Joint Resource Allocation Scheme for OFDM Wireless-Powered Cooperative Communication Networks

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Abstract

Energy harvesting techniques, particularly radio frequency energy harvesting (RF-EH) techniques, which are known to provide feasible solutions to enhance the performance of energy constrained wireless communication systems, have gained increasing attention. In this paper, we consider a wireless-powered cooperative communication network (WPCCN) for transferring energy in the downlink and forwarding signals in the uplink. The objective is to maximize the average transmission rate of the system, subject to the total network power constraint. We formulate such a problem as a form of wireless energy transmission based on resource allocation that searches for the joint subcarrier pairing and the time and power allocation, and this can be solved by using a dual approach. Simulation results show that the proposed joint optimal scheme can efficiently improve system performance with an increase in the number of subcarriers and relays.

Keywords: Wireless energy transmission, radio frequency energy harvesting, HTC protocol

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1. Introduction

Radio frequency energy harvesting (RF-EH) techniques are known to provide feasible solutions to enhance the performance of energy constrained wireless communication systems by improving the system average transmission rate, communication probability, and energy efficient [1-2]. Prior research on RF-EH were focused on achieving simultaneous wireless information and power transfer (SWIPT), which has been addressed in various scenarios [3-4]. Another related research focuses on a novel type of wireless network termed wireless powered communication network (WPCN), in which wireless terminals are powered only via wireless energy transmission (WET) and transmit data information using the harvested energy [5-7]. In [5], the energy transmission time and the information transfer time were jointly optimized to maximize the system average transmission rate. The authors in [6] investigated the energy-efficient resource allocation scheme for orthogonal frequency division multiple (OFDM) systems, which employs a different WPCN scenario in wireless communication networks. A multiple user WPCN, where terminals harvest energy from a power station and then transmit signals using the harvested energy to a receiving station, was studied in [7].

Cooperative communication techniques that can significantly boost system capacity and extend communication coverage have attracted enormous interests over the past few years due to their numerous advantages [8-9]. In practice, relay networks have been adopted to improve the performance of cellular networks, wireless sensor networks, and WLANs [9]. The authors in [10] presented a joint network selection and channel allocation optimization problem to minimize accumulated interference in 5G Heterogeneous Networks. A new type of wireless network named wireless powered cooperation communication network (WPCCN), which introduces the concept of cooperation in WPCN, was recently studied in [11-15].

Reference [11] proposed a novel cooperative mechanism for an energy harvesting cognitive radio scenario that allows secondary users to harvest energy from both ambient signals and the signals from primary users. By considering the secondary users as relays, the authors in [11] formulated an optimization problem to jointly allocate the power and energy harvesting time slot without considering the subcarrier pairing. Reference [12] considered a jointly optimal power and time allocation scheme for a three-node decode-and-forward (DF) half-duplex relaying network, where the source initially harvests the radio frequency (RF) energy from the relay, and then uses this energy to transmit information to the destination via the relay. By considering a hybrid relay and several energy transmission nodes, the authors in [13] proposed an energy cooperation protocol and a dual cooperation protocol to maximize the average transmission rate. The joint resource allocation scheme for the two protocols were formulated and resolved. An exact outage performance and the average transmission rate of two-way cognitive DF relaying wireless sensor networks were presented in [14]. The authors also provided practical insights into the impact of transceiver hardware impairments on network performance, such as the fundamental capacity ceiling of the network with various configurations and the transceiver selection strategy for the network nodes. In [15], the harvest-then-cooperate (HTC) protocol for WPCCN, which comprises of an energy harvesting node, a relay, and a hybrid access point (HAP), was presented. The HTC protocol allows for the relay of harvested energy from the energy source in the downlink and then works cooperatively in the uplink for the source’s information transmission. The authors deduced the approximate average transmission rate over Rayleigh fading channels with a closed-form expression for the presented protocol. Simulation results are then analyzed and compared with other popular relay selection strategies. It is be noted that the above-mentioned studies on energy transfer only focus on improving the average transmission rate of a single relay system [10-15], but few studies concentrate on multiple relay scenarios.

In this paper, we consider a WPCCN where multiple relays and one source node harvest energy from a hybrid access point (HAP) and then transmit signals using the harvested energy with the HTC protocol [15]. The HAP can broadcast energy to the source node and relay in the downlink and can also receive the signal from the source node and relay in the uplink. We formulate the system average transmission rate maximization problem for a multiple relay WPCCN with joint subcarrier pairing, power allocation, and time-slot assignment, subject to the total network power constraint. Moreover, the improved HTC protocol in our system is explicitly considered. We allow the source node to retransmit the same signal sent in the previous time slot on another subcarrier, and this can further improve the system performance. The proposed optimization problem is a mixed-integer nonlinear programming (MINLP) problem that is simplified by the introduction of the equivalent channel gain and is solved by using a dual method.

The main contributions of the work are summarized below:

- We proposed a new, improved HTC protocol in OFDM WPCCN by allowing the source node to retransmit the same signal sent in the third time slot on another subcarrier, further improving the system performance.
- Based on the improved HTC protocol, we deduce the equivalent channel gain for this energy harvesting relaying system, which simplifies the expression of the end-to-end transmission rate for further optimization.
- Adopting the equivalent channel gain, we aim to maximize the system average transmission rate with the strategy of joint subcarrier pairing, power allocation, and time-slot assignment by using the Lagrangian method and continuity relaxation processing.

This paper is organized as follows. In Section 2, the proposed system model and some basic assumptions are described. In Section 3, the problem is formulated and solved by the proposed algorithm. In Section 4, the performance is evaluated through extensive simulations and Section 5 concludes the paper.

2. System Model

2.1 System Model

As shown in **Fig. 1**, this work studies a two-hop multi-relay WPCCN with energy transfer in the downlink and cooperative information transmission in the uplink. The WPCCN consists of one HAP, one source node S, and K relays. The HAP has a constant power supply that guarantees reliable communication. The source node S and all relays, with no constant power supply, are equipped with rechargeable batteries. Applying the HTC protocol, the source node S and all relays can harvest energy that can be used by the HAP energy broadcast.

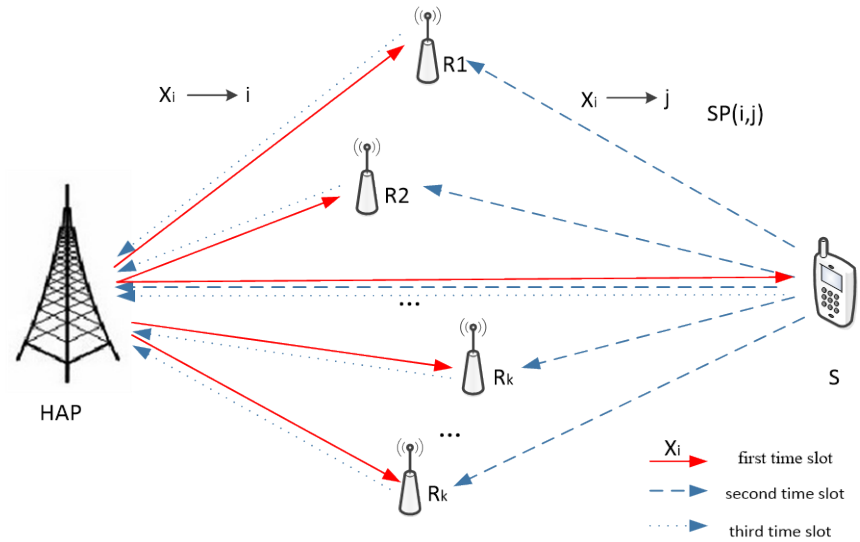

Fig. 1. System model for WPCCN with energy transfer in the DL and cooperative information transmission in the UL.

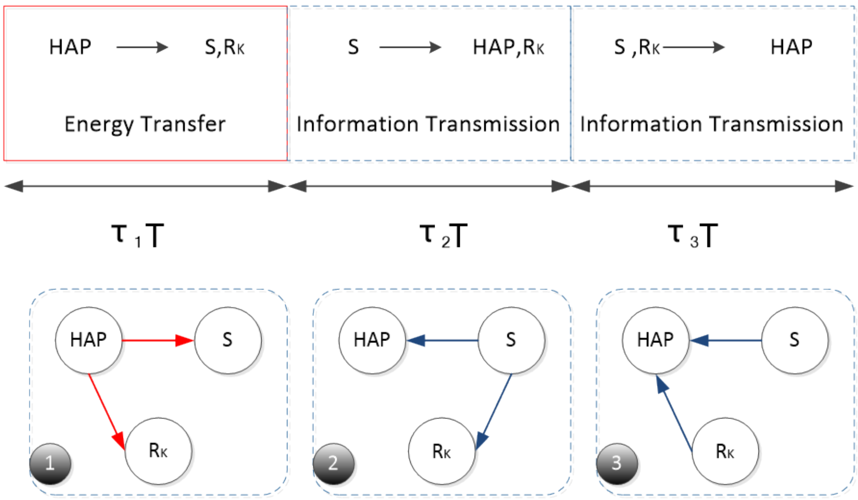

Fig. 2. The block diagrams for the improved HTC protocol proposed.

In the WPCCN, each relay operates in amplify forward (AF) half duplex mode and the whole transmission bandwidth is equally divided into N subcarriers. As shown in **Fig. 2**, different from traditional relay-based OFDM networking [16], for the presented improved HTC protocol in the scenario considered, the transmission process of each data block T is divided into three time slots. The three time slots are denoted as $\tau_1 T$, $\tau_2 T$, and $\tau_3 T$, such that $\tau_1 T+\tau_2 T+\tau_3 T=T$. To simplify the expression, we assume that $\tau_1=\tau$ and $\tau_2=\tau_3$. Thus the length of the second and the third time slot is $(1-\tau)T/2$. In the first time slot τT with $0<\tau<1$, the HAP broadcasts energy to the source node S, and all relays in the downlink. After the source node S and the relays harvest enough energy for the signal transmission in the succeeding two time slots, the first time slot is closed. The second and third time slot with equal lengths of $(1-\tau)T/2$ are allocated for cooperative signal transmission in the uplink. In the second time slot, S simultaneously broadcasts its signals to all relays and the HAP. In the third time slot, all relays forward the signals received in the second time slot to the HAP. Different from the

HTC protocol in [15], we allow S to retransmit the same signal sent in the previous time slot on another subcarrier, and this can further improve the system performance.

It is to be noted that the considered scenario is suited for both indoor and outdoor applications. For instance, for indoor applications, users would need information on the source node S, which can be represented as an intelligent terminal with a flexible position but an unstable power supply, while the HAP and relays can be represented as intelligent terminals with relatively fixed positions and a stable power supply. In addition, this system model is also an example of a wireless sensor network with cooperative energy transmission, where the HAP, the relays, and the source node are all considered wireless sensor nodes with or without stabilized power supply.

2.2 Improved HTC Protocol

In this paper, we adopt subscript-A for the HAP, subscript-S for the source node, and subscript- $R_k, k=1,2,...,K$ for each relay node. $h_{I,J}^{XY} \sim CN(0,\sigma_{Y(I,J)}^2)$ denote the channel power gain from X to Y on the I-th subcarrier in the J-th time slot with $X,Y \in \{A,S,R_k\}, k=1,2,...,K$ and $I \in \{1,2,...,N\}$, $J \in \{1,2,3\}$. $\sigma_{Y(I,J)}^2$ denote the AWGN at the destination Y on the I-th subcarrier in the J-th time slot, respectively [17]. P_A denote the transferring power of the HAP, which is large enough so that the harvested energy from the noise can be ignorable in the first time slot. Therefore, the harvested energy at the S, each relay, and total all terminals can be obtained as follow, which are as same as that in [5].

$$E_S = \eta \tau T P_A \sum_{i=1}^{N} h_{i,1}^{AS} \tag{1}$$

$$E_{R_k} = \eta \tau T P_A \sum_{i=1}^{N} h_{i,1}^{AR_k}, \forall k \quad k \in \{1,2,...,K\} \tag{2}$$

$$E_{EH} = \eta \tau T P_A \sum_{i=1}^{N} \left(h_{i,1}^{AS} + \sum_{k=1}^{K} h_{i,1}^{AR_k} \right) \tag{3}$$

where η is the efficiency of energy harvesting, such that $0<\eta<1$. Applying subcarrier-pair $SP_{i,j}$ based AF relay protocol, each relay receives the signal from S on i-th subcarrier in the second time slot, amplifies and forwards it on j-th subcarrier in the third time slot. We define a $N \times N$ decision matrix $\Phi_{NxN} = \{\phi_{i,j}\}$, where $\phi_{i,j}$ is the subcarrier pairing factor. $\phi_{i,j}=1$ implies that subcarrier i is paired with subcarrier j, and $\phi_{i,j}=0$ implies otherwise. Each subcarrier must pair with only one subcarrier, so $\phi_{i,j}$ would given by

$$\phi_{i,j} \in \{0,1\}, \forall i, j \tag{4}$$

$$\sum_{i=1}^{N} \phi_{i,j} = 1, \sum_{j=1}^{N} \phi_{i,j} = 1, \forall i, j \tag{5}$$

Thus, the received signal at the k-th relay and the HAP on i-th subcarrier in the second time slot, which denoted as $y_i^{R_k}$ and y_i^A, are given by

$$y_i^{R_k} = \sqrt{P_i^{S2}} h_{i,2}^{SR_k} x_i + n_{i,2}^{R_k} \quad \forall i,k \tag{6}$$

$$y_i^A = \sqrt{P_i^{S2}} h_{i,2}^{SA} x_i + n_{i,2}^A \quad \forall i \tag{7}$$

where P_i^{S2}, x_i, $n_{i,2}^A$ and $n_{i,2}^{R_k}$ denote the power assigned to the S, the transmission signal from the S to the HAP, the additive white Gaussian noise at the S and the k-th relay on the i-th subcarrier in the second time slot, respectively.

Different from [16], we jointly pair subcarriers and allocate power on different subcarriers and terminals, which satisfies the constrain conditions as follow

$$\sum_{i=1}^{N}\sum_{j=1}^{N}\left(P_i^{S2}+P_{i,j}^{S3}\right)\le P_S=\frac{\tau}{1-\tau}2\eta P_A\sum_{i=1}^{N}h_{i,1}^{AS} \tag{8}$$

$$\sum_{i=1}^{N}\sum_{j=1}^{N}\sum_{k=1}^{K}P_{i,j}^{R_k}\le\sum_{k=1}^{K}P_{R_k}=\frac{\tau}{1-\tau}2\eta P_A\sum_{k=1}^{K}\sum_{i=1}^{N}h_{i,1}^{AR_k} \tag{9}$$

where $P_{i,j}^{S3}$, $P_{i,j}^{R_k}$, P_S and P_{R_k} denote the power assigned to the S, the k-th relay on the j-th subcarrier, the total transmission power of the S and the k-th relay in the third time slot, respectively. According to (4-5), the sum power expending on subcarrier pair $SP_{i,j}$ in the second and the third time slot is denoted as $P_{i,j}$, which gives total power P_T constrain condition as follow

$$\sum_{i=1}^{N}\sum_{j=1}^{N}\phi_{i,j}P_{i,j}=P_S+\sum_{k=1}^{K}P_{R_k}\le P_T \tag{10}$$

In the third time slot, all relays consume the harvested energy to assist the S to forward information, which employs the same AF protocol as that in [17]. Different form the HTC protocol in [15], source node S will allow to send the same data information to the HAP again on the another subcarrier, and this can further improve the system performance. Thus, for the $SP_{i,j}$, the combination signal from the S and all the relays is received at the HAP and can be expressed by

$$y_{(i,j)}^{A}=\sqrt{P_{i,j}^{S3}}h_{j,3}^{SA}x_i+\sum_{k=1}^{K}h_{j,3}^{R_kA}\rho_{i,3}^{R_k}y_i^{R_k}+n_{j,3}^{A} \tag{11}$$

where $P_{i,j}^{S3}$, $\rho_{i,3}^{R_k}$ and $n_{j,3}^{A}$ denote the power allocated to the S on the $SP_{i,j}$, the k-th relay amplification factor on the $SP_{i,j}$ and the additive white Gaussian noise at the S on the j-th subcarrier in the third time slot, respectively.

$$\rho_{i,3}^{R_k}=\sqrt{P_{i,j}^{R_k}\Big/P_{i,2}^{S2}\,|\,h_{i,2}^{SR_k}\,|^2+\sigma_{R_k(i,2)}^2} \tag{12}$$

According to [18] and utilizing the above-mentioned improvement, the corresponding signal-to-noise ratios (SNRs) are denoted as SNR_i^{TS2} and $SNR_{(i,j)}^{TS3}$ in the second and the third time slot on the $SP_{i,j}$ in the information transmission phase, which can be expressed by

$$SNR_i^{TS2}=\left|h_{i,2}^{SA}\right|^2P_i^{S2}\Big/\sigma_{A(i,2)}^2 \tag{13}$$

$$SNR_{(i,j)}^{TS3}=\frac{\left(\sum_{k=1}^{K}\frac{\left|h_{i,2}^{SR_k}h_{j,3}^{R_kA}\right|\sqrt{P_i^{S2}P_{i,j}^{R_k}}}{\sqrt{P_i^{S2}\left|h_{i,2}^{SR_k}\right|^2+\sigma_{R_k(i,2)}^2}}+\left|h_{j,3}^{SA}\right|\sqrt{P_{i,j}^{S3}}\right)^2}{\sigma_{A(j,3)}^2+\sum_{k=1}^{K}\left(\frac{\left|h_{j,3}^{R_kA}\right|\sqrt{P_{i,j}^{R_k}}}{\sqrt{P_i^{S2}\left|h_{i,2}^{SR_k}\right|^2+\sigma_{R_k(i,2)}^2}}\right)^2\sigma_{R_k(i,2)}^2} \tag{14}$$

Finally, we adopt MRC to combine signals received from the three time slots and the end-to-end transmission rate on the $SP_{i,j}$ can be obtained as [19]

$$R_{(i,j)}=\frac{1-\tau}{2}\log(1+SNR_i^{TS2}+SNR_{(i,j)}^{TS3}) \tag{15}$$

3. Proposed Joint Resource Allocation Scheme

3.1 Problem Formulation

In this section, the joint resource allocation is concerned. We first formulate the optimization problem aimed at maximizing the total end-to-end transmission rate as

$$\textbf{P1}: \quad \max_{\tau, P_i^{S2}, P_{i,j}^{S3}, P_{i,j}^{R_k}, \phi_{i,j}} \sum_{i=1}^{N}\sum_{j=1}^{N} \phi_{i,j} R_{(i,j)} \qquad (16)$$
$$s.t. \quad (4), (5) \text{ and } (8-10).$$

The objective function in P1 is to maximize $\sum_{i=1}^{N}\sum_{j=1}^{N} \phi_{i,j} R_{(i,j)}$, where $R_{(i,j)}$ and $\phi_{i,j}$ are end-to-end transmission rate and subcarrier pairing factor on the subcarrier pair (i,j), respectively. Constraints (4-5) imply each subcarrier can be paired with only one subcarrier. Constraints (8-10) imply the transmission power restricted condition for source, relays and total power, respectively. Generally, (16) is a mixed-integer nonlinear programming (MINLP) problem which is computationally undesirable because of high computation complexity and can be solved by using the dual method [15]. In the following section, we will transfer the P1 to another form and solve it hierarchically.

Thus, we can denote the total power consumed on the $SP_{i,j}$ in the second time slot and in the third time slot as $P_{(i,j)}^{TS2}$ and $P_{(i,j)}^{TS3}$, respectively. We therefore have

$$P_{(i,j)}^{TS3} = P_{i,j}^{S3} + \sum_{k=1}^{K} P_{i,j}^{R_k}, \qquad P_{i,j}^{S3} \geq 0, P_{i,j}^{R_k} \geq 0 \qquad (17)$$

$$P_{(i,j)} = P_{(i,j)}^{TS2} + P_{(i,j)}^{TS3} \qquad (18)$$

where $P_{(i,j)}^{TS2} = P_i^{S2}$ for the convenience of understanding.

In order to acquire the power allocation in (17), we simplify (18) by means of taking the optimization problem correlated with $P_{(i,j)}$ and then to obtain the equivalent channel gain of systems, which will be help to assign subcarrier pairs in the succeeding sections. We define

$$P_{(i,j)}^{TS2} = \varepsilon_{(i,j)} P_{(i,j)}, \varepsilon_{(i,j)} \in (0,1] \qquad (19)$$

$$P_{(i,j)}^{TS3} = (1-\varepsilon_{(i,j)}) P_{(i,j)} \qquad (20)$$

where $\varepsilon_{(i,j)}$ denotes the ratio of $P_{(i,j)}^{TS2}$ to $P_{(i,j)}$, where 1-$\varepsilon_{(i,j)}$ denotes the ratio of $P_{(i,j)}^{TS3}$ to $P_{(i,j)}$. Particularly, $\varepsilon_{(i,j)} = 1$ implies that S transfers the information directly in the second time slot with the total power of $P_{(i,j)}$ because the direct link between S and HAP on i-th subcarrier is sensational.

For a given $P_{(i,j)}$, $\phi_{i,j}$ and τ, a joint resource allocation scheme for $P_{i,j}^{S3}$ and $P_{i,j}^{R_k}$ to maximize $R_{(i,j)}$ is proposed where the $P_{(i,j)}^{TS2}$ and $P_{(i,j)}^{TS3}$ can be easily obtained by golden section method to search a optimal $\varepsilon_{(i,j)}$. For a given $P_{(i,j)}^{TS2}$ and $P_{(i,j)}^{TS3}$, the SNR_i^{TS2} is determined according to (13). Hence, in order to maximize $R_{(i,j)}$ in (15), the optimization power allocation problem P1 is simplified as

$$\textbf{P2}: \quad \max_{\{P_{i,j}^{R_k}, P_{i,j}^{S3}\}} \sum_{i=1}^{N}\sum_{j=1}^{N} SNR_{(i,j)}^{TS3} \qquad s.t. \ (17) \qquad (21)$$

To solve the optimization problem P2, first, we rewrite the expression of $SNR_{(i,j)}^{TS3}$ in (21) as

$$SNR_{(i,j)}^{TS3}=\frac{P_i^{S2}}{N_0}\cdot\frac{\left(\sum_{k=1}^{K}\frac{\left|h_{i,2}^{SR_k}h_{j,3}^{R_kA}\right|\sqrt{P_{i,j}^{R_k}}}{\sqrt{P_i^{S2}\left|h_{i,2}^{SR_k}\right|^2+N_0}}+\left|h_{j,3}^{SA}\right|\sqrt{\frac{P_{i,j}^{S3}}{P_i^{S2}}}\right)^2}{1+\sum_{k=1}^{K}\frac{\left|h_{j,3}^{R_kA}\right|^2P_{i,j}^{R_K}}{P_i^{S2}\left|h_{i,2}^{SR_k}\right|^2+N_0}} \tag{22}$$

Applying the same approach proposed in [17] and for a given $P_{(i,j)}$, the optimization power allocation over the relays and the source node can be expressed as

$$P_{i,j}^{R_k}=\frac{\left|h_{i,2}^{SR_k}h_{j,3}^{R_kA}\right|^2\theta_{i,j}^k}{\left(\frac{\left|h_{j,3}^{R_kA}\right|^2}{P_i^{S2}}+\sum_{k=1}^{K}\frac{\left|h_{i,2}^{SR_k}h_{j,3}^{R_kA}\right|^2\theta_{i,j}^k}{(1+\theta_{i,j}^k\left|h_{j,3}^{R_kA}\right|^2P_{i,j}^{S3})^2}\right)\left(\frac{1}{\sqrt{P_{i,j}^{S3}}}+\theta_{i,j}^k\left|h_{j,3}^{R_kA}\right|^2\sqrt{P_{i,j}^{S3}}\right)^2} \tag{23}$$

$$P_{i,j}^{S3}=P_{(i,j)}^{TS3}\left|h_{j,3}^{SA}\right|^2\Bigg/\left(\left|h_{j,3}^{R_kA}\right|^2+\sum_{k=1}^{K}\frac{\left|h_{i,2}^{SR_k}h_{j,3}^{R_kA}\right|^2\theta_{i,j}^kP_i^{s1}}{(1+\theta_{i,j}^k\left|h_{j,3}^{R_kA}\right|^2P_{(i,j)}^{TS3})^2}\right) \tag{24}$$

where $\theta_{i,j}^k$ equal to $1\Big/(P_i^{S2}\left|h_{i,2}^{SR_k}\right|^2+N_0),k=1,2,\cdots\cdots K$. According to (23) and (24), which are all the function of $P_{(i,j)}$, we have

$$SNR_{(i,j)}\approx\alpha_{(i,j)}P_{(i,j)} \tag{25}$$

where $SNR_{(i,j)}$ denotes the signal noise ratio of the subcarrier pair (i,j), $\alpha_{(i,j)}$ denotes equivalent channel gain for a given $SP_{i,j}$,which simplifies the expression of the end-to-end transmission rate for further optimization, and can be expressed as [20]

$$\alpha_{(i,j)}=\frac{1}{N_0}[\left|h_{j,3}^{SA}\right|^2+\varepsilon_{(i,j)}(\left|h_{i,2}^{SA}\right|^2-\left|h_{j,3}^{SA}\right|^2)+\sum_{k=1}^{K}\frac{\varepsilon_{(i,j)}(1-\varepsilon_{(i,j)})\left|h_{i,2}^{SR_k}\right|^2\left|h_{j,3}^{R_kA}\right|^2}{\varepsilon_{(i,j)}\left|h_{i,2}^{SR_k}\right|^2+(1-\varepsilon_{(i,j)})\left|h_{j,3}^{R_kA}\right|^2}] \tag{26}$$

According to (26) and applying the golden section method in [20], the optimization $\varepsilon_{(i,j)}$ can be achieved. Then the optimization problem **P2** can be rewritten as

$$\mathbf{P3}:\quad\max_{P_{(i,j)},\phi_{i,j},\tau}\sum_{i=1}^{N}\sum_{j=1}^{N}\frac{1-\tau}{2}\phi_{i,j}\log(1+\alpha_{(i,j)}P_{(i,j)}) \tag{27}$$
$$s.t.\qquad (4),\ (5),\ \text{and}\ (10)$$

When number of subcarriers becomes large enough, the optimization problem (27) satisfies the time-sharing condition and the duality gap can be negligible.

3.2 Joint Resource Allocation Iterative Algorithm

After transforming optimization problem several times in last section, we adopt iterative algorithm to maximize system average transmission rate for a multiple relay WPCCN with jointly subcarrier pairing, power allocation and time-slot assignment subject to total network power constraint.

To be specific, applying a dual approach we can solve it to obtain asymptotically optimal solution [21]. The Lagrange dual problem (27) is expressed as

$$\begin{aligned} g(\mu,\lambda) = & \max_{P_{(i,j)},\phi_{i,j},\tau} \frac{1-\tau}{2}\sum_{i=1}^{N}\sum_{j=1}^{N}\phi_{i,j}\log(1+\alpha_{(i,j)}P_{(i,j)}) \\ & -\mu\left[\sum_{i=1}^{N}\sum_{j=1}^{N}\phi_{i,j}P_{(i,j)} - \frac{2\tau}{1-\tau}\eta P_A\sum_{i=1}^{N}(h_{i,1}^{AS}+\sum_{k=1}^{K}h_{i,1}^{AR_k})\right] \\ & -\lambda\left[\frac{2\tau}{1-\tau}\eta P_A\sum_{i=1}^{N}(h_{i,1}^{AS}+\sum_{k=1}^{K}h_{i,1}^{AR_k}) - P\right] \\ & s.t. \quad (4), (5), \text{and } (10) \end{aligned} \tag{28}$$

where $\mu \ge 0,\ \lambda \ge 0$ are dual variables. The optimal dual problem is given by

$$\min_{\mu,\lambda} g(\mu,\lambda) \quad s.t.\ u \ge 0, \lambda \ge 0. \tag{29}$$

For a given $SP_{i,j}$, let

$$\begin{aligned} L_{(i,j)} = & \frac{1-\tau}{2}\phi_{i,j}\log(1+\alpha_{(i,j)}P_{(i,j)}) \\ & -\mu\left[\phi_{i,j}P_{(i,j)} - \frac{2\tau}{1-\tau}\eta P_A\sum_{i=1}^{N}(h_{i,1}^{AS}+\sum_{k=1}^{K}h_{i,1}^{AR_k})\right] \\ & -\lambda\left[\frac{2\tau}{1-\tau}\eta P_A\sum_{i=1}^{N}(h_{i,1}^{AS}+\sum_{k=1}^{K}h_{i,1}^{AR_k}) - P\right] \end{aligned} \tag{30}$$

Obviously, $L_{(i,j)}$ is a concave of $P_{(i,j)}$. Thus, for the problem of maximizing (28), while subjecting to $P_{(i,j)} \ge 0$ and using Karush-Kuhn-Tucher conditions, we can acquire

$$P_{(i,j)} = \left(\frac{1-\tau}{2\mu} - \frac{1}{\alpha_{(i,j)}}\right)^{+} \tag{31}$$

$$\tau = 1 - \sqrt{4(\mu-\lambda)\eta P_A\sum_{i=1}^{N}(h_{i,1}^{AS}+\sum_{k=1}^{K}h_{i,1}^{AR_k}) \Big/ \sum_{i}\sum_{j}\phi_{i,j}\log\left(1+\alpha_{(i,j)}P_{(i,j)}\right)} \tag{32}$$

where $x^{+} = \max(0,x)$. Substituting (31) and (32) into (28), the dual function with alternative expression can be given by

$$\begin{aligned} g(\mu,\lambda) = & \max_{\alpha_{(i,j)}} \sum_{i=1}^{N}\sum_{j=1}^{N}\alpha_{(i,j)}L_{(i,j)}^{*} + \frac{2\mu\tau}{1-\tau}\eta P_A\sum_{i=1}^{N}(h_{i,1}^{AS}+\sum_{k=1}^{K}h_{i,1}^{AR_k}) \\ & -\lambda\left[\frac{2\tau}{1-\tau}\eta P_A\sum_{i=1}^{N}(h_{i,1}^{AS}+\sum_{k=1}^{K}h_{i,1}^{AR_k}) - P\right] \end{aligned} \tag{33}$$

where

$$L_{(i,j)}^{*} = \frac{1-\tau}{2}\log\left(\frac{(1-\tau)\alpha_{(i,j)}}{2\mu}\right)^{+} - \mu\left(\frac{1-\tau}{2\mu} - \frac{1}{\alpha_{(i,j)}}\right)^{+} \tag{34}$$

$L_{(i,j)}^{*}$ is an $N \times N$ matrix, which is the matrix of subcarrier pairing, and can be settled by standard Hungarian method [22].

Applying the subgradient method, we can gain the Lagrange dual function $g(\mu,\lambda)$ for a given value of Lagrange multipliers μ and λ. The subgradient-update equations of μ and λ are given by

$$\mu(n+1) = \left[\mu(n) - \beta_{\mu}(n)\left(\sum_{i=1}^{N}\sum_{j=1}^{N}\frac{t_{(i,j)}}{2}\log(1+\gamma_{(i,j)}P_{(i,j)}) - R_{req}\right)\right]^{+} \tag{35}$$

$$\lambda(n+1) = \left[\lambda(n) - \beta_{\lambda}(n)\left(P_{max} - \sum_{i=1}^{N}\sum_{j=1}^{N}t_{(i,j)}P_{(i,j)}\right)\right]^{+} \tag{36}$$

where n, $\beta_{\mu}(n)$ and $\beta_{\lambda}(n)$ denote the iteration index, the positive diminishing step sizes of the n^{th} inner iteration for the dual variables $\boldsymbol{\lambda}$ and $\boldsymbol{\mu}$, respectively. The subgradient method above guarantee the optimal dual variables is achieved if the step sizes are chosen following the diminishing step size policy [21].

The proposed joint resource allocation algorithm can be described in the **Table 1** as follow. We first initialize maximum outer loops $M_{\max}$, dual variables $\boldsymbol{\lambda}$ and $\boldsymbol{\mu}$, set iteration index $m=0$, and then start to repeat outer loop until the m reach the $M_{\max}$. In every outer loop, the maximum inner loops $N_{\max}$, τ and iteration index n are installed. We adopt golden section method to compute $\alpha_{(i,j)}$ according to the formula (26) and then begin to repeat inner loop. In every inner loop, we use Hungarian method to compute $\phi_{i,j}$ and update τ and n until convergence or $n=N_{\max}$. When every inner loop is ended, we compute $P_{(i,j)}$ and update the $\boldsymbol{\lambda}$ and $\boldsymbol{\mu}$ with subgradient method in the outer loop. After the end of the outer loop, the best value of P_i^{S2}, $P_{i,j}^{S3}$ and $P_{i,j}^{R_k}$ are achieved.

The computation complexities of the proposed joint subcarrier pairing, time and power allocation strategy is $O\left(N^3+N^2K\right)$, which implies that our proposed joint resource allocation scheme can be carried out in polynomial time. Since N is much larger than K in practical scenarios, the computation complexity is mainly depended on the Hungarian method, whose complexity is $O\left(N^3\right)$.

Table 1. The Joint Resource Allocation Iterative Algorithm

Algorithm 1
1: Initialize maximum outer loops $M_{\max}$, $\boldsymbol{\lambda}$, $\boldsymbol{\mu}$ and set iteration index $m=0$;
2: **repeat** outer loop
3: Initialize maximum inner loops $N_{\max}$, τ and set iteration index $n=0$;
4: Compute $\alpha_{(i,j)}$ according to (26) with $\varepsilon_{(i,j)}$ using golden section method;
5: **repeat** inner loop
6: Compute $\phi_{i,j}$ according to (34) and using Hungarian method;
7: Update τ according to (31)- (32);
8: Update iteration index n by $n=n+1$;
9: **until** convergence or $n=N_{\max}$;
10: Compute $P_{(i,j)}$ according to (31) with τ and $\alpha_{(i,j)}$;
11: Update $\boldsymbol{\lambda}$ and $\boldsymbol{\mu}$ with τ, $P_{(i,j)}$, $\alpha_{(i,j)}$ and using subgradient method according to (35)- (36);
12: Update iteration index m by $m=m+1$;
13: **until** convergence or $m=M_{\max}$;
14: Compute P_i^{S2}, $P_{i,j}^{S3}$ and $P_{i,j}^{R_k}$ according to (10) and (23)-(24);
15: Algorithm ends.

4. Simulation Results and Analysis

In this section, we present some simulation results to evaluate the performance of the proposed joint resource allocation that includes the schemes in [11], [17], [15], and [20]. For simplicity, we assume that the instantaneous channel power gain $h_{i,1}^{AS}, h_{i,2}^{SA}, h_{i,3}^{SA} \sim CN(0,1/8)$ and $h_{i,1}^{AR_k}, h_{i,2}^{SR_k}, h_{i,3}^{R_kA} \sim CN(0,1)$ remain constant in the three time slots of the improved HTC protocol cycle. The variances of additional white Gaussian noise at the k-th relay and the HAP are $\sigma_{S(i)}^2 = \sigma_{R_k(i)}^2 = \sigma_{A(i)}^2 = N_0 = -110dBm$. The energy harvesting efficiency $\eta = 0.5$ is of the same value as that of the setting in reference [15]. At present, the RF energy harvesting scenario is only suitable for short-haul indoor communications. In our HTC protocol, which is the same as that in [15], the energy harvesting time slot is long enough such that enough energy has been harvested to cooperatively forward the signal in the later time slots. Because we adopt the subcarrier pairing strategy which assigns one subcarrier pair to S and one of the relays in order to achieve better system performance, the parameters will be set as $K < N$ in the simulation figures.

We first compare the average transmission rate of various schemes when P_A increases with $K = 5,\ N = 30$ as shown in **Fig. 3** and with $K = 10,\ N = 40$ as shown in **Fig. 4**. In both **Fig. 3** and **Fig. 4**, our proposed scheme provides better spectral performance compared with other schemes with the increase of P_A and a constant number of relays and subcarriers. Because of joint subcarrier pairing, time and power allocation strategy, the resource allocation scheme we proposed has the highest average transmission rate than all other related work.

It can be seen from **Fig. 3** that when $P_A = 30dBm$, our scheme can obtain about 0.54 dB , 0.76 dB, 1.7 dB, and 2.0 dB gain compared with the schemes proposed in [11],[17],[15] and [20], respectively. Compared with the joint subcarrier pairing, time and power allocation scheme that we proposed, [20] only considered the joint subcarrier pairing and power allocation strategy without considering time allocation, and this led to reduced performance compared with our scheme. The joint resource allocation scheme in [11], which addressed the power allocation and energy harvesting time assignment without subcarrier pairing, offers an even worse performance compared with [20]. [15] with an equal power allocation strategy offers the worst system performance than the other schemes when $P_A \le 25dBm$, but it offers better performance than [17], in which one subcarrier pair can be allocated to only one relay when $P_A > 25dBm$.

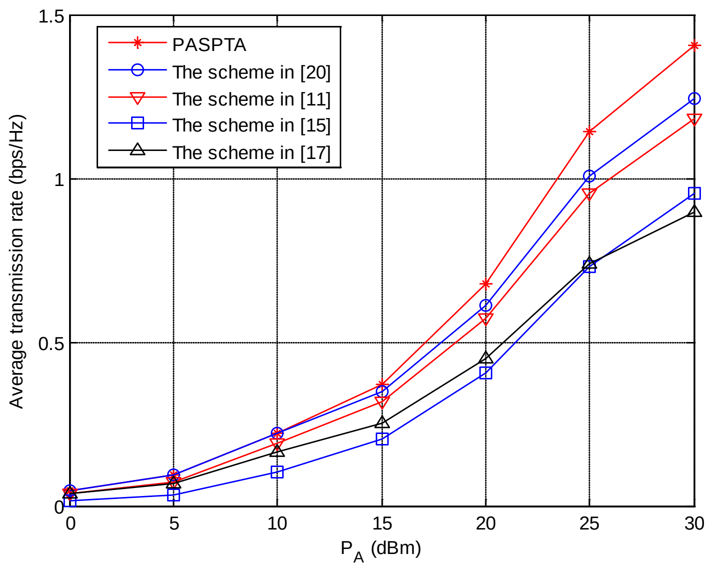

Fig. 3. Average transmission rate versus P_A when $K=5,\ N=30$.

In addition, in **Fig. 4**, we can see that the proposed joint subcarrier pairing, time and power allocation scheme has the best average transmission rate than the other resource allocation schemes. Compared with **Fig. 3**, the joint resource allocation strategy offers better system performance because more number of relays and subcarriers can be assigned. Particularly in the high SNR regime when $P_A = 30dBm$, our scheme can obtain about 0.77 dB , 0.84 dB, 1.8 dB, and 2.2 dB gain compared with the schemes proposed in [11],[17],[15] and [20], respectively.

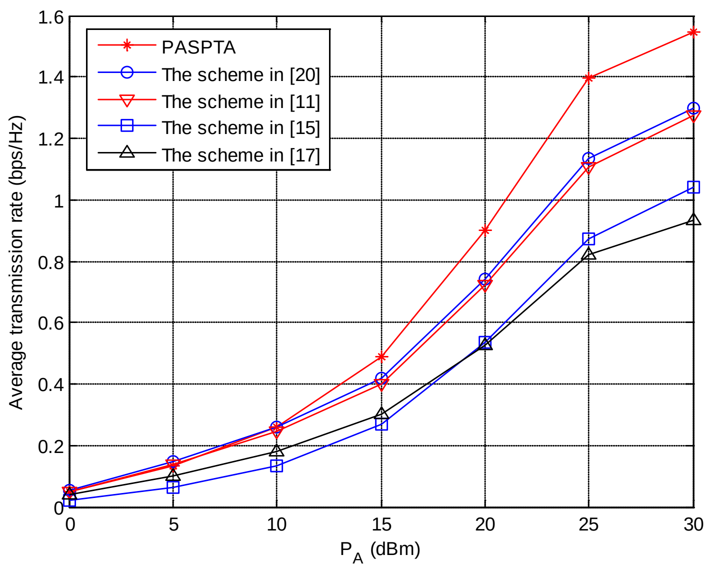

Fig. 4. Average transmission rate versus P_A when $K=10,\ N=40$.

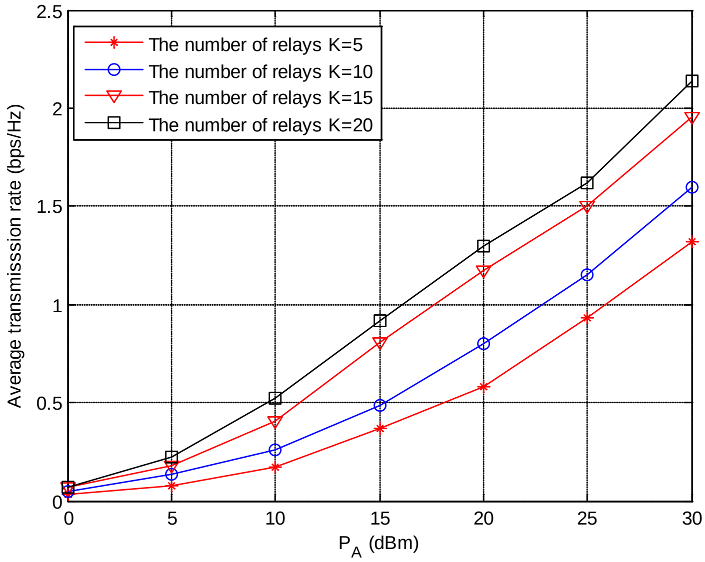

Fig. 5. Average transmission rate versus P_A with different of K when $N = 40$.

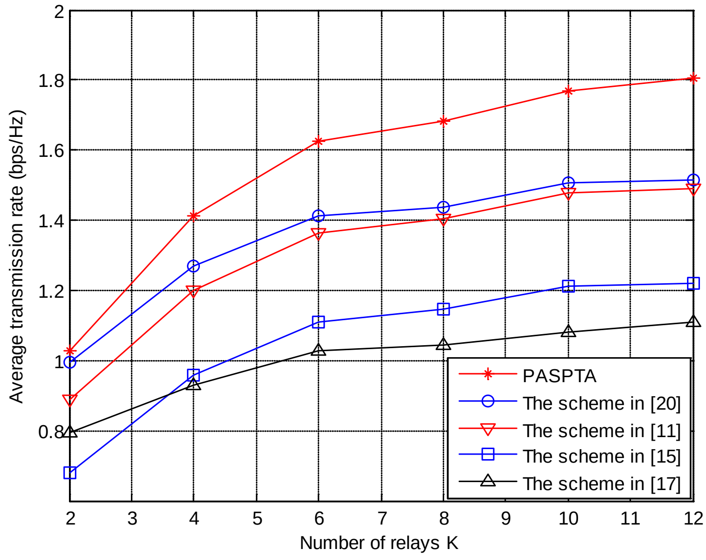

Fig. 6. Average transmission rate rate versus numbers of relays K when $P_A = 30dBm,\ N = 30$.

From another point of view, it is shown in **Fig. 5** that the average transmission rate of the joint resource allocation scheme we proposed increases with different number of relays. Compared with $K = 5$ and $K = 10$, the system performance with $K = 15$ is outstandingly enhanced when the number of subcarriers is settled at $N = 40$ and the P_A increases. The strategy with $K = 20$ has the biggest average transmission rate at the cost of the highest computational complexity.

It is observed from **Fig. 6** that the average transmission rate of different methods are contrasted with the increase in the number of the relays K when $P_A = 30dBm,\ N = 30$.The performance of the proposed method compared with other methods is shown in the figure when the number of relays increase. Particularly in [17], which offers the worst performance than the other resource allocation schemes when $K \geq 4$, one subcarrier pair can be allocated to only one relay. [15] with an equal power allocation scheme offers a worse performance than [17] when $K < 4$, but increases rapidly as more relays are available. [20] offers a better performance than [11], which has the third-best performance.

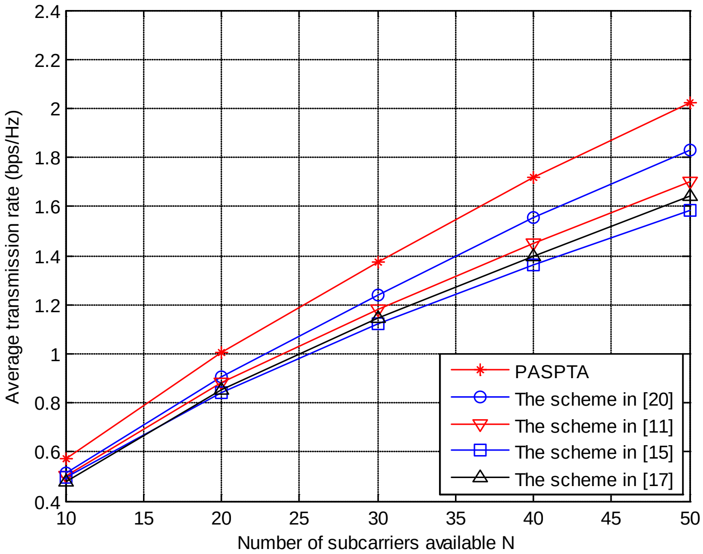

Fig. 7. Average transmission rate rate versus numbers of subcarriers available N when $P_A = 30dBm,\ K = 5$.

Fig. 7 shows the channel performance of the proposed joint resource allocation scheme compared with other methods where $P_A = 30dBm,\ K = 5$. Obviously, the average transmission rate of different methods increases with the increase in the number of subcarriers. Particularly, our scheme offers the best performance due to the new HTC protocol and the joint subcarrier pairing, time and power allocation scheme. Successively, [20] and [11] offer a much worse performance. With the number of increasing relays, [17] has the worst performance compared with the other schemes.

5. Conclusion

In this paper, we considered a WPCCN where multiple relays and one source node harvest energy from a HAP and then transmit signals using the harvested energy with the HTC protocol. We proposed a new improved HTC protocol in OFDM WPCCN by allowing the source node to retransmit the same signal sent in the third time slot on another subcarrier; thus, further improving system performance. Based on the improved HTC protocol, we deduced the equivalent channel gain for the energy harvesting relaying which simplifies the expression of the end-to-end transmission rate for further optimization. We formulated the system average transmission rate maximization problem for a multiple relay WPCCN with joint subcarrier pairing, power allocation, and time-slot assignment, subject to total network power constraint. Moreover, the improved HTC protocol was explicitly considered in our system. The optimization problem proposed was a MINLP problem, which was simplified by introducing the equivalent channel gain and solved by using a dual method.

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