China*
[6] *Epithelial Systems Biology Laboratory, Systems Biology Center, National Heart Lung and Blood Institute, National Institutes of Health, Bethesda, Maryland, USA*

Correspondence should be addressed to Yu Zhang; zhangyu2@sgeri.sgcc.com.cn

Received 2 May 2018; Accepted 8 July 2018; Published 27 September 2018

Academic Editor: Lei Yang

The mobile fog computing-assisted resource allocation (RA) is studied for simultaneous wireless information and power transfer (SWIPT) two-hop orthogonal frequency division multiplexing (OFDM) networks, where a decode-and-forward (DF) relay first harvests energy from signals emitted by a source and then helps the source to forward information to its destination by using the harvested energy. Power splitting (PS) strategy is adopted at the relay and a different PS (DPS) receiver architecture is proposed, where the PS factors of all subcarriers are different. A RA problem is formulated to maximize the system's achievable rate by jointly optimizing subcarrier pairing, power allocation, and PS factors. Since the RA problem is a nonconvex problem and is difficult to solve, an efficient RA algorithm is designed. As the wireless channels are fast time-varying, the computation is performed in mobile fog node close to end nodes, instead of remote clouds. Results demonstrate that the achievable rate is significantly increased by using the proposed RA algorithm. It is also found that the computation complexity of RA algorithm of DPS receiver architecture is much lower than the existing identical PS (IPS) receiver architecture, and thus the proposed DPS architecture is more suitable for computation-constrained fog system.

1. Introduction

In the past decade, cloud computing has emerged as a new paradigm. It enables computing, storage, and network managements to centralize in the clouds, which are referred to as data centers, cellular core networks, and so on. With the clouds, vast resources can be provided to resource-constrained devices to satisfy their requirements of computing and storage. However, there is an inherent limitation for cloud computing [1], i.e., the long propagation distance from the end user to the remote cloud center, resulting in very long latency.

Recently, a new trend has been happening; that is, the computing is pushed to the network edge devices due to their progressively enhanced computation capacity. This is called mobile fog computing (MFC) or mobile edge computing (MEC) [2, 3], where the network edge devices perform computing tasks instead of remote clouds. Thanks to closer distance to end users, the latency is less and thus real-time tasks can be achieved via MFC, which is an effective supplement to cloud computing. MFC is applicable to delay sensitive tasks while cloud computing to sophisticated but delay-insensitive data processing work.

One potential application of MFC is in Internet of Things (IoT), such as wireless sensor networks (WSN). In WSN, sensor nodes are responsible for data gathering, and sink nodes for collecting and preprocessing data from surrounding sensor nodes and then delivering data to the remote clouds, which perform further complicated data processing and information mining. For WSN, resource allocation (RA) is a key approach to improve system performance. It is carried out according to different channel states and deemed to be a real-time task, as the wireless channels are fast time-varying channels and RA needs to be processed rapidly to adapt the dynamic channels. So MFC is a more appropriate option than cloud computing.

In the field of WSN, cooperative relay communication is deemed as an important technique, as it can guarantee that the far sensor nodes can complete communication with each other via intermediate relaying sensor nodes [4, 5]. On the other hand, orthogonal frequency division multiplexing (OFDM) is employed in wireless communication networks [6]. The combination of relay and OFDM is able to significantly enhance the performance of the system [7, 8].

MFC-assisted cooperative relay systems [9, 10] and OFDM systems [11, 12] have attracted much attention and been widely investigated. In [9], a fog-enabled cooperative communication network was considered, where multiple fog nodes were configured to support two-hop transmissions, and the optimal system performance was achieved by designing time reuse patterns. In [10], cooperative fog computing for the Internet of Vehicles (IoV) was studied, where the cooperation of fog nodes was explored to enhance the system performance. In [11], a MFC-assisted multiuser OFDM network was considered, and the total consumed energy of mobile users was minimized by jointly optimizing subcarrier and CPU time allocation. In [12], the joint subcarrier and power allocation problem in an MFC-based OFDM system was investigated to minimize the maximal delay of all devices.

Meanwhile, WSN are usually energy-constrained networks, and connecting sensor nodes to power grid is impossible sometimes. Batteries can be deployed in sensor nodes, but the batteries capacity is limited and may be hard to be replaced frequently. Recently, wireless power transfer has attracted much attention, in which energy-constrained devices can harvest energy by using wireless signals emitted by system nodes with sufficient energy source. Noting that wireless signal can simultaneously carry and transfer information and energy, this is deemed as the simultaneous wireless information and power transfer (SWIPT) [13].

SWIPT has been widely investigated [14–24]. In [14], it was assumed that information decoding (ID) and energy harvesting (EH) are simultaneously carried out by using the received identical signals. Nevertheless, this is deemed not to be realized, and therefore some practical SWIPT receivers were also presented, such as time switching (TS) and power splitting (PS) in [13]. In TS receivers, ID and EH are performed in two different phases, respectively. In PS receivers, the wireless signal is split into two streams: one stream enters into the energy receiver to harvest energy, and the other enters into the information receiver to obtain information. In [16], these SWIPT receiver architectures were applied to cooperative two-hop network, and the achievable rate performance was investigated. These architectures have also been widely studied in OFDM systems; see, e.g., [17–20]. But, the existing work mainly concerns point-to-point OFDM systems. For example, in [17, 19], the performances of throughput and weighted sum-rate were investigated for multiuser OFDM networks. In [20], max-min fair resource allocation was studied for multigroup multicast OFDM systems. In [18], a new SWIPT receiver architecture was proposed, where one part of the subcarriers was used for ID, and the other part was used for EH.

Recently, some work discussed the SWIPT-enabled two-hop OFDM system. In [21, 22], the authors considered amplify-and-forward (AF) relaying protocol and the achievable information rates were maximized for two-hop MIMO-OFDM AF relay system. In [23, 24], the SWIPT-enabled two-hop OFDM decode-and-forward (DF) relay system was considered, but the subcarrier pairing over the two hops was not involved. In [15], a PS receiver architecture was considered and a RA algorithm was proposed to improve the achievable rate; however, the complexity of algorithm was so high that it was hard to be applied to computation-constrained fog system.

This paper investigates the SWIPT for a MFC-assisted two-hop OFDM network, in which a source node transmits information to a destination with the help of a DF relay. The source is assumed with fixed energy source, while the relay is an energy-constrained node and thus has to obtain energy from wireless signal emitted by the source and further forwards the information of source to destination.

The main contributions of this paper are given as follows.

Firstly, to achieve the simultaneous information and energy transmission, we adopt a different PS ratio PS (DPS) architecture, where a frequency selective power splitter splits the signal on each subcarrier into two streams and thus all subcarriers are of the different PS ratios, which can adaptively change. Further, a particular energy cooperation strategy is considered; i.e., the energy harvested on some subcarrier of the first hop is only used to forward the information received on the corresponding subcarrier, in order to reduce the excessive computational complexity. Unlike the existing work [15], it is assumed that PS receiver splits all subcarriers into two streams with identical PS ratio, which is called identical PS ratio PS (IPS) receiver architecture in this paper.

Secondly, in order to explore the system performance limit of the proposed DPS architecture, a RA optimization problem is formulated to maximize the achievable rate of the system by jointly optimizing the subcarrier pairing (SP), the PS ratios, and the PA at both source and the relay. As the problem is nonconvex and hard to solve, a low-complexity efficient RA algorithm is designed by decomposing it into three separate subproblems. The related computation is operated at the source node, which is generally a sink node of higher computation capacity in WSN.

Thirdly, extensive simulation experiments are performed to discuss the system performance. The results demonstrate that although there are some performance loss of achievable rate of the proposed DPS architecture compared with the existing IPS architecture, the computation complexity of DPS architecture is much lower than IPS architecture. So DPS architecture may be a better option for computation-constrained fog system.

This paper is organized as follows. In Section 2, the network architecture and system model are presented, and then RA optimization problem is formulated. In Section 3, an efficient RA algorithm is designed. Simulation results are

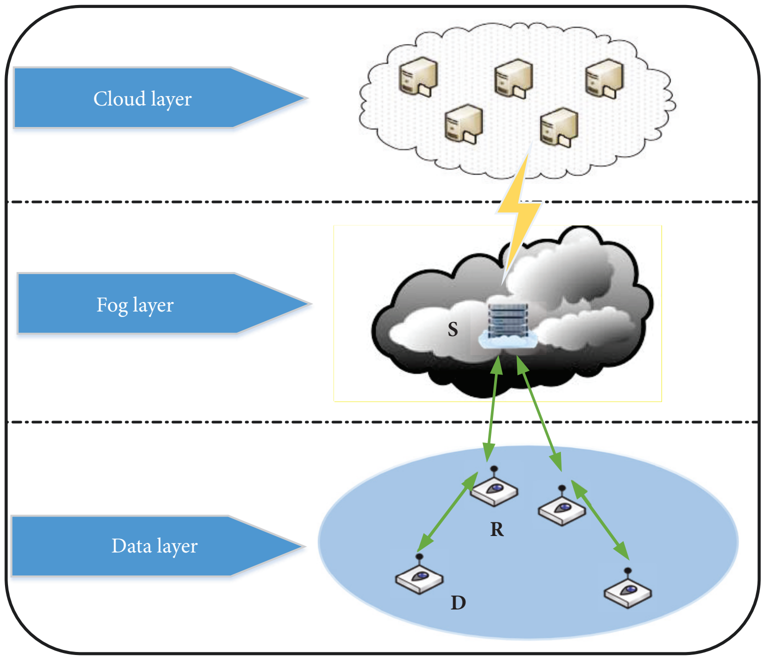

Figure 1: Network architecture of MFC-assisted two-hop OFDM system.

shown in Section 4 to discuss the performance of the DPS receiver architecture and RA algorithm. In Section 5, this paper is summarized.

2. Network Architecture and System Model

The considered network architecture is shown as in Figure 1, which is divided into three layers, i.e., data layer, fog layer, and cloud layer. Data layer comprises data nodes, which are responsible for gathering data from surrounding environment. Cloud layer contains vast resources to store and process the amount of data from data layer; meanwhile, it also sends control information to data nodes to instruct their operations. Fog layer is a bridge between data layer and cloud layer, which means that on one hand, it is responsible for collecting and preprocessing data from data layer and delivering data to cloud layer to further process it; on the other hand, it is responsible for forwarding control information from cloud layer to data layer. The information between cloud layer and fog layer is transmitted on wired channels while the information between fog layer and data layer is transmitted on wireless channels.

In this paper, we consider the transmission of control information from cloud layer to data layer. The cloud layer first sends control information to fog layer; fog layer stores the information and then forwards it to data layer. The reason of introducing the fog layer instead of directly using cloud computing is that the wireless channels are deemed to be fast time-varying channels and thus information transmission and RA task have to be performed rapidly to adapt the dynamic channels. It is worth noting that due to the enhanced computing capacity, the fog layer has the capability of performing RA algorithm according to the channel state information (CSI).

To study the information transmission from fog layer to data layer, a MFC-assisted two-hop OFDM network is considered, which consists of one source (S) in fog layer, and one destination (D) and one relay (R) in data layer, as shown in Figure 1. S desires to send information to D with the help of R. No direct link exists between S and D. S is of steady energy supply by connecting to power grid in fog layer and P_S denotes its power. R is an energy-constrained node operating in half-duplex mode and deploying DF relaying protocol, so it has to obtain energy from the signals of S and then uses the harvested energy to help S to forward information to D. The PS receiver architecture is adopted at R so that it can split the received RF signals into two streams to perform EH and ID, respectively. For such a SWIPT-enabled communication network, each transmission is based on frame of length T, which is divided into two subphases of equal length.

In the first subphase, S sends OFDM symbols to R. The received signal at R on subcarrier i can be expressed as

$$y_{r,i} = \sqrt{P_{s,i}} h_i x_i + z_{r,i}, \quad \forall i \in \{1, \ldots, N\}, \tag{1}$$

where x_i and h_i, respectively, represent transmitted symbol and channel coefficient on subcarrier i and N is the number of subcarriers. $z_{r,i}$ represents the additive white Gaussian noise (AWGN) from the antenna on subcarrier i at R, which is of zero mean and variance $\sigma^2_{r,\text{att}}$. $P_{s,i}$ represents the transmission power at S on subcarrier i and satisfies

$$\sum_{i=1}^{N} P_{s,i} \le P_S, \quad P_{s,i} \ge 0, \ \forall i. \tag{2}$$

In the second subphase, using the stream for ID and EH, R, respectively, decodes the received information and harvests the energy and then reencodes the received information and forwards the reencoded information to D. Subcarrier pairing is adopted, so the information of the first hop received on subcarrier i can be transmitted on the subcarrier j in the second hop. The signal on subcarrier j received at D can be expressed as

$$y_{d,j} = \sqrt{P_{r,j}} g_j x_i + z_{d,j}, \quad \forall j \in \{1, \ldots, N\}, \tag{3}$$

where g_j is channel coefficient on subcarrier j at D, and $P_{r,j}$ is the power on subcarrier j at R. $z_{d,j}$ is AWGN from the antenna on subcarrier j at D, which is of zero mean and variance $\sigma^2_{d,\text{att}}$.

To realize SWIPT, a PS receiver architecture is proposed, where all subcarriers are of different PS (DPS) ratios and can adaptively adjust, which is called DPS architecture. To implement DPS architecture, an analog adaptive passive frequency selective power splitter is required [21, 24]. In this paper, we consider a particular energy cooperation strategy which makes the computational complexity of the RA algorithm of the DPS architecture significantly decrease and is very meaningful for some communication scenarios where the processing capacity of communication nodes is limited, such as MFC-based WSN.

Let the PS ratios θ_i^I and θ_i^E represent the fraction of the signal power used for ID and EH received on subcarrier i, respectively, which satisfy the constraints of

$$\theta_i^I + \theta_i^E = 1, \quad \theta_i^I \geq 0, \; \theta_i^E \geq 0, \; \forall i \in \{1, \ldots, N\} \tag{4}$$

Thus, the harvested energy on subcarrier i at R is given by

$$E_i = \frac{T}{2} \eta \theta_i^E \left|h_i\right|^2 P_{s,i}, \tag{5}$$

where η denotes the EH efficiency.

We consider such an *energy cooperation* strategy adopted in [21, 24], in which the energy harvested on subcarrier i of the first hop is only used to forward the information received on subcarrier i and thus the available power $P_{r,j}$ on subcarrier j at R can be inferred as

$$P_{r,j} = \frac{E_i}{T/2} = \eta \theta_i^E \left|h_i\right|^2 P_{s,i}. \tag{6}$$

The achievable information rate between S and D for DF relay system on a subcarrier pair (i, j) can be expressed as [4]

$$R_{i,j}^{DPS} = \frac{1}{2} \min \left\{ \log_2 \left(1 + \frac{\theta_i^I \left|h_i\right|^2 P_{s,i}}{\theta_i^I \sigma^2_{r,\text{att}} + \sigma^2_{r,\text{proc}}} \right), \log_2 \left(1 + \frac{\left|g_j\right|^2 P_{r,j}}{\sigma_d^2} \right) \right\}, \tag{7}$$

where $\sigma_d^2 = \sigma^2_{d,\text{att}} + \sigma^2_{d,\text{proc}}$ represents the total noise power of D on each subcarrier, $\sigma^2_{r,\text{proc}}$ and $\sigma^2_{d,\text{proc}}$, respectively, represent the power of signal processing noise on any subcarrier of R and D. In (7), the first part $\log_2(1 + \theta_i^I |h_i|^2 P_{s,i} / (\theta_i^I \sigma^2_{r,\text{att}} + \sigma^2_{r,\text{proc}}))$ represents the mutual information from S to R on subcarrier i, and the second part $\log_2(1 + |g_j|^2 P_{r,j}/\sigma_d^2)$ represents the mutual information from R to D on subcarrier j. The coefficient 1/2 in (7) is because each frame is composed of two subphases of equal length.

Substituting (6) into (7), then we can write (7) as

$$R_{i,j}^{DPS} = \frac{1}{2} \min \left\{ \log_2 \left(1 + \frac{\theta_i^I \left|h_i\right|^2 P_{s,i}}{\theta_i^I \sigma^2_{r,\text{att}} + \sigma^2_{r,\text{proc}}} \right), \log_2 \left(1 + \frac{\eta \theta_i^E \left|h_i\right|^2 \left|g_j\right|^2 P_{s,i}}{\sigma_d^2} \right) \right\}. \tag{8}$$

Thus, the achievable rate of the system can be expressed as

$$R^{DPS} (\mathcal{P}, \mathcal{S}, \boldsymbol{\theta}) = \sum_{i=1}^{N} \sum_{j=1}^{N} s_{i,j} R_{i,j}^{DPS}, \tag{9}$$

where $\boldsymbol{\theta} = \{\theta_i^I, \theta_i^E, \forall i\}$ is PS policy and satisfies the constraint (4). $\mathcal{P} = \{P_{s,i} \geq 0, | \; \forall i, j\}$ is power allocation (PA) policy and satisfies (2). $\mathcal{S} = \{s_{i,j} \in \{0, 1\} \mid \forall i, j\}$ is SP policy, which represents that if the first hop subcarrier i is matched with the second hop subcarrier j, $s_{i,j}$ =1; else $s_{i,j} = 0$. Further, one first hop (second hop) subcarrier can only match with one second hop (first hop) subcarrier. That is,

$$\begin{gathered} \sum_{j=1}^{N} s_{i,j} \leq 1, \quad \forall i, \\ \sum_{i=1}^{N} s_{i,j} \leq 1, \quad \forall j. \end{gathered} \tag{10}$$

With the objective of maximizing the achievable information rate of the system, by jointly optimizing the SP, the PA, and the PS ratio, the optimization problem is formulated as (**P1**):

$$\begin{aligned} \max_{\mathcal{P}, \mathcal{S}, \boldsymbol{\theta}} \quad & R^{DPS} (\mathcal{P}, \mathcal{S}, \boldsymbol{\theta}) \\ \text{s.t.} \quad & (2), (4), (10). \end{aligned} \tag{11}$$

3. Resource Allocation Design

In this section, we first describe our proposed resource allocation (RA) algorithm for problem P1 and then we shall prove that it is able to achieve the global optimal solution of problem P1.

3.1. The Proposed Resource Allocation. Our proposed RA is described as Algorithm 1, which is divided into three separate subproblems. In what follows of this subsection (Section 3.1), the detailed process of each step in Algorithm 1 is described, and its global optimality is proven in Section 3.2.

(1) The Optimal SP $\mathcal{S}^*$. The proposed SP scheme is only based on the channel power gains. Firstly, according to the channel power gains of the two hops $|h_i|^2$ and $|g_j|^2$, the first hop subcarriers and the second hop subcarriers are, respectively, sorted from highest to lowest. Next, the kth first hop subcarrier is matched with the kth second hop subcarrier, which is equivalent to the optimal $\mathcal{S}^*$ satisfying that

$$s_{i,j} = \begin{cases} 1, & \text{if } Number\left(|h_i|^2\right) = Number\left(|g_j|^2\right), \\ 0, & \text{otherwise,} \end{cases} \quad (12)$$

where $Number(|u_i|^2)$ represents the serial number of $|u_i|^2$ inside all $|u_k|^2$ for $k \in \{1, 2, \ldots, N\}$ with an degressive sorting sequence for $u \in \{h, g\}$, respectively. This scheme is called the channel gain- (CG-) sorted SP scheme. The optimality of this scheme is given as follows.

Lemma 1. *The optimal SP scheme of problem P1 is the CG-sorted SP scheme.*

Proof. To prove this lemma, two-subcarrier case is first considered and proved. Then it is further extended to general multisubcarrier case. See the Appendix for details. □

(2) The Optimal PS $\boldsymbol{\theta}^*$ with the Obtained $\mathcal{S}^*$. First, it is easily found that the problem can be decomposed into N subproblems due to the independence of each subcarrier pair. For any given subcarrier pair (i, j), the subproblem can be expressed as (**P2**):

$$\max_{\theta_i^I,\theta_i^E} \quad R_{i,j}$$
$$\text{s.t.} \quad \theta_i^I + \theta_i^E = 1, \quad \theta_i^I \geq 0, \; \theta_i^E \geq 0. \quad (13)$$

To simplify the expressions, let $A = |h_i|^2, B = \eta|g_j|^2/\sigma_d^2$ and denote $P_{s,i}$ as P_i. Since the subcarrier pair is fixed, we further drop the indexes *i,j* in this subsection. Thus the achievable information rate in (8) on a fixed subcarrier pair can be expressed as

$$R = \frac{1}{2} \min \left\{ \log_2 \left(1 + \frac{A\theta^I P}{\theta^I \sigma_{r,\text{att}}^2 + \sigma_{r,\text{proc}}^2} \right), \log_2 \left(1 + AB\theta^E P \right) \right\}. \quad (14)$$

It is easy to find that in (14) the first term, i.e., $\log_2(1 + A\theta^I P/(\theta^I \sigma_{r,\text{att}}^2 + \sigma_{r,\text{proc}}^2))$, is a monotonically increasing function of θ^I, and the second term, i.e., $\log_2(1 + AB\theta^E P)$, is a monotonically decreasing function of θ^I, so, to obtain the optimal solution, the two terms should be equal. Meanwhile, using $\theta^I + \theta^E = 1$, the optimal PS factor θ^I can be calculated, according to

$$B\sigma_{r,\text{att}}^2 \left(\theta^I\right)^2 + \left(1 - B\sigma_{r,\text{att}}^2 + B\sigma_{r,\text{proc}}^2\right)\theta^I - B\sigma_{r,\text{proc}}^2 = 0. \quad (15)$$

This is a quadratic equation and its two roots are given as

$$\theta^I = \frac{-\left(1 - B\sigma_{r,\text{att}}^2 + B\sigma_{r,\text{proc}}^2\right) \pm \sqrt{\left(1 - B\sigma_{r,\text{att}}^2 + B\sigma_{r,\text{proc}}^2\right)^2 + 4B^2\sigma_{r,\text{att}}^2\sigma_{r,\text{proc}}^2}}{2B\sigma_{r,\text{att}}^2}, \quad (16)$$

where only the one satisfying the constraints in problem P2 can be considered as the optimal solution. Since $\theta^I + \theta^E = 1, \theta^I, \theta^E \geq 0$, we have that $0 \leq \theta^I, \theta^E \leq 1$.

It is easy to observe that the one of the two roots

$$\theta^I = \frac{-1 + B\sigma_{r,\text{att}}^2 1 B\sigma_{r,\text{proc}}^2 - \sqrt{\left(1 - B\sigma_{r,\text{att}}^2 + B\sigma_{r,\text{proc}}^2\right)^2 + 4B^2\sigma_{r,\text{att}}^2\sigma_{r,\text{proc}}^2}}{2B\sigma_{r,\text{att}}^2} \quad (17)$$

is always less than 0, so it is discarded. For the other one, we can prove that it satisfies the above constraint.

Thus, the optimal PS factors can be given by

$$\theta^{I*} = \frac{-1 + B\sigma_{r,\text{att}}^2 - B\sigma_{r,\text{proc}}^2 + \sqrt{\left(1 - B\sigma_{r,\text{att}}^2 + B\sigma_{r,\text{proc}}^2\right)^2 + 4B^2\sigma_{r,\text{att}}^2\sigma_{r,\text{proc}}^2}}{2B\sigma_{r,\text{att}}^2}. \quad (18)$$

(1) Find the optimal $\mathcal{S}^*$ from (12).
(2) Calculate the optimal $\boldsymbol{\theta}^*$ with the obtained $\mathcal{S}^*$ from (18).
(3) Calculate the optimal $\mathcal{P}^*$ with the obtained $\mathcal{S}^*$ and $\boldsymbol{\theta}^*$ from (22).

Algorithm 1: Resource allocation algorithm.

(3) The Optimal PA $\mathcal{P}^*$ with the Obtained $\mathcal{S}^*$ and $\boldsymbol{\theta}^*$. We have obtained the optimal PS factors θ^{I*} and θ^{E*}. As the optimal PS factors are related to the channel gain of the second hop from (18), θ_i^{I*}, θ_i^{E*} are represented as $\theta_{i,j}^{I*}, \theta_{i,j}^{E*}$ for given subcarrier pair (i,j). Since the two terms are equal in (8) for optimal $\theta_{i,j}^{I*}, \theta_{i,j}^{E*}$, (8) can be transformed as

$$R_{i,j} = \frac{1}{2}\log_2\left(1 + \frac{|h_i|^2 \theta_{i,j}^{I*} P_i}{\theta_{i,j}^{I*}\sigma_{r,\mathrm{att}}^2 + \sigma_{r,\mathrm{proc}}^2}\right). \tag{19}$$

We denote $|h_i|^2\theta_{i,j}^{I*}/(\theta_{i,j}^{I*}\sigma_{r,\mathrm{att}}^2 + \sigma_{r,\mathrm{proc}}^2)$ as $\gamma_{i,j}$, and then (19) is transformed into

$$R_{i,j} = \frac{1}{2}\log_2\left(1 + \gamma_{i,j}P_i\right). \tag{20}$$

So for given $\mathcal{S}^*$ and $\boldsymbol{\theta}^*$, the PA problem can be formulated as (**P3**):

$$\begin{aligned} &\max_{\mathcal{P}} \quad \sum_{(i,j)\in\mathcal{SP}} R_{i,j} \\ &\text{s.t.} \quad (2), \end{aligned} \tag{21}$$

where $\mathcal{SP}$ is the set of subcarrier pairs. From (18), it can be easily found that the optimal PS factors are not related to PA and thus $\gamma_{i,j}$ is also not related to PA. So this problem is a classical water-filling PA problem, and we can obtain its optimal solution as

$$P_i^* = \left[\frac{1}{\nu\ln 2} - \frac{1}{\gamma_{i,j}}\right]^+, \quad \forall i, \tag{22}$$

where $[x]^+ = \max\{0, x\}$, and ν is Lagrangian multiplier and can be solved using $\sum_{i=1}^{N}[1/(\nu\ln 2) - 1/\gamma_{i,j}]^+ = P_S$.

3.2. Global Optimum of Our Proposed RA. In this subsection, we shall prove that although Algorithm 1 is divided into three separate subproblems, it can still achieve the global optimal solution of problem P1, and the result is given by the following theorem.

Theorem 2. *The RA in Algorithm 1 achieves the global optimum of problem P1.*

Proof. To prove that the RA policy in Algorithm 1 can achieve the global optimal solution of problem P1, we only need to prove that each step of Algorithm 1 maintains the global optimum. From Lemma 1, we have known that the CG-sorted SP scheme in step 1 of Algorithm 1 gives the globally optimal SP policy. The scheme is only related to channel gains, which does not require the knowledge of the optimal PS and PA. According to the derivation process in step 2 of Algorithm 1, the obtained PS is optimal under the given optimal SP, and it does not require the knowledge of optimal PA. Then in step 3 of Algorithm 1, the obtained PA is optimal under the given optimal SP and optimal PS. Since each step maintains the global optimum, Theorem 2 is proved. □

3.3. Complexity Analysis. The complexity of step 1 of Algorithm 1 depends on the adopted sorting method, which is $O(N\log N)$ if the quick-sort method is applied. Moreover, the complexity of step 2 of Algorithm 1 is $O(N)$, and the complexity of step 3 of Algorithm 1 is also $O(N)$ (the water-filling over the sorted $\gamma_{i,j}$) [25]. Thus, the total computational complexity can be expressed by $O(N\log N)$. For comparison, the computational complexity of RA algorithm for IPS architecture in [15] is $O(N\log N + MN(N+2)^q)$, where M is the number of loops in the algorithm [15], so it can be found that the computational complexity of proposed DPS architecture's RA algorithm is on the order of $M(N+2)^q/\log N$ less than the IPS architecture. So the proposed DPS architecture may be more proper for MFC-assisted networks, where the devices are of lower computation capacity.

4. Simulation Results

In this section, some simulation results are given to illustrate the performance of the presented DPS receiver architecture and RA algorithm. The noise powers are assumed follows: ${\sigma_r}^2{}_{\mathrm{att}} = {\sigma_r}^2{}_{\mathrm{proc}} = -33$ dBm and ${\sigma_d}^2 = -30$ dBm. The three network nodes (S, R, and D) are assumed to be placed on a straight line. The distance from S to D is reference distance and represented by d_0, where $d_0 = 10$ m. The location of R is expressed as d_r/d_0, where d_r denotes the distance from S to R. h_i and g_j are, respectively, obtained from the distribution as

$$\begin{aligned} h_i &\sim CN\left(0, \frac{1}{L(1+d_r)^\alpha}\right), \\ g_j &\sim CN\left(0, \frac{1}{L(1+(d_0-d_r))^\alpha}\right), \end{aligned} \tag{23}$$

where α is the path loss factor and set to be 3 and L is the number of taps and set to be 4.

Firstly, we discuss the performance of our proposed Algorithm 1. For comparisons, the three other methods are also simulated, i.e., (1) OPAwoSP method: Optimal PA without SP; (2) EPAwSP method: Equal PA with SP; (3) EPAwoSP

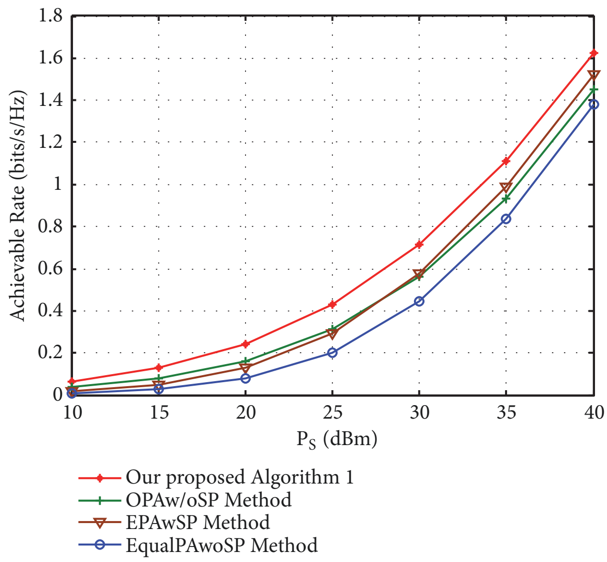

FIGURE 2: Achievable information rate versus P_S with $N = 64$ and R located at the midpoint between S and D for DPS architecture.

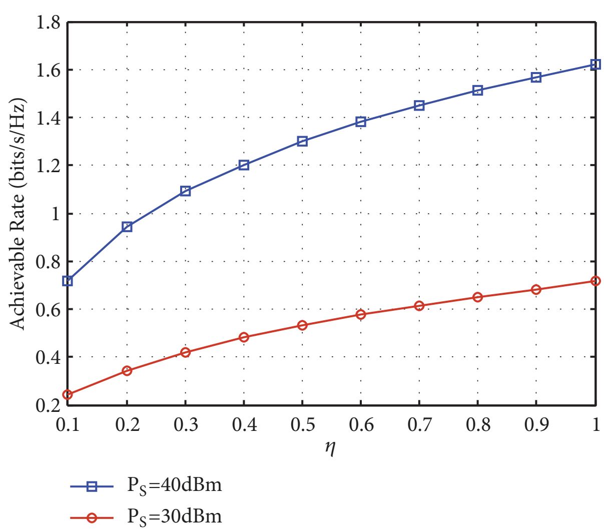

FIGURE 3: Achievable information rate versus EH efficiency η with $N = 64$ and R located at the midpoint between S and D for DPS architecture.

method: Equal PA without SP. EH efficiency $\eta = 1$. In Figure 2, we plot the achievable rates versus the total power P_S. It is easily seen that our proposed Algorithm 1 is superior to the three other methods.

We also show the effect of EH efficiency η on the achievable rate in Figure 3 and it can be found that when $\eta = 1$, the achievable rate is maximum. In the following simulations, to discuss the SWIPT-enabled system's performance limit, EH efficiency is always set to be $\eta = 1$.

Secondly, to figure out the system performance of the DPS receiver architecture, we compare the achievable information rates of the proposed DPS architectures and IPS architecture in [15]. For IPS architecture, let ρ be the PS ratio used for ID, and the rest $1 - \rho$ part is used for EH; ρ should satisfy

$$0 \le \rho \le 1. \tag{24}$$

The energy obtained by R is $E_R = (T/2)\eta(1-\rho)\sum_{i=1}^{N} |h_i|^2 P_{s,i}$ and the available power of R is $P_R = E_R/(T/2) = \eta(1 - \rho)\sum_{i=1}^{N} |h_i|^2 P_{s,i}$. So the available power$P_{r,j}$ on subcarrier j at R satisfies

$$\sum_{j=1}^{N} P_{r,j} \le \eta (1-\rho) \sum_{i=1}^{N} |h_i|^2 P_{s,i}. \tag{25}$$

The achievable rate from S to D on each subcarrier pair (i, j) can be expressed as

$$R_{i,j}^{IPS} = \frac{1}{2} \min \left\{ \log_2 \left(1 + \frac{\rho |h_i|^2 P_{s,i}}{\rho \sigma_{r,\text{att}}^2 + \sigma_{r,\text{proc}}^2} \right), \log_2 \left(1 + \frac{|g_j|^2 P_{r,j}}{\sigma_d^2} \right) \right\}, \tag{26}$$

and thus the achievable rate of the system is given by

$$R^{IPS}(\mathcal{P}, \mathcal{S}, \rho) = \sum_{i=1}^{N} \sum_{j=1}^{N} s_{i,j} R_{i,j}^{IPS}. \tag{27}$$

To maximize the achievable rate of the system, an optimization problem is formulated as

$$\begin{aligned} \max_{\mathcal{P},\mathcal{S},\rho} \quad & R^{IPS}(\mathcal{P}, \mathcal{S}, \rho) = \sum_{i=1}^{N}\sum_{j=1}^{N} s_{i,j} R_{i,j} \\ \text{s.t.} \quad & (2), (8), (24), (25). \end{aligned} \tag{28}$$

The solution of the problem is given in [15]. In addition, conventional non-SWIPT two-hop OFDM system is also compared in order to show the difference between SWIPT-enabled and non-SWIPT systems. For the non-SWIPT system, we use the optimal RA algorithm proposed in [8].

In Figures 4 and 5, the achievable rates of the DPS/IPS architectures and non-SWIPT system with respect to P_S and d_r/d_0 are given, respectively. In these two figures, it can be found that the achievable rate of the non-SWIPT system is higher than SWIPT-enabled IPS/DPS architectures, and DPS architecture is worse than IPS architecture.

Moreover, from Figure 5, one can find that, for the SWIPT-enabled system, when R is placed close to S or D, the system can obtain the better performance, and the proposed DPS architecture agrees with the existing IPS architecture. One can also find that, for conventional non-SWIPT system, the achievable information rate achieves maximum when R is placed at the midpoint on the line from S to D.

Finally, we also compare the average running time of IPS and DPS architectures in Figure 6. It shows that the running efficiency of the DPS architecture is far superior to the IPS architecture, which agrees with the analysis

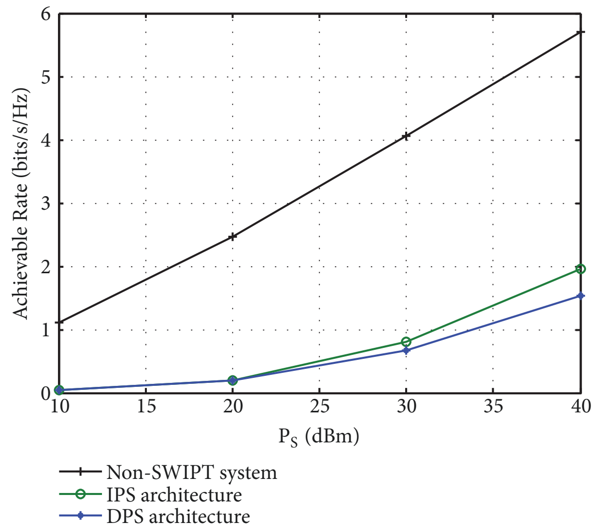

Figure 4: Comparison of achievable information rates of DPS architecture, IPS architecture, and non-SWIPT system versus P_S with $N = 4$ and R located at the midpoint between S and D.

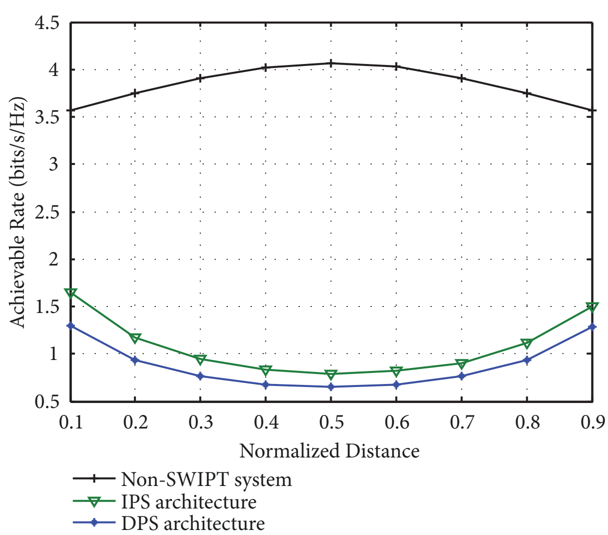

Figure 5: Comparison of achievable information rates of DPS architecture, IPS architecture, and non-SWIPT system versus relay location with P_S=30dBm and $N = 4$.

of computational complexity in Section 3.3, and thus, for computation-constrained MFC system, DPS architecture is a better option although there are some loss of the achievable rate compared with IPS architecture.

5. Conclusion

This paper investigated SWIPT for MFC-assisted two-hop OFDM network and proposed DPS receiver architectures. To study the system achievable rate limit, an efficient RA algorithm was given. In simulations, it was found that the achievable rate of the DPS architecture is worse than the existing IPS architecture; however, the computation complexity

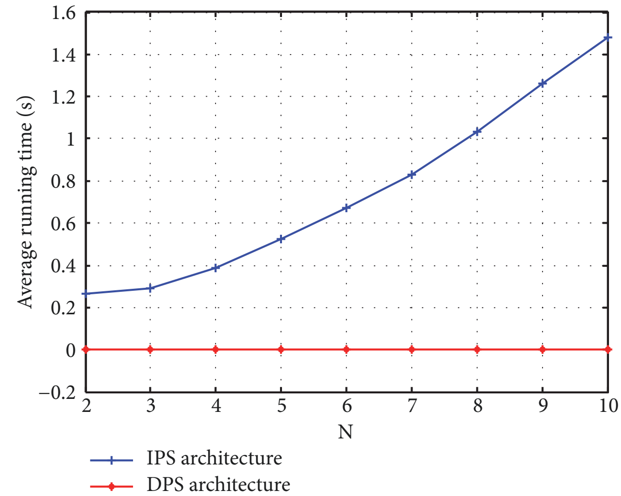

Figure 6: Comparison of running time of IPS and DPS architectures versus the number of subcarriers N with R located at the midpoint from S to D and P_S=10dBm.

of DPS architecture is much lower than IPS architecture. So DPS architecture may be a better option for computation-constrained MFC system.

Appendix

Proof of Lemma 1

(a) Two-Subcarrier Case (N=2). Firstly, it is assumed that two hops' channel gains satisfy $|h_1|^2 > |h_2|^2, |g_1|^2 > |g_2|^2$. Observing Algorithm 1, we know the second step and the third step can be applied to any given subcarrier pairing policy in fact, although they are derived from the optimal subcarrier pairing policy. So the achievable information rate of the system using sorted subcarrier pairs (1,1) and (2,2) can be expressed as

$$R_{\text{sort}} = \frac{1}{2}\log_2\left(1+\gamma_{1,1}P_1^*\right) + \frac{1}{2}\log_2\left(1+\gamma_{2,2}P_2^*\right), \quad \text{(A.1)}$$

and the achievable rate using nonsorted subcarrier pairs (1,2) and (2,1) can be expressed as

$$\begin{aligned} R_{\text{nonsort}} &= \frac{1}{2}\log_2\left(1+\gamma_{1,2}P_1{}'^*\right) \\ &\quad + \frac{1}{2}\log_2\left(1+\gamma_{2,1}P_2{}'^*\right), \end{aligned} \quad \text{(A.2)}$$

where $P_1{}'^*, P_2{}'^*$ are the optimal powers for nonsorted pairing scheme.

To prove Lemma 1, we need to prove $R_{\text{sort}} > R_{\text{nonsort}}$; i.e.,

$$\begin{aligned} &\left(1+\gamma_{1,1}P_1^*\right)\left(1+\gamma_{2,2}P_2^*\right) \\ &\quad > \left(1+\gamma_{1,2}P_1{}'^*\right)\left(1+\gamma_{2,1}P_2{}'^*\right). \end{aligned} \quad \text{(A.3)}$$

We define a new function $f(\theta_{i,j}^{I*}) = \theta_{i,j}^{I*}/(\theta_{i,j}^{I*}\sigma_{r,\text{att}}^2 + \sigma_{r,\text{proc}}^2)$, so $\gamma_{i,j} = |h_i|^2 f(\theta_{i,j}^{I*})$. For further simplifying the expressions, let $H_i = |h_i|^2$ and $G_j = f(\theta_{i,j}^{I*})$. Note that, from (18), we can observe that for given noise power, the optimal PS factor $\theta_{i,j}^{I*}$ is only related to B, that is, to the channel gain $|g_j|^2$ of the second hop since $B = \eta|g_j|^2/\sigma_d^2$. Thus, for G_j, we only reserve the subscript j. One sees that $\gamma_{i,j} = H_i G_j$; thus (A.3) is equivalent to

$$\begin{aligned}&\left(H_1G_1P_1^* + H_2G_2P_2^* + H_1G_1H_2G_2P_1^*P_2^*\right)\\&\quad - \left(H_1G_2P_1{'}^* + H_2G_1P_2{'}^* + H_1G_2H_2G_1P_1{'}^*P_2{'}^*\right)\\&\quad > 0.\end{aligned} \tag{A.4}$$

Secondly, we can prove that $G_1 > G_2$ for the assumption $|g_1|^2 > |g_2|^2$. From (18), the derivative of $\theta_{i,j}^{I*}$ with respect to B can be computed as

$$\left(\theta_{i,j}^{I*}\right)' = \frac{1}{2\sigma_{r,\text{att}}^2 B^2}\left(1 - \frac{1/B - \left(\sigma_{r,\text{att}}^2 - \sigma_{r,\text{proc}}^2\right)}{\sqrt{\left(1/B - \left(\sigma_{r,\text{att}}^2 - \sigma_{r,\text{proc}}^2\right)\right)^2 + 4\sigma_{r,\text{att}}^2\sigma_{r,\text{proc}}^2}}\right). \tag{A.5}$$

One can easily find that $(\theta_{i,j}^{I*})' > 0$; that is to say, $\theta_{i,j}^{I*}$ is a monotonically increasing function of B. Meanwhile we know $B = \eta|g_j|^2/\sigma_d^2$, so with the increase of $|g_j|^2$, $\theta_{i,j}^{I*}$ increases. The increment of $\theta_{i,j}^{I*}$ will further result in the increment of $f(\theta_{i,j}^{I*})$. Thus, according to the assumption $|g_1|^2 > |g_2|^2$, we have $f(\theta_{i,1}^{I*}) > f(\theta_{i,2}^{I*})$; that is, $G_1 > G_2$.

Thirdly, for the two-subcarrier case, the explicit solutions of optimal PA can be obtained. When only total power constraint in (2) is considered and inequality constraints are ignored, the optimal P_1^*, P_2^* for sorted pairing scheme can be derived as

$$\begin{aligned}P_1^* &= \frac{P_S}{2} + \frac{H_1G_1 - H_2G_2}{2H_1G_1H_2G_2},\\ P_2^* &= \frac{P_S}{2} - \frac{H_1G_1 - H_2G_2}{2H_1G_1H_2G_2}.\end{aligned} \tag{A.6}$$

Similarly, the optimal $P_1{'}^*, P_2{'}^*$ for nonsorted pairing scheme can be derived as

$$\begin{aligned}P_1{'}^* &= \frac{P_S}{2} + \frac{H_1G_2 - H_2G_1}{2H_1G_1H_2G_2},\\ P_2{'}^* &= \frac{P_S}{2} - \frac{H_1G_2 - H_2G_1}{2H_1G_1H_2G_2}.\end{aligned} \tag{A.7}$$

It is worth noting that, due to nonnegative power constraint in (2), (A.6) and (A.7) are valid only for $0 \le P_1^*, P_2^*, P_1{'}^*, P_2{'}^* \le P_S$. If $P_1^*, P_2^*, P_1{'}^*, P_2{'}^*$ do not satisfy this condition, then $P_1^* = P_S, P_2^* = 0$ or $P_1{'}^* = P_S, P_2{'}^* = 0$.

So we consider the following three cases, namely, Case 1 ($0 < P_1^*, P_2^*, P_1{'}^*, P_2{'}^* < P_S$), Case 2 ($P_1^* = P_S, P_2^* = 0$, $P_1{'}^* = P_S, P_2{'}^* = 0$), and Case 3 ($P_1^* = P_S, P_2^* = 0, 0 < P_1{'}^*, P_2{'}^* < P_S$). For the remaining case ($0 < P_1^*, P_2^* < P_S, P_1{'}^* = P_S, P_2{'}^* = 0$), it is easy to find that it will not occur, because we can derive that P_1^* is necessarily larger than $P_1{'}^*$ according to our assumptions $|h_1|^2 > |h_2|^2$ and $|g_1|^2 > |g_2|^2$. Noting that here we only consider $P_1{'}^* > P_2{'}^*$, that is, $H_1G_2 - H_2G_1 > 0$, the analysis for $P_1{'}^* \le P_2{'}^*$ is similar. Then we can derive and prove (A.4) for the three cases.

Case 1. For this case, using (A.6) and (A.7), we can obtain

$$\begin{aligned}&H_1G_1P_1^* + H_2G_2P_2^* + H_1G_1H_2G_2P_1^*P_2^*\\&\quad - \left(H_1G_2P_1{'}^* + H_2G_1P_2{'}^* + H_1G_2H_2G_1P_1{'}^*P_2{'}^*\right)\\&\quad = \frac{(H_1 - H_2)(G_1 - G_2)}{2}P_S\\&\quad + \frac{\left(H_1^2 - H_2^2\right)\left(G_1^2 - G_2^2\right)}{4H_1G_1H_2G_2} > 0,\end{aligned} \tag{A.8}$$

where inequality is obtained from our assumption $H_1 > H_2$ and the obtained result $G_1 > G_2$.

Case 2. For this case, we can derive that

$$\begin{aligned}&H_1G_1P_1^* + H_2G_2P_2^* + H_1G_1H_2G_2P_1^*P_2^*\\&\quad - \left(H_1G_2P_1{'}^* + H_2G_1P_2{'}^* + H_1G_2H_2G_1P_1{'}^*P_2{'}^*\right)\\&\quad = H_1P_S(G_1 - G2) > 0,\end{aligned} \tag{A.9}$$

where inequality is obtained since$G_1 > G_2$.

Case 3. For this case, using (A.7), we can obtain

$$\begin{aligned}&H_1G_1P_1^* + H_2G_2P_2^* + H_1G_1H_2G_2P_1^*P_2^*\\&\quad - \left(H_1G_2P_1{'}^* + H_2G_1P_2{'}^*\right.\\&\quad \left. + H_1G_2H_2G_1P_1{'}^*P_2{'}^*\right) = H_1G_1P_S\\&\quad - \left(\frac{H_1G_2 + H_2G_1}{2}P_S + \frac{H_1G_2H_2G_1}{4}P_S^2\right.\\&\quad \left. + \frac{(H_1G_2 - H_2G_1)^2}{4H_1G_2H_2G_1}\right).\end{aligned} \tag{A.10}$$

According to $0 < P_1{'}^*, P_2{'}^* < P_S$ and (A.7), one can see that P_S satisfies

$$\frac{H_1G_2 - H_2G_1}{H_1G_1H_2G_2} < P_S \le \frac{H_1G_1 - H_2G_2}{H_1G_1H_2G_2}. \tag{A.11}$$

In this interval, we can prove that (A.10) is a monotonically increasing function of P_S. So we substitute the lower bound of the interval $(H_1G_2 - H_2G_1)/H_1G_1H_2G_2$ into (A.10), and then derive that

$$\begin{aligned} & H_1G_1P_1^* + H_2G_2P_2^* + H_1G_1H_2G_2P_1^*P_2^* \\ & \quad - \left(H_1G_2P_1{'}^{*} + H_2G_1P_2{'}^{*} \right. \\ & \quad \left. + H_1G_2H_2G_1P_1{'}^{*}P_2{'}^{*} \right) \\ & \quad = \frac{2H_1 \left(H_1G_2 - H_2G_1\right)\left(G_1 - G_2\right)}{2H_1G_1H_2G_2} > 0, \end{aligned} \tag{A.12}$$

where inequality is obtained from the aforementioned condition $H_1G_2 - H_2G_1 > 0$ and $G_1 > G_2$.

Since (A.10) is a monotonically increasing function of P_S in the whole interval, (A.10) is always more than 0.

In summary, it is proved that, for all cases, (A.4) always holds. So, for two-subcarrier case, Lemma 1 is proved.

(b) Multisubcarrier Case ($N > 2$). The two-subcarrier case can be generalized to the multisubcarrier case. A proof by contradiction is adopted. For an N-subcarrier relay system with $N > 2$, suppose the optimal pairing does not follow the sorted pairing rule of Lemma 1, so there are at least two pairs of incoming and outgoing subcarriers that are mismatched according to their channel gains. Without loss of generality, it is assumed that there are two pairs (i_1, j_1) and (i_2, j_2) satisfying $|h_{i_1}|^2 > |h_{i_2}|^2, |g_{j_1}|^2 < |g_{j_2}|^2$. Using the result for $N = 2$, it is found that pairing subcarrier i_1 with subcarrier j_2 and pairing subcarrier i_2 with subcarrier j_1 can achieve a higher rate than the nonsorted pairings. Hence, by using this new pairing while maintaining the other subcarrier pairs invariant, the total achievable rate can be increased. This contradicts our assumption on the optimality of a nonsorted pairing scheme.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

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

Acknowledgments

This work was supported by the National Natural Science Foundation of China (no. 61602034), by the Beijing Natural Science Foundation (no. 4162049), and by the Young Talents Programme of State Grid Energy Research Institute Co., Ltd. (no. XM2018020035180), Key Technologies on Two-Path Cooperative Relay Transmission for Energy-Constrained Wireless Networks.

References

[1] H. T. Dinh, C. Lee, D. Niyato, and P. Wang, "A survey of mobile cloud computing: Architecture, applications, and approaches," *Wireless Communications and Mobile Computing*, vol. 13, no. 18, pp. 1587–1611, 2013.

[2] Y. Mao, C. You, J. Zhang, K. Huang, and K. B. Letaief, "A Survey on Mobile Edge Computing: The Communication Perspective," *IEEE Communications Surveys & Tutorials*, 2017.

[3] C. Huang, R. Lu, and K. R. Choo, "Vehicular Fog Computing: Architecture, Use Case, and Security and Forensic Challenges," *IEEE Communications Magazine*, vol. 55, no. 11, pp. 105–111, 2017.

[4] J. N. Laneman, D. N. C. Tse, and G. W. Wornell, "Cooperative diversity in wireless networks: efficient protocols and outage behavior," *IEEE Transactions on Information Theory*, vol. 50, no. 12, pp. 3062–3080, 2004.

[5] T. Wang, R. C. De Lamare, and A. Schmeink, "Alternating optimization algorithms for power adjustment and receive filter design in multihop wireless sensor networks," *IEEE Transactions on Vehicular Technology*, vol. 64, no. 1, pp. 173–184, 2015.

[6] W. Yu and R. Lui, "Dual methods for nonconvex spectrum optimization of multicarrier systems," *IEEE Transactions on Communications*, vol. 54, no. 7, pp. 1310–1322, 2006.

[7] T. Wang and L. Vandendorpe, "Sum rate maximized resource allocation in multiple DF relays aided OFDM transmission," *IEEE Journal on Selected Areas in Communications*, vol. 29, no. 8, pp. 1559–1571, 2011.

[8] N. Kumar, S. Sharma, and V. Bhatia, "Performance Analysis of OFDM-Based Nonlinear AF Multiple-Relay Systems," *IEEE Wireless Communications Letters*, vol. 6, no. 1, pp. 122–125, 2017.

[9] S. Jin, Z. Zhu, Y. Yang, M. Zhou, and X. Luo, "Alternate distributed allocation of time reuse patterns in Fog-enabled cooperative D2D networks," in *Proceedings of the 2017 IEEE Fog World Congress (FWC)*, pp. 1–6, Santa Clara, CA, October 2017.

[10] W. Zhang, Z. Zhang, and H. Chao, "Cooperative Fog Computing for Dealing with Big Data in the Internet of Vehicles: Architecture and Hierarchical Resource Management," *IEEE Communications Magazine*, vol. 55, no. 12, pp. 60–67, 2017.

[11] Y. Yu, J. Zhang, and K. B. Letaief, "Joint subcarrier and CPU time allocation for mobile edge computing," in *Proceedings of the 59th IEEE Global Communications Conference, GLOBECOM 2016*, USA, December 2016.

[12] M. Li, S. Yang, Z. Zhang, J. Ren, and G. Yu, "Joint subcarrier and power allocation for OFDMA based mobile edge computing system," in *Proceedings of the 2017 IEEE 28th Annual International Symposium on Personal, Indoor, and Mobile Radio Communications (PIMRC)*, pp. 1–6, Montreal, QC, October 2017.

[13] K. Xiong, B. Wang, and K. J. R. Liu, "Rate-Energy Region of SWIPT for MIMO Broadcasting under Nonlinear Energy Harvesting Model," *IEEE Communications Letters*, vol. 16, no. 8, pp. 5147–5161, 2017.

[14] L. R. Varshney, "Transporting information and energy simultaneously," in *Proceedings of the IEEE International Symposium on Information Theory (ISIT '08)*, pp. 1612–1616, IEEE, Toronto, Canada, July 2008.

[15] X. Di, K. Xiong, Y. Zhang, and Z. Qiu, "Simultaneous wireless information and power transfer in two-hop OFDM decode-and-forward relay networks," *KSII Transactions on Internet and Information Systems*, vol. 10, no. 1, pp. 152–167, 2016.

[16] X. Di, K. Xiong, P. Fan, and H.-C. Yang, "Simultaneous wireless information and power transfer in cooperative relay networks with rateless codes," *IEEE Transactions on Vehicular Technology*, vol. 66, no. 4, pp. 2981–2996, 2017.

[17] K. Huang and E. Larsson, "Simultaneous information and power transfer for broadband wireless systems," *IEEE Transactions on Signal Processing*, vol. 61, no. 23, pp. 5972–5986, 2013.

[18] W. Lu, Y. Gong, J. Wu, H. Peng, and J. Hua, "Simultaneous wireless information and power transfer based on joint subcarrier and power allocation in OFDM systems," *IEEE Access*, vol. 5, pp. 2763–2770, 2017.

[19] X. Zhou, R. Zhang, and C. K. Ho, "Wireless information and power transfer in multiuser OFDM systems," *IEEE Transactions on Wireless Communications*, vol. 13, no. 4, pp. 2282–2294, 2014.

[20] O. T. Demir and T. E. Tuncer, "Max–Min Fair Resource Allocation for SWIPT in Multi-Group Multicast OFDM Systems," *IEEE Communications Letters*, vol. 21, no. 11, pp. 2508–2511, 2017.

[21] K. Xiong, P. Fan, C. Zhang, and K. B. Letaief, "Wireless information and energy transfer for two-hop non-regenerative MIMO-OFDM relay networks," *IEEE Journal on Selected Areas in Communications*, vol. 33, no. 8, pp. 1595–1611, 2015.

[22] G. Huang and W. Tu, "Wireless Information and Energy Transfer in Nonregenerative OFDM AF Relay Systems," *Wireless Personal Communications*, vol. 94, no. 4, pp. 3131–3146, 2017.

[23] Y. Liu and X. Wang, "Information and Energy Cooperation in OFDM Relaying: Protocols and Optimization," *IEEE Transactions on Vehicular Technology*, vol. 65, no. 7, pp. 5088–5098, 2016.

[24] K. Xiong, C. Chen, G. Qu, P. Fan, and K. B. Letaief, "Group Cooperation with Optimal Resource Allocation in Wireless Powered Communication Networks," *IEEE Transactions on Wireless Communications*, vol. 16, no. 6, pp. 3840–3853, 2017.

[25] D. P. Palomar and J. R. Fonollosa, "Practical algorithms for a family of waterfilling solutions," *IEEE Transactions on Signal Processing*, vol. 53, no. 2, part 1, pp. 686–695, 2005.