r-RADAR: Obtain the Maximum Throughput When an Energy Harvesting Relay Node is Applied in Multiuser OFDMA Networks

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Abstract —The joint resource allocation for multiuser Orthogonal Frequency Division Multiple Access (OFDMA) relay networks is studied in the paper, where the relay node has renewable energy supplies and can be driven by energy collected from Radio Frequency (RF) signals from the source node. The relay node with green energy supplies uses Power Splitting (PS) scheme for Simultaneous of Wireless Information and Power Transfer (SWIPT). The joint resource allocation problem is formulated to maximize the throughput under several constraints including subcarrier pairing, power splitting ratio, power allocation, and subcarrier pairing allocation while satisfying data rate requirements for multiuser OFDMA relay networks. Due to the specialized problem is non-convex and difficult to be solved in finite polynomial time, a reconfigurable resource allocation by using the decoupling approach in a framework of repetitive (r-RADAR) algorithm with low computational complexity is proposed in the paper, which takes advantage of the unique problem structure and reduce the domain of search space. The global optimality is theoretically proven and well obtained when we using r-RADAR algorithm. Simulation results further validate the better performances of our proposed r-RADAR algorithm when it is compared to the other two related benchmark algorithms.

Index Terms—Energy Harvesting (EH), Simultaneous Wireless Information and Power Transfer (SWIPT), Orthogonal Frequency Division Multiple Access (OFDMA), resource allocation, Power Splitting (PS)

I. Introduction

A. Motivation and Related Work

With green communications gradually coming into reality, Energy Harvesting (EH) by actually transforming the Radio Frequency (RF) signals into available energy is arising as innovative explorations for intelligent terminals, which are capable of harvesting energy from their local environment, and also has been regarded as a promising approach to prolong the lifetimes of energy constrained wireless communication networks such as wireless sensor networks, cognitive radio networks and other ad hoc networks [1]-[3]. Since RF signal is usually used as the transmission medium to transfer both information and energy, one feasible research direction is to jointly investigate that how to disclose internal relationships in a wireless networking system that achieves Simultaneous of Wireless Information and Power Transfer (SWIPT) [2]. The performances of SWIPT networking system were studied in some works [4], [5], which assume that the receiver is able to simultaneously decode information and harvest energy via the received RF signal. However, as explained in [6], this may be impractical in applications because the hardware that supporting EH technology is not yet able to decode the information [7]. In practice, two major schemes i.e., Time Switching (TS) and Power Splitting (PS) are studied and have been widely accepted as approaches to achieve SWIPT. For that, TS scheme help receiver be switched between operation status i.e., decoding information and harvesting energy, while PS scheme can split the harvested signal energy for using in both decoding information and ongoing energy storage. These schemes were firstly proposed by Zhou *et al.* in general wireless networks [8]. Then they were further extended to relay networks [9]-[11].

In conventional cooperative relay networks, the relay node has limited energies and is reluctant to consume its precious resources on helping the source node relay information. When EH technology is introduced, the relay node can gain energy and do not need to protect itself from energy depletion in cooperative communication. Thus, EH technology in such networks is particularly important as it can enable information relaying [9]. In [9], EH technology was developed in a simple relay network with only three nodes by considering the AF (amplify-and-forward) relay strategy and the outage probability that is modulated with the ergodic capacity. The work in [10] was improved on the basis of [9], and it considers an adaptive TS scheme for SWIPT relay networks and the analytical expressions of

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the achievable throughput derived in both AF and DF (decode-and-forward) relay networks. However, it is notable that the TS scheme cannot achieve wireless information and power transfer simultaneously authentically. In [11], the SWIPT was considered with spatially random relays in a cooperative network, where performance metrics such as outage probability and diversity gain are given by using stochastic geometry. However, all those works mentioned above try to demonstrate SWIPT in relay networks using for single user with single carrier.

When wireless relay networks with multiple carriers are considered, Orthogonal Frequency Division Multiple Access (OFDMA) has been widely accepted as the air interface in high speed wireless relay communication networks. Moreover, it can facilitate multiplexing of users' data and make use of diversity to achieve better performances in multiuser networks [12]. In OFDMA-based SWIPT relay networks, RF signals used as carriers will impose research challenges in domains of wireless information and power transfer. The authors in [13] developed a power allocation algorithm with known EH parameters in cooperative communications. However, when parameters related to EH were unknown and discussed in [14], a prototype of SWIPT was modeled and tested in single user networks by using both TS and PS scheme. As to cooperative relaying with multiple frequency carriers, the relay node can process the receiving and transmitting signals adaptively by using the channel diversity, i.e., subcarrier pairing, which is mainly addressed in Medium Access Control (MAC) layer in domain of frequency. Thus, the authors in [15] considered a joint optimization problem that incorporates with power allocation, EH parameters and subcarrier pairing in an AF relay network. However, they did not take into account the network scalability and just simplify relay networks as a single user network. Moreover, it is important to point out that, according to the results in [16], AF scheme may induce high peak power and lead to more energy consumption. As an alternative to AF scheme, DF scheme is more practical for those devices with limited energy supplies. To meet the requirement on increasingly higher throughput, data rate allocation for each user in multiuser OFDMA relay networks considering differential services for SWIPT is considered. The authors in [17] proposed a resource allocation algorithm assuming that the pattern of subcarrier pairing allocation is unvaried, neglecting data multiplexing of different users on different subcarriers formulated in problem formulation. Thus the proposal in [17] did not make full use of the spectrum efficiency and also do not consider different data rate requirements for multiple users. Additionally, in order to facilitate obtaining the optimal solutions, the authors in [18] maximized the sum harvested power in multiuser OFDMA networks without no participant of relay node and formulated a joint design problem of the subcarrier pairing allocation and EH parameters for PS scheme while satisfying the data rate requirement for differential services. However, the proposal in both [17] and [18] cannot be directly transplanted to relay networks due to their distinguished network topologies.

B. Contributions

In this paper, we consider multiuser relaying scenario, where a source node transfers a portion of its energy to a Decode-and-Forward (DF) relay node in return for its assistance in information transmission using OFDMA. The main contributions and results of this paper are summarized as follows:

- Unlike the relay behavior in other papers, the relay used here is not an energy-selfish node that is unwilling to dissipate its own energy. Even the relay in the paper is a passive device without energy supply, but it can generate and store energy using RF signals from source node. Moreover, SWIPT in multiuser OFDMA relay networks has not yet received much attention and also not been further studied. By making full use of the architecture of multiuser OFDMA relay networks, the arising SWIPT techniques can be further configured and improved by developing efficient resource allocation algorithm, which motivates our joint resource optimization.
- For the PS protocol, it is more suitable to SWIPT. A DF relay strategy is used in multiuser OFDMA networks by incorporating SWIPT. For that, a joint resource allocation problem that maximizes the throughput is formulated by considering subcarrier pairing, power splitting ratio, power allocation, and subcarrier pairing allocation and meeting the data rate requirement for differential services. The formulated problem that integrates resource allocation with three-dimensional allocation is non-convex integer nonlinear optimization. The reconfigurable resource allocation by using the decoupling approach in a framework of repetitive (r-RADAR) algorithm according to the problem characteristics is proposed and used to solve the original NP-hard problem. The global optimality of the proposed r-RADAR algorithm is proved and obtained in the paper. Simulation results further validate performances of our proposed r-RADAR algorithm are better than those of its counterparts i.e., the other two related benchmark algorithms.

C. Organization

The remainder of this paper is organized as follows. Section II gives problem formulation in which energy harvesting relay transmission are described and realized with DF transmission strategy. Our proposed r-RADAR algorithm and its global optimality are analyzed and proved in Section III. Section IV studies the computational complexity. Simulation results and performance evaluations are given in Section V. Section VI concludes the paper and points out future research direction. To simplify the expressions, we summarize some commonly used symbols throughout the paper in Table I.

TABLE I: THE NOTATIONS DEFINED IN THE PAPER

Property	Notations	Representation
Network Model parameter	M	The set of users in the networks
	N	The set of subcarriers in the networks
	B	Total network bandwidth
	T	Block time of transmission
Channel State Information	$h_{s,r}^{i}$	Channel gain on SR fwd link over ith subcarrier
	$g_{r,m}^{j}$	Channel gain on RD fwd link over jth subcarrier
	$z_{r,a}^{2}$	AWGN at receiving antenna of relay node
	$z_{r,c}^{2}$	AWGN introduced by the RF band to baseband signal conversion
	z_{m}^{2}	AWGN at receiving antenna of user m
Power Control parameter	$P_{s,m}^{i}$	Available transmit power at source node over ith subcarrier
	$P_{r,m}^{j}$	Available transmit power at relay node over jth subcarrier
	P_{tot}	Total available transmission power at source node
EH parameter	$E_{s,r}^{i}$	Harvested energy at relay node over ith subcarrier from source node
	ρ_{m}^{i}	Power splitting factor at relay node over ith subcarrier for user m
	η	Energy conversion efficiency
Channel scheduling parameter	$SP(i,j)$	A feasible paired subcarriers grouped the ith subcarrier on SR fwd link with jth subcarrier on RD fwd link
channel scheduling parameter	$\chi_{i,j}$	Subcarrier pairing indictor whether an optimal $SP(i,j)^{*}$ is formed
	$\pi_{(i,j,m)}$	Subcarrier pairing allocation indictor whether a $SP(i,j)$ allocated to user m
	$\pi_{m}^{i,j}$	Subcarrier pairing allocation indictor whether an optimal $SP(i,j)^{*}$ allocated to user m
Data rate parameter	$R_{(s,i,j,m)}$	Data rate from source node to user m with a $SP(i,j)$
	R_{m}	Data rate for available paired subcarriers allocated to user m
	Q_{m}	Threshold value of meeting data rate requirement for user m
	$R_{s,m}^{i,j}$	Data rate from source node to user m with an optimal $SP(i,j)^{*}$
Mathematical operators	λ	Lagrange multiplier associated with the source power constraint
	$\boldsymbol{\mu}$	Matrix of the Lagrange multiplier associated with the data rate requirement of each user
	δ	Step size associated with the source power constraint

II. ENERGY HARVESTING RELAY TRANSMISSIONS AND PROBLEM FORMULATION

Consider a two-hop OFDMA relay networks, source node transmits data to M users denoted by m, which is $m \in \mathcal{M} \triangleq \{1,2,\cdots,M\}$, and at the same time, users have requirements on data rate for service differentiation. Due to long transmission distance, users are usually positioned outside the communication range of source node. Also, there are unavoidable shielding effects always caused by some barriers between them. As a result, all data transmitted by source node should be first forwarded by a relay node, which are capable of harvesting energy by sensing the wireless channels and maintaining their continuous operation. Such a relaying model, also well-known as the Type-II relaying in IEEE and 3GPP standards [14], has been widely adopted and used to extend the communication coverage. Different from the selfness of previous generation relay node appeared i.e., unwilling to deplete its own energy on helping source node forward data, the self-sufficient relay node is now given capability of energy harvesting, which support it forwarding signals to M users regardless of energy cost. The total bandwidth B is equally divided into N orthogonal subcarriers. Let N be the set of all subcarriers, that is, $\mathcal{N} \triangleq \{1,2,\cdots N\}$. According to the analysis given ahead, relay node uses DF strategy to join the cooperative communication. The block time T is separated into two time slots and they have the same length of time. Time span of the first time slot accommodates instructions such as wireless data transmission from source node to relay node on forward link (SR fwd link), signal sensing and energy harvesting, as well as energy conversion etc, could all be done at relay node. The second time slot includes baseband signal processing and data transmission from relay node to destination on forward link (RD fwd link). The DF transmission strategy with EH relay in a framework of SWIPT by introducing PS scheme is shown in Fig. 1, which will be further explained in the following.

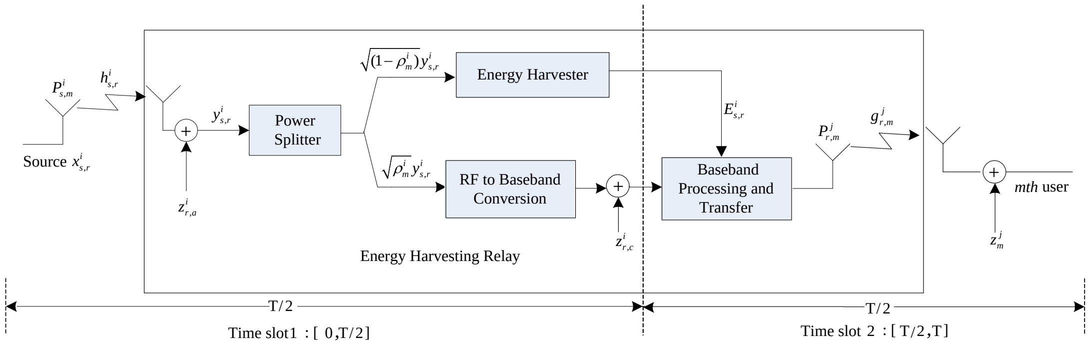


Fig. 1. DF transmission strategy with energy harvesting relay by using PS scheme

Within the first time slot $[0,T/2]$, source node transmit signal to relay node. And the received RF signal strength at relay node can be calculated as Eq. (1).

$$y^i_{s,r}(t)=\sqrt{P^i_{s,m}}h^i_{s,r}x^i_{s,r}(t)+z^i_{r,a}(t), \qquad \forall i\in\mathcal{N} \tag{1}$$

where the superscript i marked in all variables of Eq. (1) indicates that their definitions are confined to the *ith* subcarrier. $x^i_{s,r}$ is the normalized amplitude of source node signal, i.e., $\mathbb{E}\{|x^i_{s,r}(t)|^2\}=1$, where $\mathbb{E}\{\cdot\}$ is the mathematical expectation and $|\cdot|$ represents the absolute value of operator. $h^i_{s,r}$ and $P^i_{s,m}$ represent channel gain on the SR fwd link over the *ith* subcarrier and the transmission power used by source node to communicate with user m over the *ith* subcarrier, respectively. $z^i_{r,a}$ represents the additive white Gaussian noise (AWGN) with zero mean and variance $\sigma^2_{r,a}$, which is related to the antenna types and parameters.

Subsequently, in order to efficiently use the collected renewable energy, relay node separates the transformed energy into two parts, i.e., the power used for information processing and the remainder is used for relay node forwarding source data to M users. Power splitting ratio is thus ρ^i_m introduced [8], by which $\rho^i_m P^i_{s,m}$ denote the proportion of total source power that is used for information processing. Then $(1-\rho^i_m)P^i_{s,m}$ is the remainder power and used to sustain the operation of energy harvester. It is obvious that power splitting ratio ρ^i_m should meet the constraint shown as Eq. (2).

$$0\le\rho^i_m\le 1,\ \rho^i_m\ge 0, \qquad \forall i\in\mathcal{N},\ \forall m\in\mathcal{M} \tag{2}$$

The energy harvester transforms electromagnetic waves into rechargeable energy and supplies energy to circuitry while maintain the operating conditions. The harvested energy at relay node over the *ith* subcarrier from source node is expressed as following Eq. (3).

$$E^i_{s,r}=\frac{T}{2}\eta(1-\rho^i_m)\left|h^i_{s,r}\right|^2 P^i_{s,m}, \quad \forall i\in\mathcal{N},\ \forall m\in\mathcal{M} \tag{3}$$

where $\eta\ (0\le\eta\le 1)$ denotes the energy conversion efficiency that is affected by the rectification process and the efficiency of energy harvesting circuitry.

The information processor embedded in relay node can down convert the high frequency RF signal to baseband and then further process the down converted baseband signal. After down conversion, the sampled baseband signal strength $y^i_{s,r}(k)$ at relay node can be given by Eq. (4)

$$y^i_{s,r}(k)=\sqrt{\rho^i_m P^i_{s,m}}h^i_{s,r}x^i_{s,r}(k)+\sqrt{\rho^i_m}z^i_{r,a}(k)+z^i_{r,c}(k), \quad \forall i\in\mathcal{N},\ \forall m\in\mathcal{M} \tag{4}$$

where k denotes the symbol index, $x^i_{s,r}(k)$ is the sampled and normalized signal from source node and $z^i_{r,c}(k)$ is the sampled AWGN with zero mean and variance $\sigma^2_{r,c}$ caused by the imported noises as RF band being converted to baseband signal. In practice, the antenna noise $z^i_{r,a}$ has trivial effects on the data receiving and energy harvester, because $\sigma^2_{r,a}$ is generally much more less than the noise power introduced by the baseband processing circuit, and it is even much lower than the average power of the received signal [19]. For simplicity, we ignore the noise term i.e., by setting $\sigma^2_{r,a}=0$ in the following analysis [19].

In the second time slot $[T/2,T]$, with the harvested energy for information processing, the information processor can decode the baseband signal over the *ith* subcarrier. By using the scheduled energy used for EH, relay node can then forward re-encoded signal to user m over the jth subcarrier. If subcarrier pairing is disregarded, the received data at relay node over the *ith* subcarrier could be directly transmitted to user m over the jth subcarrier on RD fwd link and restriction $i=j$ must be satisfied. As subcarrier pairing is applied, the jth subcarrier used on RD fwd link can distinct from *ith* subcarrier on SR fwd link. Thus, each paired subcarriers such as *ith* subcarrier and jth subcarrier are grouped in a pair of subcarriers denoted as $SP(i,j)$, which can be allotted to only one user m. In the second time slot

$y_{r,m}^{j}(k)$ over the jth subcarrier at user m can be deduced as Eq. (5).

$$y_{r,m}^{j}(k)=\sqrt{P_{r,m}^{j}}g_{r,m}^{j}x_{r,m}^{j}(k)+z_{m}^{j}(k),\ \forall j\in\mathcal{N},\ \forall m\in\mathcal{M} \quad (5)$$

where $g_{r,m}^{j}$ and $x_{r,m}^{j}$ represent the channel gain and the re-encoded signal transferred to user m over the jth subcarrier, respectively. z_{m}^{j} represents the AWGN with zero mean and variance σ_{m}^{2} at user m. The superscript j in each notation of Eq. (5) actually confines the remarked notations' definitions over the jth subcarrier.

There are always two time slots in the proposed DF scheme, energy cooperation is particularly designed in these two different time slots, where the energy harvested over the *ith* subcarrier on SR fwd link is used for data transmission via its paired subcarrier e.g., the jth subcarrier on RD fwd link [13]. $P_{r,m}^{j}$ is the available power at relay node communicate with user m over the jth subcarrier in the second time slot, and it can be given as Eq. (6).

$$P_{r,m}^{j}=\frac{E_{s,r}^{i}}{T/2}=\eta(1-\rho_{m}^{i})\left|h_{s,r}^{i}\right|^{2}P_{s,m}^{i},\quad \forall i,j\in\mathcal{N},\ \forall m\in\mathcal{M} \quad (6)$$

The maximum instantaneous data rate at which source node communicate with user m over the *ith* subcarrier on SR fwd link assisted by relay node over the *jth* subcarrier on RD fwd link can be calculated as follows Eq. (7).

$$R_{(s,i,j,m)}=\frac{1}{2}\min\left\{\log_2\left\{1+\frac{\rho_{m}^{i}\left|h_{s,r}^{i}\right|^{2}P_{s,m}^{i}}{\sigma_{r,c}^{2}}\right\},\log_2\left(1+\frac{\left|g_{r,m}^{j}\right|^{2}P_{r,m}^{j}}{\sigma_{m}^{2}}\right)\right\} \quad (7)$$

where the maximum data rate is scaled by $1/2$ because the DF transmission occupies two time slots. Substituting Eq. (7) with Eq. (6), we can obtain Eq. (8) which gives an equivalent transformation to the theoretically maximum data rate obtained in Eq. (7).

$$\begin{aligned}R_{(s,i,j,m)}=\frac{1}{2}\min\{&\log_2(1+\frac{\rho_{m}^{i}\left|h_{s,r}^{i}\right|^{2}P_{s,m}^{i}}{\sigma_{r,c}^{2}}),\\&\log_2(1+\frac{\eta(1-\rho_{m}^{i})\left|h_{s,r}^{i}\right|^{2}\left|g_{r,m}^{j}\right|^{2}P_{s,m}^{i}}{\sigma_{m}^{2}})\}\end{aligned} \quad (8)$$

The total achievable data rate for available paired subcarriers, which are designated and allocated to user m, can be given by

$$R_m=\sum_{i=1}^{N}\sum_{j=1}^{N}\chi_{i,j}\pi_{(i,j,m)}R_{(s,i,j,m)},\qquad \forall m\in\mathcal{M} \quad (9)$$

where $\chi_{i,j}\in\{0,1\}$ is actually a binary indicator that denotes subcarrier pairing, i.e., if the *ith* subcarrier on SR fwd link is successfully matched to the optimal jth subcarrier on RD fwd link, then pairing indicator $\chi_{i,j}=1$; otherwise $\chi_{i,j}=0$. $\pi_{(i,j,m)}\in\{0,1\}$ is also a binary variable indicates that whether a pair of subcarriers $SP(i,j)$ can be used by user m. If both two forward links i.e., SR and RD fwd links use the paired subcarriers e.g., $SP(i,j)$ to transfer data to user m, then $\pi_{(i,j,m)}=1$, otherwise, $\pi_{(i,j,m)}=0$.

The objective of reconfigurable resource allocation is to maximize the network throughput, i.e., the sum rate of M users, by incorporating subproblems such as optimal subcarrier pairing, power splitting ratio, the divided power allocated to each paired subcarriers and the subcarrier pairing allocation indicator that makes each user meet their requirement on data rate. Therefore, the formulated optimization problem can now be reorganized and given as the following optimization problem P1.

$$\begin{aligned}&\text{(P1) maximize} && \sum_{i=1}^{N}\sum_{j=1}^{N}\sum_{m=1}^{M}\chi_{i,j}\pi_{(i,j,m)}R_{(s,i,j,m)}\\&\text{subject to} && C1:\ 0\le\rho_{m}^{i}\le 1,\forall i,m\\&&& C2:\ \sum_{m=1}^{M}\sum_{i=1}^{N}\sum_{j=1}^{N}\chi_{i,j}\pi_{(i,j,m)}P_{s,m}^{i}\le P_{tot}\\&&& C3:\ R_m\ge Q_m,\forall m\\&&& C4:\ \chi_{i,j}\in\{0,1\},\forall i,j\\&&& C5:\ \sum_{i=1}^{N}\chi_{i,j}=1,\forall j;\quad \sum_{j=1}^{N}\chi_{i,j}=1,\forall i\\&&& C6:\ \pi_{(i,j,m)}\in\{0,1\},\forall i,\forall j,\forall m\\&&& C7:\ \sum_{m=1}^{M}\pi_{(i,j,m)}=1,\forall i,\forall j\end{aligned} \quad (10)$$

In optimization problem P1, the constraint denoted as C1 indicates the scale range of power splitting ratio ρ_{m}^{i}. Constraint C2 confines total available transmission power P_{tot} at source node. C3 ensures that data rate of user m should not be less than a threshold Q_m, by which it essentially allows diverse QoS for each user in actual applications especially in scenarios where high speed data transmission are needed. Two constraints on subcarrier pairing are shown as C4 and C5, where the pairing indicator $\chi_{i,j}$ is essentially binary, C5 assumes that each subcarrier on the SR fwd link can only be matched to another subcarrier on RD fwd link and vice versa. As observed in C6 and C7, the subcarrier pairing allocation indicator is also a binary variable and each user could use multiple paired subcarriers, but a selected pair of subcarriers is allowed for only one user.

III. Optimal Decoupling Approach for Resource Allocation

The objective of problem P1 in its expansion is not a concave function with respect to the product of $P^i_{s,m}$ and ρ^i_m or two binary variables $\chi_{i,j}$ and $\pi_{(i,j,m)}$ shown in constraints C4~C6. Up to now, there is no standardized method to solve the non-convex optimization problem P1. Due to increased computational complexity gradually with the extending problem size, these well-known traditional methods, e.g., exhaustive search, branch-and-bound, the bisection method etc., takes lots of computing resources when they searching the global optimal solutions, since a large number of variables to be optimized or even only getting suboptimal solutions. It can be observed that the formulation of problem P1 can be further exploited and inspired us to solve it in a repetitive process, i.e., the original non-convex optimization problem can be separated into three independent and interrelated subproblems and each can be obtained its analytical solutions. Our proposed r-RADAR algorithm for reconfiguring network resources based on decoupling method in a repetitive manner is specified in the following.

Based on the separation principle [20], binary variables $\chi_{i,j}(i \in \mathcal{N}, j \in \mathcal{N})$ can be separated from problem P1 and processed without losing global optimality or the necessity of optimizing the other variables. After that, the analytical expression of $\rho^i_m(i \in \mathcal{N}, m \in \mathcal{M})$ can be deduced to help the objective function reach its global optimum. The remaining two subproblems i.e., power allocation and subcarrier pairing allocation can then be reformulated as two relatively independent problems and solved in their dual domain.

A. *Optimal Subcarrier Pairing (OSP)*

The OSP method is proposed by pairing subcarriers on SR and RD fwd links based on the magnitudes of their channel gains i.e., $h^i_{s,r}$ and $g^j_{r,m}$. For that, all available subcarriers on SR and RD fwd links are prioritized in ascending order of their own channel gains respectively. Then the new ordered subcarriers available on SR fwd link are enforced pairing with its counterparts, also in order of ascending, i.e., subcarriers on RD fwd link with the same indices. For example, the subcarrier with the most channel gain on SR fwd link should be matched to the subcarrier with the most channel gain on RD fwd link. Similarly, the subcarrier with the second most channel gain on SR fwd link should be paired with the subcarrier that has the same priority on RD fwd link, and so on.

Theorem 1: The optimal $\chi^*_{i,j}(i \in \mathcal{N}, j \in \mathcal{N})$ obtained by OSP method can achieve its global optimality.

Proof: As OSP method is used, two correlated subproblems i.e., subcarrier pairing and power allocation, are essentially independent with each other. The obtained optimal solutions to subcarrier pairing by using OSP method is actually related to global optimum searching [20]. Due to power splitting ratio ρ^i_m only affects the amount of collected energy at relay node, and it practically does not have effects on channel gains overall subcarriers, the optimal power splitting ratio ρ^i_m can be neglected and kept undetermined when the ascending ordered subcarriers are paired by using OSP method. The subcarrier pairing indicator $\chi_{i,j}$, which is a binary variable and uncorrelated to ρ^i_m, thus can be optimized without knowing all the other variables in advance.

As a result, when OSP method is applied, problem P1 which is an original three-dimensional allocation problem can be reorganized as the following two-dimensional allocation optimization P2 by replacing $R_{(s,i,j,m)}$, $\pi_{(i,j,m)}$ with $R^{i,j}_{s,m}$, $\pi^{i,j}_m$, respectively.

$$\begin{aligned}
\text{(P2)}\ \ \text{maximize}\ \ & \sum_{m=1}^{M}\sum_{(i,j)}\pi^{i,j}_m R^{i,j}_{s,m} \\
\text{subject to}\ C1:\ & 0 \le \rho^i_m \le 1\ , \forall i,m \\
C2:\ & \sum_{m=1}^{M}\sum_{(i,j)}\pi^{i,j}_m P^i_{s,m} \le P_{tot} \\
C3:\ & R_m \ge Q_m, \forall m \\
C4:\ & \pi^{i,j}_m \in \{0,1\}, \forall (i,j)\ \ \forall m \\
C5:\ & \sum_{m=1}^{M}\pi^{i,j}_m = 1,\ \forall (i,j)\ \ \forall m
\end{aligned} \tag{11}$$

B. *Optimal Power Splitting Ratio (OPSR)*

The power splitting ratio ρ^i_m in C1 of the optimization problem P2, which directly affects the proportion of harvested energies for information processing and sustaining the operation of energy harvester, should be adjustable in accordance with the channel state information rather than kept as a constant value that ignores the practical channel quality. An adaptive power splitting ratio ρ^i_m by taking into account channel conditions is given in its analytical expression as follows.

To simplify the notations, variable substitution is introduced and we have $a = \frac{|h^i_{s,r}|^2}{\sigma^2_{r,c}}, b = \frac{\eta |h^i_{s,r}|^2 |g^j_{r,m}|^2}{\sigma^2_m}$.

Then the achievable maximal data rate shown in Eq. (8) over paired subcarrier $SP(i,j)^*$ for user m can be represented as Eq. (12).

$$R^{i,j}_{s,m} = \tfrac{1}{2}\min\{\log_2(1 + a\rho^i_m P^i_{s,m}), \log_2(1 + bP^i_{s,m} - b\rho^i_m P^i_{s,m})\} \tag{12}$$

It can be observed that the first item i.e., $\log_2(1 + a\rho^i_m P^i_{s,m})$ in Eq. (12) is a monotonically increasing function of variable ρ^i_m, and similarly the second term i.e., $\log_2(1 + bP^i_{s,m} - b\rho^i_m P^i_{s,m})$ is a monotonically decreasing function of ρ^i_m. When $P^i_{s,m}$ is regarded as constant and kept unvaried. Thus, the data rate of paired subcarriers $SP(i,j)^*$ for user m will be maximized if there exists specific variable ρ^i_m that makes these two items in Eq. (12) be equal to each other. The optimal power splitting ratio $\rho_m^{i^*} = \frac{b}{a+b}$ is hence obtained through equivalent transformation to Eq. (13).

$$1 + a\rho_m^i P_{s,m}^i = 1 + bP_{s,m}^i - b\rho_m^i P_{s,m}^i \tag{13}$$

where $\rho_m^{i^*}$ is confined in a closed interval [0,1], just as indicated by C1 in the optimization P2.

The data rate $R_{s,m}^{i,j}$ in Eq. (12) is able to get its maximal value as variable $\rho_m^{i^*} = \frac{b}{a+b}$, and hence we have Eq. (14),

$$R_{s,m}^{i,j} = \tfrac{1}{2}\log_2(1 + \gamma_{s,m}^{i,j} P_{s,m}^i) \tag{14}$$

where $\gamma_{s,m}^{i,j} = a\rho_m^{i^*} = \frac{ab}{a+b}$.

Theorem2: The optimal power splitting ratio $\rho_m^{i^*}(i \in \mathcal{N}, m \in \mathcal{M})$ obtained after equivalent transformation of Eq. (13) is a global optimum to the optimization problem P2.

Proof: By observing the mathematical expansion of $\rho_m^{i^*}$, which is a fraction function of only channel gains on SR and RD fwd links, and also independent of power allocation and subcarrier pairing allocation. In another word, the selection of $\rho_m^{i^*}$ does not depend upon the other variables to be optimized. Hence, for any optimal paired subcarriers e.g. $SP(i,j)^*$ for user m, $\rho_m^{i^*}$ $(i \in \mathcal{N}, m \in \mathcal{M})$ is globally optimal in the optimization problem P2.

C. *Joint Optimal Power Allocation and Subcarrier Pairing Allocation (JOPASPA)*

After obtained optimal power splitting ratio $\rho_m^{i^*}$, the unsolved subproblems in optimization problem P2 is essentially a mixed integer nonlinear optimization problem and is also non-convex. Because binary variable $\pi_m^{i,j}$ is shown in constraints C4 and the nonlinearity arises in the sum of nonlinear items appeared in both the objective function and constraint C2, e.g., the sum of product of two variables to be optimized on the left side of C2, i.e., $\pi_m^{i,j} R_{s,m}^{i,j}$. Fortunately, problem P2 satisfies the time-sharing condition [21], which demonstrates that the duality gap between the optimization problem P2 and its dual problem can be negligible if there are adequate number of subcarriers on both the SR and RD fwd links. Thus unsolved subproblems such as power allocation and subcarrier pairing allocation can then be solved in their dual domain.

By introducing the non-negative Lagrangian multipliers λ and $\boldsymbol{\mu} = [\mu_m]_{1\times M}$ rated with the constraints C2 and C3, respectively. The Lagrangian function for P2can be expanded as Eq. (15).

$$\begin{aligned}
&L(\boldsymbol{\pi}', \lambda, \mathbf{P}, \boldsymbol{\mu}) \\
&= \sum_{m=1}^{M}\sum_{(i,j)} \pi_m^{i,j} R_{s,m}^{i,j} + \lambda(P_{tot} - \sum_{m=1}^{M}\sum_{(i,j)} \pi_m^{i,j} P_{s,m}^i) + \sum_{m=1}^{M} \mu_m (R_m - Q_m) \\
&= \sum_{m=1}^{M}\sum_{(i,j)} \pi_m^{i,j} \left[(1+\mu_m)\frac{1}{2}\log_2(1+\gamma_{s,m}^{i,j} P_{s,m}^i) - \lambda P_{s,m}^i \right] + \lambda P_{tot} \\
&- \sum_{m=1}^{M} \mu_m Q_m
\end{aligned} \tag{15}$$

where $\boldsymbol{\pi}' = [\pi_m^{i,j}]_{N\times M}$ is a matrix of binary variables indicating the subcarrier pairing allocation. λ and $\mathbf{P} = [P_{s,m}^i]_{N\times M}$ represent the Lagrange multiplier for the power constraint C2 in problem P2 and a matrix of transmission power allocated to user m by source node using *ith* subcarrier, respectively. $\boldsymbol{\mu} = [\mu_m]_{1\times M}$ is the matrix of the Lagrange multipliers associated with the data rate requirement of each user.

The dual function $g(\lambda, \boldsymbol{\mu})$ can be derived as follows Eq. (16).

$$\begin{aligned}
g(\lambda, \boldsymbol{\mu}) &= \max_{\boldsymbol{\pi}', \mathbf{P}} L(\boldsymbol{\pi}', \lambda, \mathbf{P}, \boldsymbol{\mu}) \\
\text{subject to} & \sum_{m=1}^{M} \pi_m^{i,j} = 1, \quad \forall (i,j)
\end{aligned} \tag{16}$$

The dual problem of our reshaped optimization problem P2 is hence obtained in the following Eq. (17).

$$\min_{\lambda, \mu_m \ge 0} g(\lambda, \boldsymbol{\mu}) \tag{17}$$

1) *Optimal power allocation*

The constant items i.e., λP_{tot} and $\sum_{m=1}^{M} \mu_m Q_m$ in Eq.(15) can be removed from the Lagrangian function, since both of them are unrelated to the variable $P_{s,m}^i (i \in \mathcal{N}, m \in \mathcal{M})$ that is to be optimized. To any optimal paired subcarriers $SP(i,j)^*$ for user m, $\pi_m^{i,j} (i \in \mathcal{N}, j \in \mathcal{N}, m \in \mathcal{M})$ can be reasonably supposed as a fixed binary number 0 or 1, by which notation $L_m^{i,j}$, which is a multi-function of variables $\lambda, \mu_m (m \in \mathcal{M}), P_{s,m}^i (i \in \mathcal{N}, m \in \mathcal{M})$, can be correspondingly defined and used as a substitute for the Lagrangian function shown as Eq.(18).

$$L_m^{i,j}(\mu_m, P_{s,m}^i, \lambda) = (1+\mu_m)\frac{1}{2}\log_2(1+\gamma_{s,m}^{i,j} P_{s,m}^i) - \lambda P_{s,m}^i \tag{18}$$

For $L_m^{i,j}(\mu_m, P_{s,m}^i, \lambda)$ in Eq. (18), the partial derivative with respect to $P_{s,m}^i$ can be calculated as Eq. (19).

$$\frac{\partial L_m^{i,j}}{\partial P_{s,m}^i} = \frac{(1+\mu_m)\gamma_{s,m}^{i,j}}{2\ln(2)(1+\gamma_{s,m}^{i,j} P_{s,m}^i)} - \lambda \tag{19}$$

Let Eq. (19) be equal to 0, the optimal power $P_{s,m}^{i^*}$ from source node over the *ith* subcarrier and is allocated to user m is derived as follows Eq. (20).

$$P_{s,m}^{i^*} = \left[\frac{1+\mu_m}{2\lambda \ln(2)} - \frac{1}{\gamma_{s,m}^{i,j}} \right]^+ \tag{20}$$

where $[x]^+ = \max\{x, 0\}$.

2) Optimal subcarrier pairing allocation

Each item appeared in the analytic expression of $L_m^{i,j}(\mu_m, P_{s,m}^i, \lambda)$ (shown as Eq. (18)) can be interpreted by its own economic explanation. The Lagrange multipliers can be interpreted as a set of shadow prices for the network resources [22]. The first item in Eq. (18) can be viewed as the intrinsic worth that user m benefits from the data rate over any optimal paired subcarriers $SP(i,j)^*$, and the second item represents the cost that source node should be paid at cost of power consumption. Therefore, $L_m^{i,j}(\mu_m, P_{s,m}^i, \lambda)$ can be essentially regarded as the transmission profit when source node communicating with user m by using any optimal paired subcarriers $SP(i,j)^*$. The dual function in Eq. (16) can be maximized by choosing an optimal pair of subcarriers $SP(i,j)^*$ among all optimal paired subcarriers to user m via OSP method. In order to help user $m (m \in \mathcal{M})$ gain the most profit, and the optimal paired subcarriers $SP(i,j)^*$ should be allocated to user m, which uses Eq. (21) to decide its allocated optimal paired subcarriers.

$$\pi_m^{i,j^*} = \begin{cases} 1, & \text{if } m = \arg\max_m L_m^{i,j}(\mu_m, P_{s,m}^i, \lambda) \\ 0, & \text{otherwise.} \end{cases} \tag{21}$$

Theorem 3: The optimal solutions $P_{s,m}^{i^*} (i \in \mathcal{N}, m \in \mathcal{M})$ and $\pi_m^{i,j*} (i \in \mathcal{N}, j \in \mathcal{N}, m \in \mathcal{M})$ obtained via Eq. (20) and Eq. (21) are global optimal.

Proof: If optimal paired subcarriers $SP(i,j)^*$ is selected by user m using Eq. (21), the power allocation at source node can be separated as $N \times M$ independent subproblems i.e., how to allocate N paired subcarriers to M different users. The objective function $L_m^{i,j}(\mu_m, P_{s,m}^i, \lambda)$ as shown in Eq. (18) is actually a concave function of $P_{s,m}^i$. As a result, when $L_m^{i,j}(\lambda, \mu_m, P_{s,m}^i)$ is taken partial derivative with respect to $P_{s,m}^i$ just as shown in Eq.(20), the pole obtained is also an extreme point without losing global optimality. Since all subcarriers on SR fwd link can be obtain the optimal subcarriers on RD fwd link through finding $\chi_{i,j}^*$, the matrix $\boldsymbol{\pi}' = [\pi_m^{i,j}]_{N \times M}$ is now simplified as a two-dimensional allocation matrix. The optimal solution $\pi_m^{i,j*}$ can be found in a two-dimensional space $\mathbf{L} = [L_m^{i,j}]_{N \times M}$ by using Eq. (21), which can also be used to ensure the global optimality.

By observing Eq. (20), if the optimal value λ^*, μ_m^* are known, $P_{s,m}^{i^*}$ can be directly calculated. Since the dual function in Eq. (17) is always a convex function of Lagrange multipliers, we can simultaneously updating λ, μ_m through subgradient method. The Lagrange multipliers λ, μ_m are synchronously updated as the following Eq. (22).

$$\begin{aligned} \lambda(\tau+1) &= [\lambda(\tau) - \delta(\tau)(P_{tot} - \sum_{i=1}^{N}\sum_{m=1}^{M} \pi_m^{i,j^*} P_{s,m}^{i^*})]^+ \\ \mu_m(\tau+1) &= [\mu_m(\tau) - \upsilon(\tau)(R_m - Q_m)]^+ \end{aligned} \tag{22}$$

where both $\delta(\tau)$ and $\upsilon(\tau)$ are the gradually reducing step sizes and τ indicates the iteration index, which shows the current iteration times. The subgradient method above is used to guarantee convergence, if the step sizes are chosen in accordance with the diminishing step size policy [23]. The subgradient updating method as indicated in Eq. (22) can be further interpreted as the pricing adjustment rule popularly used in demand and supply model [22]. If the demand for the network resources exceeds supply, then the subgradient method will raise the shadow prices, i.e. increasing the Lagrange multipliers in the next iteration; otherwise, it will reduce the shadow prices until some users can afford. With continuously updates, shadow prices will finally reach the optimum and unvaried, while the network resources are optimally configured among different users.

In order to master the intact idea of our proposal, the pseudo code of r-RADAR algorithm is summarized in Table II.

TABLE II: THE PROPOSED r-RADAR ALGORITHM

1: Putting all the available subcarriers on SR and RD fwd links in ascending order of their channel gains.
2: The *ith* subcarrier on SR fwd link can be paired with *jth* subcarrier on RD fwd link if both of them have the same indices in the new ordered sequence of subcarriers. Group them and forms a new paired subcarriers i.e., $SP(i,j)^*$.
3: Obtain the optimal subcarrier pairing indicator $\chi_{i,j}^*$ based on above Step1 and Step2.
4: **for** $i = 1 \to N$ **do**
5: **for** $m = 1 \to M$ **do**
6: Obtain the optimal power splitting ratio $\rho_m^{i^*}$ using Eq.(13).
7: **end for**
8: **end for**
9: **Set** the subgradient iteration index $\tau = 1$.
10: **Initialize** $\{\lambda, \boldsymbol{\mu}\}$ as non-negative values.
11: **for** $i = 1 \to N$ **do**
12: **for** $m = 1 \to M$ **do**
13: Obtain the power allocation $P_{s,m}^i$ using Eq.(20) for given λ, μ_m.
14: Computer the matrix $\mathbf{L}$ using Eq.(18) and obtain subcarrier pairing allocation $\pi_m^{i,j}$ using Eq.(21).
15: **end for**
16: **end for**
17: Update $\tau = \tau + 1$.
18: Update λ using $\lambda(\tau+1) = [\lambda(\tau) - \delta(\tau)(P_{tot} - \sum_{i=1}^{N}\sum_{m=1}^{M} \pi_m^{i,j^*} P_{s,m}^{i}{}^*)]^+$ in Eq.(22).

19: **for** $m=1\rightarrow M$ **do**

20: update μ_m using $\mu_m(\tau+1)=[\mu_m(\tau)-\upsilon(\tau)(R_m-Q_m)]^+$ in Eq.(22).

21: **end for**

22: Repeat from Step 11until convergence and find the optimal λ^*,μ_m^*.

23: With the optimal λ^*,μ_m^*, the optimal $P_{s,m}^{i^*},\pi_m^{i,j^*}$ are determined.

IV. Complexity Analysis

In single user OFDMA relay networks, if there is merely one source node and one relay node, then OSP method complexity is easily known as $O(N\log N)$. In contrast, our proposed r-RADAR algorithm considers a network scenario where a source node communicating with M different users over N paired subcarriers through two neighboring forward links. Obviously, the r-RADAR algorithm needs allocating N paired subcarriers to M users, OSP method complexity in our proposed multiuser OFDMA relay networks can then be recalculated as $O(NM\log NM)$.

In a session between source node and its user $m(m\in\mathcal{M})$, there are totally N available paired subcarriers on both two forward links. Source node should compute power splitting ratio ρ_m^i for each available paired subcarrier, even though source node is unaware of the results of optimal subcarrier pairing allocation. Due to source node responds to M user sessions in such relay networks, the complexity of the OPSR method is $O(NM)$.

As to JOPASRA method, $N\times M$ function values are needed to find the optimal power allocation. We also need optimal subcarrier pairing allocation to be completed among N different pairs of subcarriers each iteration. Thus, the complexity of JOPASRA method is $O(NM)$.

If the complexity of subgradient method can be represented by a notation V_1, which is actually a polynomial function of $M+1$ Lagrange multipliers [21], then the computational complexity of r-RADAR algorithm is $O(V_1NM\log NM)$ based on all above analyses. The proposed r-RADAR algorithm effectively reduces the feasible domain via multi-phases design philosophy in manner of repetition.

V. Simulation Results and Performance Evaluations

A. Relay Network Model and Settings

In order to analyze and evaluate the performance of r-RADAR algorithm, the section designs a series of numerical experiments using the M language. It is divided into four groups of experiments to comprehend our proposed r-RADAR algorithm, i.e., the relay location, transmission power, the number of users, the data rate requirements and user rate distributions, specifically.

Considering a typical relay network model for SWIPT just as shown in Fig. 2, where the source node and relay node are located at coordinates $(0,0)$ and $(\alpha D,0)$ respectively, where $\alpha\in(0,1)$ is used to denote the ratio of distance between the source and relay node to a reference distance D. Users are randomly distributed in a $0.5D*0.5D$ square region. The distance between the source node and the farthest side of the user region is denoted by $3D$.

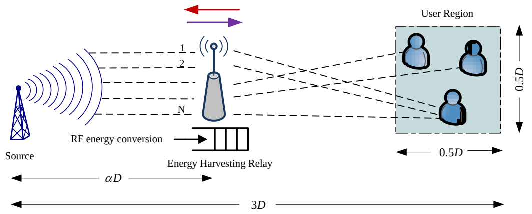


Fig. 2. Relay network model for SWIPT

The available bandwidth in our model is unvaried and maintained as 1MHz.The channel gains on the two fwd links suffer from influences of both a small-scale Rayleigh fading component and a large-scale path loss component. The pass loss component factor is kept unchanged as 3, while the effects of small-scale fading can be modeled as a frequency selective channel that consists of six independent Rayleigh paths. The Clarke's flat fading model is used to get the fading component on each path, which assumes that the power delay profile is exponentially decaying with e^{-2l}, where l is the path index. The other parameters related to r-RADAR algorithm are set as $N=128,\sigma_{r,c}^2=\sigma_m^2=10^{-3}$w, η=0.9. It is noted that all numerical results illustrated in the following paper are the average number of statistical results by simulating 1000 different channel states.

To show the performances of r-RADAR algorithm with clarity, two benchmark algorithms are also proposed as follows.

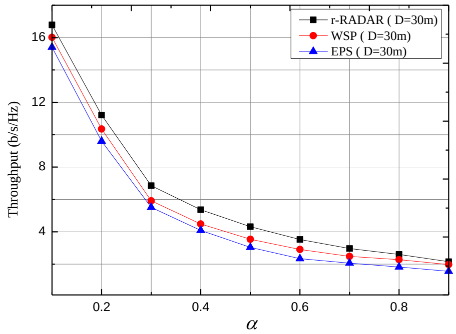
1) Without Subcarrier Pairing (WSP): In WSP algorithm, the *ith* subcarrier in the first time slot is always matched with the *jth* subcarrier in the second time slot without the process of subcarrier pairing. In other word, it is notable that $i=j$ is always satisfied in WSP algorithm. The OPSR method and JOPASRA method are similar algorithms that are used to assist subproblems such as power splitting ratio, power allocation and subcarrier pairing allocation.

2) Equal Power Splitting (EPS): In EPS algorithm, the power splitting ratio $\rho_m^i(i\in\mathcal{N},m\in\mathcal{M})$ is set as 0.7. The OSP method and JOPASRA method are used to solve subproblems including subcarrier pairing, power allocation and subcarrier pairing allocation.

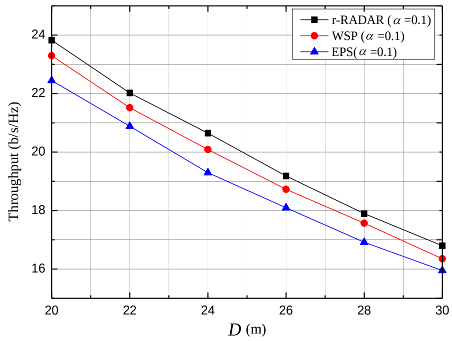
B. Numerical Experiment I: Network Throughput vs. Relay Position

In the subsection, we study the network throughput by varying the location of relay node with the other parameters being kept as $P_{tot}=1.0w$, $M=6$. In Fig. 3(a), the reference distance D is selected as 30 meters, and the distance ratio α can be varied from 0.1 to 0.9. The reference distance D ranges from $20m$ to $30m$ in Fig. 3(b). The minimum data rate for three selected users is normalized as 0.3b/s/Hz in the experiment I, e.g., $Q_1=Q_2=Q_3=0.3$b/s/Hz, while the other three users are assumed without such a threshold, i.e., $Q_4=Q_5=Q_6=0$b/s/Hz.

By observing Fig. 3(a), as increasing distance ratio α, relay node is gradually getting farther from source node and moving nearer the user region. It can be inferred from Fig. 3(a) that when relay node locates much nearer the source node, all three algorithms can attain their own maximal throughput. However, in traditional OFDMA relay networks [23], [24], it showed that when relay node is right in the middle position between the source and center of user region, three algorithms can obtain their maximal throughput. This is the difference that distinguishes SWIPT system from the other general OFDMA networks.



(a)



(b)

Fig. 3 Network throughput as moving relay in two situations (a) by changing the ratio α within $[0.1, 0.9]$ (b) by changing the reference distance D from $20m$ to $30m$

The performance index, i.e., network throughput, in three algorithms all descend with increase of α. But our proposed r-RADAR algorithm has advantage over the other two algorithms. As $\alpha=0.9$, the differences among them are unobvious. Since the farther the distance between the source and relay is, the less the EH efficiency is applied at the relay node due to increasingly serious path loss effect.

Fig. 3(b) shows that the network throughput decreases with reference distance D increases, since a definite ratio α will also extend the transmission distance between the source and relay when we just increasing reference distance D. As a result, relay node should be deployed nearer the source node to help network gain more throughput, by which it also supply important guidelines for relay scheduling in such SWIPT relay transmission system.

C. Numerical Experiment II: Network Throughput vs. Transmission Power P_{tot}

The relations between the transmission power P_{tot} and network throughput is studied in the subsection, where a scenario of six users is simulated with data rates being set as $Q_1=Q_2=Q_3=2$ b/s/Hz and $Q_4=Q_5=Q_6=0$b/s/Hz. The source node utilizes transmission power P_{tot}, actually ranging from $1.0w$ to $1.6w$ on SR fwd link to communicate with relay node.

As shown in Fig. 4, significant increase of network throughput is made by increasing P_{tot}, because the more the transmission power P_{tot} is used, the better the Signal-to-Noise Ratio (SNR) is generated. From another perspective, relay node is capable of acquiring more energy since transmission power will be split proportionally and more EH energy can be distributed to relay node. Due to EPS algorithm uses a predefined number as the power splitting ratio and ignores the adaptive energy distribution in responding to channel state information in SWIPT, Fig. 4 shows that r-RADAR algorithm increases more network throughput than EPS algorithm as P_{tot} being increased. Additionally, the throughput of EPS algorithm grows slowly when compared with r-RADAR algorithm. As the maximal transmission power $P_{tot}=1.6w$ $(\alpha=0.1)$ is applied, the throughput growth of r-RADAR algorithm is 55.18% with respect to the scenario where $P_{tot}=1.0w$ $(\alpha=0.1)$, and is also much better than another case, where $\alpha=0.2$ and relay node positioned farther from the source node, only brings about 40.99% throughput growth.

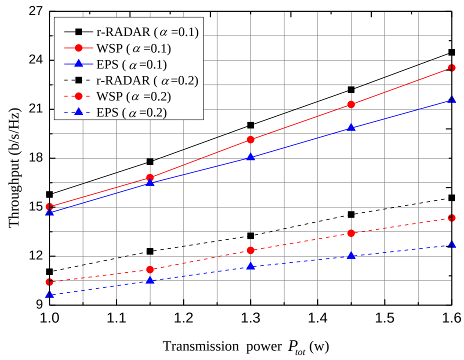


Fig. 4 Throughput versus the transmission power P_{tot} as $M=6$, $D=30m$

D. Numerical Experiment III: Network Throughput vs. Number of Users

Fig. 5 shows the improvement of network throughput when user amount increases. As in previous experiment of parameter settings, transmission power is set as $P_{tot} = 1w$, and the minimal data rates are restricted to $Q_1 = Q_2 = Q_3 = 2$ b/s/Hz and $Q_4 = Q_5 = Q_6 \cdots Q_k = 0$b/s/Hz. As seen in Fig. 5, the network throughputs are all improved in three candidates as user amount M is gradually increased from 6 to 16. The results imply that they all can accommodate multiuser diversity and user scalability in OFDMA relay networks.

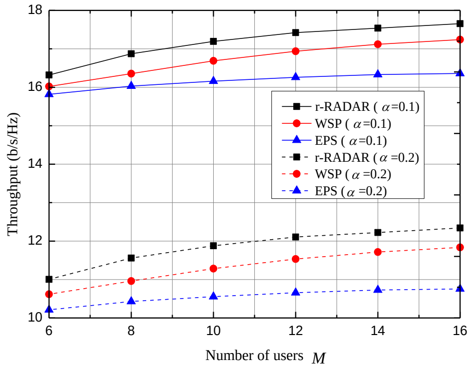


Fig. 5. Throughput versus the number of users M with $P_{tot} = 1w, D = 30m$

However, r-RADAR algorithm shows better performance improvement compared to the other two candidates, since it considers the influences of both subcarrier pairing and power splitting when maximizing network throughput on two hops in SWIPT.

It can be inferred that more users involved will aggravate severe competitions among users for the already limited network resources, which leads to less subcarriers and available power being distributed to each user. Since number of subcarriers and transmission power P_{tot} are all in very limited quantities and are not increased with user amount, the growth trend of throughput in r-RADAR algorithm is moderate with M increases.

E. *Numerical Experiment IV: Throughput vs. Data Rate Required*

In the subsection by setting parameters as $P_{tot} = 1w$ and $M = 6$, we study network throughput when minimum data rate is changeable according to user demand. For this purpose, the minimum data rates imposed on three selected users are the same and vary from 0 to 2.5 b/s/Hz. The other three users are not forced to such a threshold, i.e., $Q_4 = Q_5 = Q_6$=0b/s/Hz. Fig. 6 reveals that throughput will decrease by improving minimal data rate. When none requirement on minimum rate is applied i.e., $Q_1 = Q_2 = Q_3$=0b/s/Hz and $Q_4 = Q_5 = Q_6$=0b/s/Hz, three algorithms here just like those unconstrained allocation problems always generate maximal throughput and allocate subcarriers for users relying only on channel state information.

In both two groups of statistical data (i.e., $\alpha = 0.1$ and $\alpha = 0.2$), the throughput drops slowly until arriving turning point 1b/s/Hz, then it begins to fall quickly. When higher data rate is required (typically the case when $\alpha = 0.1$) at each user, much more paired subcarriers are used to improve the channel capacity and hence achieving higher data rate. Similarly, as relay node is positioned farther from the source node ($\alpha = 0.2$), SNR drops make even more subcarriers be used to face growing demand on higher data rate, and thus reducing flexibility in subcarrier pairing allocation.

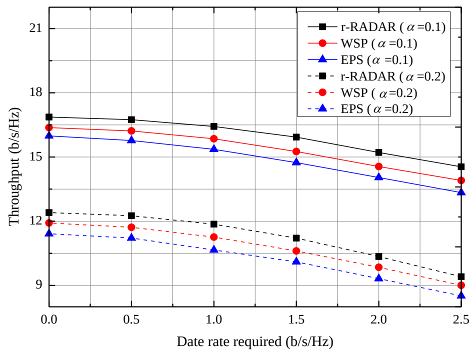


Fig. 6. Throughput versus data rate required by using parameters $P_{tot} = 1w$, $D = 30m$, $M = 6$

F. *Numerical Experiment V: User Rate Distributions in Reference Algorithms*

Similar to the parameter settings in previous numerical experiments, in experiment V we have parameters set as $\alpha = 0.1, P_{tot} = 1w$, and the minimums of user data rates are specified as $Q_1 = Q_2 = Q_3 = 2$b/s/Hz and $Q_4 = Q_5 = Q_6 = 0$b/s/Hz. For reference and performance comparison, a simplified edition of r-RADAR algorithm is proposed and named r-RADAR(se), which is distinguished from r-RADAR algorithm mainly by no restriction imposed on each user for minimal data rate. Just as shown in Fig. 7, it can be observed that by adding a threshold $Q_1 = 2$ b/s/Hz, unlike the other three algorithms for user 1, r-RADAR(se) cannot meet the needs of user data rate anymore, because there is no restriction on user data rate in r-RADAR(se) and it might happen to use the bad channels with extremely low $\gamma_{s,m}^{i,j}$ (indicated in Eq. (14)). In contrast, the optimal algorithm r-RADAR will allocate more data rates to user 3 and user 6. Due to both of them use the channels with better quality i.e., with greater $\gamma_{s,m}^{i,j}$, r-RADAR algorithm optimal algorithm correspondingly motivates more data rate to be distributed to such users for maximizing the network throughput. It is not difficult to find that r-RADAR algorithm not only releases users from the restriction on minimum rate such as $Q_1 = Q_2 = Q_3 = 2$b/s/Hz, but also effectively allocates more frequency resources to the user e.g., user 6 with best channel quality. Beside from maximizing the network throughput, it is easy to understand why r-RADAR algorithm can support differentiated communicate service very well.

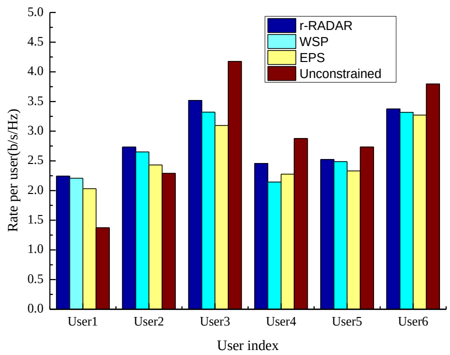


Fig. 7. User rate distribution when $P_{tot} = 1w, D = 30m, M = 6$

VI. Conclusion

An energy harvesting relay is introduced in multiuser OFDMA networks, in which a source node communicates with M users via an energy harvesting relay node is considered. In order to maximize the network throughput and allocate data rate user needs, the joint design of subcarrier pairing, power splitting ratio, power allocation and paired subcarriers allocation are all studied within a framework of non-convex optimization, by which the formulated problem is separated to multiple equivalent subproblems and solved in a repetitive manner. r-RADAR algorithm helps us obtain an equivalent global optimal solution to the original problem. Also it has relatively low computational complexity, which is further proved in the paper and can effectively reduce the searching space. Distinguished from traditional multiuser OFDMA networks, simulation results show that when EH relay is used and located nearer the source node, more throughput will be achieved. Beside from throughput maximization, r-RADAR algorithm can also support differentiated communicate service as well. In our future work, we will consider that how to allocate network resource in multihop or mulitirelay networks to increases the network throughput and improve utilization of network resources.

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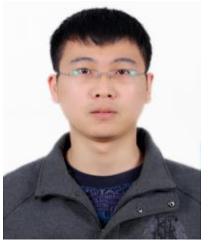

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