Joint Subcarrier and Power Allocation Methods in Full Duplex Wireless Powered Communication Networks for OFDM Systems

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***Abstract*—In this paper, we investigate wireless powered communication network for OFDM systems, where a hybrid access point (H-AP) broadcasts energy signals to users in the downlink, and the users transmit information signals to the H-AP in the uplink based on orthogonal frequency division multiple access. We consider a full-duplex H-AP which simultaneously transmits energy signals and receives information signals. In this scenario, we address a joint subcarrier scheduling and power allocation problem to maximize the sum-rate under two cases: perfect self-interference cancelation (SIC) where the H-AP fully eliminates its self-interference (SI) and imperfect SIC where residual SI exists. In general, the problems for both cases are nonconvex due to the subcarrier scheduling, and thus it requires an exhaustive search method, which is prohibitively complicated to obtain an optimal solution. In order to reduce the complexity, for the perfect SIC scenario, we jointly optimize subcarrier scheduling and power allocation by applying the Lagrange duality method. Next, for the imperfect SIC case, the problem becomes more complicated due to the SI at the H-AP. To solve this problem, we propose an iterative algorithm based on the projected gradient method. Simulation results show that the proposed algorithm for the case of perfect SIC exhibits almost the same sum-rate performance compared to the optimal algorithm, and the proposed iterative algorithm for the imperfect SIC case offers a significant performance gain over conventional schemes.**

***Index Terms*—Wireless powered communication network (WPCN), orthogonal frequency division multiple access (OFDMA), full-duplex.**

I. Introduction

RECENTLY, energy harvesting (EH) has been regarded as a promising technique which can replace traditional energy sources (e.g. batteries), since it provides more cost-effective energy supplies to wireless networks [1]. Especially, harvesting the radio frequency (RF) signal has drawn an enormous amount of attention due to its dual usage, called wireless information transmission (WIT) and wireless energy transfer (WET) [2]. Among various energy transfer systems, simultaneous wireless information and power transfer (SWIPT) systems and wireless powered communication network (WPCN) have been widely investigated [2]–[14]. In the SWIPT system where the WIT and the WET signals are transmitted in the downlink at the same time, several works identified a trade-off between the achievable sum-rate performance and the harvested energy for various situations [3]–[8].

Unlike the SWIPT system which is confined to the downlink network, in the WPCN, an energy access point radiates the RF signals intended for the downlink WET, while users harvest those energy to transmit the WIT signals to a data access point in the uplink. In [9], a single user WPCN was considered, and the optimal power allocation policy to maximize sum-rate was proposed. The work in [9] was extended to orthogonal frequency division multiplexing (OFDM) systems in [10] by jointly optimizing subcarrier scheduling over time and power allocation in a single user scenario.

For the multi-user case, the authors in [2] introduced a time division multiple access (TDMA) based harvest-then transmit protocol in the WPCN, where the downlink WET and the uplink WIT are implemented sequentially, and proposed the optimal time allocation solution for the sum-rate maximization. Also, in order to maximize the minimum sum-rate of a space division multiple access WPCN, the optimal energy beamforming, time allocation, and power allocation method has been developed in [11].

Meanwhile, full-duplex (FD) wireless systems, where a transceiver can transmit and receive signals on the same frequency at the same time, have attracted growing interest due to its potential for increasing spectral efficiency [15]. Although the FD system is capable of doubling the spectral efficiency in the ideal case, strong self-interference (SI) generated by simultaneous transmission and reception at the same node degrades the spectral efficiency in practical systems.

Recently, this FD protocol was applied to the WPCN [12], [13], where the downlink WET and the uplink WIT are concurrently carried out, and it was shown that the performance can be significantly improved compared to half-duplex systems. The authors in [12] provided the optimal time allocation algorithms to maximize the sum-rate and minimize

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the total transmission time under an assumption of perfect self-interference cancelation (SIC). In addition, a joint power and time allocation scheme for the TDMA based WPCN, considering both perfect and imperfect SIC cases, has been investigated in [13]. However, an orthogonal frequency division multiple access (OFDMA) based WPCN has not yet been studied in the literature to our best knowledge.

In this paper, we study WPCN for OFDM systems where a hybrid-access point (H-AP) operates in a FD mode and all users transmit their information signals to the H-AP based on OFDMA [16]–[18].[1] For this configuration, we propose joint subcarrier scheduling and power allocation algorithms to maximize the sum-rate under two scenarios: the ideal case where perfect SIC is performed at the H-AP, and the practical case where the residual SI remains.

First, for the perfect SIC case, the sum-rate maximization problem is non-convex owing to a subcarrier scheduling function, and thus an exhaustive search method is required to obtain the optimal solution. Since this incurs high computational complexity for comparing subcarrier candidates, we propose a joint subcarrier scheduling and power allocation algorithm based on the Lagrange duality method. The simulation results confirm that the proposed algorithm shows almost identical performance compared to the optimal exhaustive search method with much reduced complexity.

Then we examine the practical imperfect SIC case where the residual SI degrades the sum-rate performance. In this case, due to the SI, the sum-rate maximization problem becomes more complicated. To solve the problem, we provide an algorithm which first optimizes the subcarrier scheduling and the uplink power allocation with given downlink power. Then, we compute a downlink power allocation solution based on the projected gradient method with given subcarrier scheduling and uplink power. The simulation results show that the proposed algorithm provides 41% performance gain compared to conventional schemes.

The remainder of this paper is organized as follows: Section II introduces the multiuser WPCN for OFDM systems and formulate the sum-rate maximization problem. In Sections III and IV, the joint subcarrier scheduling and power allocation algorithms for the perfect and the imperfect SIC cases are proposed, respectively. Then, we evaluate the average sum-rate performance of the proposed algorithms in Section V. Finally, the paper is ended with conclusions in Section VI.

II. System Model and Problem Formulation

As shown in Figure 1, we consider a WPCN for OFDM systems which employs WET in the downlink and WIT in the uplink. The FD H-AP, equipped with a dedicated transmit and a receive antenna, broadcasts energy signals to K users, and at the same time receives information signals transmitted by the users. In contrast, each user has a single antenna and operates in a half-duplex (HD) mode where subcarriers for energy harvesting and information transmission are separated. We assume that the total bandwidth is equally divided by N subcarriers. The

[1] In [19], only perfect self-interference cancelation was considered at the H-AP.

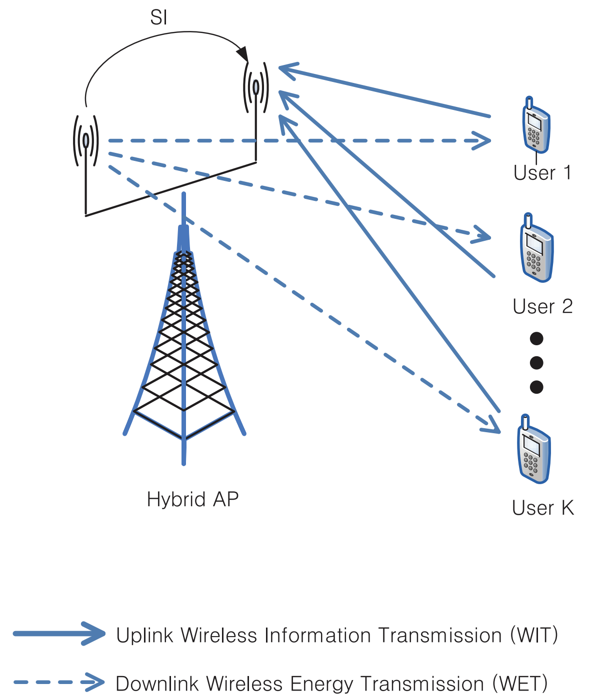

Fig. 1. The FD WPCN for OFDM system model.

TABLE I
EXAMPLE OF SUBCARRIER SCHEDULING FOR WPCN SYSTEMS BASED ON OFDMA UPLINK TRANSMISSION

	subcarrier 1	subcarrier 2	subcarrier 3	subcarrier 4
User 1	uplink	downlink	downlink	downlink
User 2	downlink	uplink	uplink	uplink

frequency selective channels at subcarrier n of user k for downlink and uplink are given as $h_{D,k}[n]$ and $h_{U,k}[n]$, respectively, and it is assumed that all the channel information is known at the H-AP and remains constant within one system operating block.

In the uplink OFDMA, each subcarrier is scheduled to at most one user during the same transmission period. Let us denote $\Pi(n)$ as the subcarrier scheduling function which indicates the index of user to which subcarrier n is assigned, and $S(k)$ as the set of subcarriers assigned to user k. For example, when the subcarrier scheduling function is given by $\Pi(1) = 1$, $\Pi(2) = 2$, $\Pi(3) = 2$, and $\Pi(4) = 2$, the subcarrier set can be defined as $S(1) = \{1\}$ and $S(2) = \{2, 3, 4\}$, as shown in Table I.

In the downlink of the WPCN for OFDM systems, the H-AP broadcasts the wireless energy to all users with the transmit power $P_D[n]$at subcarrier n.[2] Let us define the total transmit power and the peak power at the H-AP as P_T and P_{peak}, respectively. Then, the power constraint can be expressed as $\sum_{n=1}^{N} P_D[n] \leq P_T$ and $P_D[n] \leq P_{peak}$, $\forall n$. The received signal of user k at subcarrier n can be written as

$$y_k[n] = \sqrt{P_D[n]}h_{D,k}[n]x[n] + z_k[n], \quad \forall k, n, \tag{1}$$

where $x[n]$ stands for the transmitted energy signal of the H-AP at subcarrier n and $z_k[n]$ represents the circularly symmetric

[2] Throughout this paper, we normalize the time duration to unity, so that the terms power and energy are used interchangeably.

complex Gaussian (CSCG) noise at subcarrier n of user k with zero mean and variance σ_k^2. We assume that $x[n]$ and $z_k[n]$ are independent over subcarriers and $\mathbb{E}[|x[n]|^2] = 1$.

Then, the amount of the energy harvested by user k is given by

$$E_k = \zeta \sum_{n \notin S(k)} P_D[n]|h_{D,k}[n]|^2, \tag{2}$$

where $0 < \zeta < 1$ is the conversion efficiency of the energy harvesting process. In (2), the downlink power is sufficiently larger than the noise power so that we ignore it as in [4]. Note that since users operate in the HD mode, user k cannot receive the downlink energy signal through the subcarriers included in $S(k)$.

In the OFDMA-based uplink WIT, each user transmits information signals to the H-AP through the assigned subcarriers $\{S(k)\}$ by using the harvested energy E_k in (2). The received signal of the H-AP at subcarrier n after SIC can be expressed as

$$\begin{aligned}\bar{y}[n] = &\sqrt{P_{U,\Pi(n)}[n]}h_{U,\Pi(n)}[n]x_{\Pi(n)}[n] \\ &+ \sqrt{\beta P_D[n]}h[n]x[n] + z[n], \quad \forall n,\end{aligned} \tag{3}$$

where $P_{U,k}[n]$ stands for the uplink transmit power of user k at subcarrier n, $x_k[n]$ denotes the information signal which user k transmits through subcarrier n with $\mathbb{E}[|x_k[n]|^2] = 1$, $h[n]$ accounts for the complex coefficient of the SI channel at subcarrier n, and $z[n]$ represents the CSCG noise of the H-AP at subcarrier n with zero mean and variance σ^2. After SIC at the analog and digital domain, we can model the effect of the residual SI by multiplying the attenuation factor $\sqrt{\beta}$ on the downlink signal in (3) and set $\mathbb{E}[|h[n]|^2] = 1$ as in [13] and [20]. Subsequently, the achievable rate of user k is obtained by

$$R_k = \sum_{n \in S(k)} \log\left(1 + \frac{|h_{U,k}[n]|^2 P_{U,k}[n]}{\Gamma(\sigma^2 + \beta P_D[n])}\right), \tag{4}$$

where we specify Γ as the gap between the achievable rate and the channel capacity due to a practical modulation and coding scheme (MCS).

In this paper, we investigate a joint subcarrier scheduling and power allocation problem to maximize the sum-rate, which is given as

$$\max_{\{S(k)\},\{P_D[n]\},\{P_{U,k}[n]\}} \quad \sum_{k=1}^{K} R_k \tag{5}$$

$$\text{s.t.} \quad \sum_{n=1}^{N} P_D[n] \le P_T, \tag{6}$$

$$0 \le P_D[n] \le P_{peak}, \quad \forall n, \tag{7}$$

$$\sum_{n \in S(k)} P_{U,k}[n] \le E_k, \quad \forall k, \tag{8}$$

where (6) and (7) represent the total and peak power constraint at the H-AP, respectively, and (8) means that each user cannot use the power more than the harvested energy E_k for the uplink transmission. In the following sections, we solve problem (5) for two different cases. First, the perfect SIC is assumed at the H-AP in Section III. Then, the case where the residual SI exists is considered in Section IV.

III. Perfect SIC Case

In this section, we address the sum-rate maximization problem (5) in the perfect SIC case, i.e., $\beta = 0$. Owing to the subcarrier scheduling variable $\{S(k)\}$, problem (5) is non-convex. Therefore, to identify the globally optimal solution, exhaustive search over K^N possible subcarrier candidates is required, and thus the computational complexity burden becomes prohibitively high with large N and K. To reduce the complexity, we provide an efficient algorithm which jointly optimizes the subcarrier scheduling and the power allocation in what follows.

Given that the SI is perfectly canceled at the H-AP, the achievable rate of user k in (4) can be rewritten as

$$R_k^{P-SIC} = \sum_{n \in S(k)} \log\left(1 + \frac{|h_{U,k}[n]|^2 P_{U,k}[n]}{\Gamma \sigma^2}\right). \tag{9}$$

By plugging (9) into problem (5), we can reformulate following optimization problem.

$$\max_{\{S(k)\},\{P_D[n]\},\{P_{U,k}[n]\}} \quad \sum_{k=1}^{K} R_k^{P-SIC} \tag{10}$$

$$\text{s.t.} \quad \text{(6), (7), and (8).} \tag{11}$$

Although this problem (10) is generally non-convex due to $\{S(k)\}$, it has been shown that the duality gap of this problem, similar to problems in [21] where energy harvesting constraint is not included, converges to zero as N increases to infinity. Thus, we solve problem (10) using the Lagrange duality method with the zero duality gap.[3]

The Lagrangian of problem (10) is given by

$$\begin{aligned}&\mathcal{L}(\{S(k)\}, \{P_D[n]\}, \{P_{U,k}[n]\}, \{\lambda_k\}, \mu) \\ &= \sum_{k=1}^{K} R_k - \mu\left(\sum_{n=1}^{N} P_D[n] - P_T\right) \\ &\quad - \sum_{k=1}^{K} \lambda_k \left(\sum_{n \in S(k)} P_{U,k}[n] - \zeta \sum_{n \notin S(k)} P_D[n]|h_{D,k}[n]|^2\right),\end{aligned} \tag{12}$$

where μ and $\{\lambda_k\}$ are the non-negative dual variables related to the constraint (6) and (8), respectively. To obtain the dual function $g(\{\lambda_k\}, \mu)$, we need to solve the following problem

$$\max_{\{S(k)\},\{P_D[n]\},\{P_{u,k}[n]\}} \quad \mathcal{L}(\{S(k)\}, \{P_D\}, \{P_u\}, \{\lambda_k\}, \mu)$$

$$\text{s.t.} \quad 0 \le P_D[n] \le P_{peak}, \quad \forall n. \tag{13}$$

For fixed $\{S(k)\}$ (or equivalently $\{\Pi(n)\}$), problem (13) is jointly convex with respect to $\{P_D[n]\}$ and $\{P_{U,k}[n]\}$. Based on this fact, we first compute $\{S(k)\}$, and then optimize the uplink and the downlink power allocation with the given $\{S(k)\}$. In the following lemma, we derive the optimal subcarrier scheduling solution of problem (13).

[3] In our simulations in Section V, we have verified that the duality gap of problem (10) is negligible at $N = 8$. Thus, in this paper, we assume that the duality gap of problem (10) can be ignored for the practical size of N.

Lemma 1: With a given set of $\{\lambda_k\}$ and μ, the optimal subcarrier scheduling function $\Pi(n)$ which maximizes the Lagrangian (12) is chosen as

$$\Pi(n) = \arg\max_k \log\left(1 + \frac{|h_{U,k}[n]|^2 \hat{P}_{U,k}[n]}{\Gamma\sigma^2}\right) - \lambda_k \hat{P}_{U,k}[n] + \hat{P}_D[n]\left(\zeta \sum_{s\neq k} \lambda_s |h_{D,s}[n]|^2 - \mu\right), \tag{14}$$

where $\hat{P}_{U,k}[n]$ and $\hat{P}_D[n]$ for $\forall n$ are determined by

$$\hat{P}_{U,k}[n] = \left(\frac{1}{\lambda_k} - \frac{\Gamma\sigma^2}{|h_{U,k}[n]|^2}\right)^+,$$
$$\hat{P}_D[n] = \begin{cases} P_{peak}, & \zeta \sum_{s\neq k} \lambda_s |h_{D,s}[n]|^2 - \mu > 0, \\ 0, & \text{else.} \end{cases} \tag{15}$$

Here $(x)^+ \triangleq \max(0, x)$.

Proof: See Appendix A. ■

Now, with the subcarrier scheduling function $\{\Pi(n)\}$ (or equivalently $\{S(k)\}$) computed in Lemma 1, $\{P_{U,k}[n]\}$ and $\{P_D[n]\}$ which maximize the Lagrangian (12) can be obtained by setting $\frac{\partial}{\partial P_{U,\Pi(n)}[n]}\mathcal{L} = 0$ and $\frac{\partial}{\partial P_D[n]}\mathcal{L} = 0$, respectively. Then, the optimal uplink and downlink power allocations for problem (13) become

$$P_{U,k}[n] = \begin{cases} \hat{P}_{U,k}[n], & k = \Pi(n), \\ 0, & \text{else,} \end{cases} \tag{16}$$

$$P_D[n] = \begin{cases} P_{peak}, & \zeta \sum_{k\neq\Pi(n)}^K \lambda_k |h_{D,k}[n]|^2 - \mu > 0, \\ 0, & \text{else,} \end{cases} \tag{17}$$

Notice that if $\zeta \sum_{k\neq\Pi(n)}^K \lambda_k |h_{D,k}[n]|^2 - \mu = 0$, the optimal $P_D[n]$ of problem (13) is not unique and can be any nonnegative value. Thus, we take $P_D[n] = 0$ for such n which satisfies $\zeta \sum_{k\neq\Pi(n)}^K \lambda_k |h_{D,k}[n]|^2 - \mu = 0$, only for solving problem (13). From Lemma 1 and equation (16), and (17), we can calculate the dual function $g(\{\lambda_k\}, \mu)$ with given dual variables $\{\lambda_k\}$ and μ. Then, the dual problem is defined as $\min_{\{\lambda_k\},\mu} g(\{\lambda_k\}, \mu)$ and this can be solved by the ellipsoid method [22]. The sub-gradient of the dual function are expressed by $\nu = [\nu_{\lambda_1}, \ldots, \nu_{\lambda_K}, \nu_\mu]^T$, where

$$\nu_{\lambda_k} = \zeta \sum_{n\notin S(k)}^N P_D[n]|h_{D,k}[n]|^2 - \sum_{n\in S(k)} P_{U,k}[n], \quad \forall k,$$
$$\nu_\mu = P_T - \sum_{n=1}^N P_D[n].$$

Then, the optimal solution $\{S(k)\}$ and $\{P_{U,k}[n]\}$ for the dual problem are determined with the optimal $\{\lambda_k^\star\}$ and $\mu^\star$. It is worth noting that the objective function of problem (10) is an increasing function of each individual $P_{U,k}[n]$. Therefore, the inequality constraints in (6) and (8) hold with equality at the optimal $\{P_{U,k}^\star[n]\}$ and $\{P_D^\star[n]\}$. However, a solution from (17) may not achieve equality in (6), since it is either P_{peak} or 0.

Thus, defining the set $\mathcal{D}_1 = \{n|\zeta \sum_{k\neq\Pi^\star(n)}^K \lambda_k^\star |h_{D,k}[n]|^2 - \mu^\star = 0\}$, $\mathcal{D}_2 = \{n|\zeta \sum_{k\neq\Pi^\star(n)}^K \lambda_k^\star |h_{D,k}[n]|^2 - \mu^\star > 0\}$, and $\mathcal{D}_3 = \{n|\zeta \sum_{k\neq\Pi^\star(n)}^K \lambda_k^\star |h_{D,k}[n]|^2 - \mu^\star < 0\}$ where $\{\lambda_k^\star\}$ and $\mu^\star$ are the optimal solutions of the dual problem and $\{\Pi^\star(n)\}$ is the corresponding optimal solution obtained from the ellipsoid method, the optimal downlink power allocation can be set as for $\{P_D^\star[n]\} = P_{peak}$ if $n \in \mathcal{D}_2$ and $\{P_D^\star[n]\} = 0$ if $n \in \mathcal{D}_3$.

To satisfy the constraint (6) with equality, $\{P_D[n]\}$ for $n \in \mathcal{D}_1$ can be determined by solving the following problem:

$$\max_{\{P_D[n]\}_{n\in\mathcal{D}_1}, \{P_{U,k}[n]\}} \sum_{k=1}^K \sum_{n\in S(k)} \log\left(1 + \frac{|h_{U,k}[n]|^2 P_{U,k}[n]}{\Gamma\sigma^2}\right)$$
$$s.t. \quad \sum_{n\in\mathcal{D}_1} P_D[n] = P_T - P_{peak}|\mathcal{D}_2|,$$
$$\sum_{n\in S(k)} P_{U,k}[n] = \zeta \sum_{n\notin S(k)}^N P_D[n]|h_{D,k}[n]|^2, \ \forall k,$$
$$0 \leq P_D[n] \leq P_{peak}, \ \forall n. \tag{18}$$

With fixed $\{S(k)\}$, problem (18) is jointly convex over $\{P_{U,k}[n]\}$ and $\{P_D[n]\}_{n\in\mathcal{D}_1}$. This convex problem (18), which contains the reduced number of the optimization variables,[4] can now be efficiently solved by existing software, e.g., CVX [23]. Our algorithm for problem (10) is summerized in Algorithm 1.[5] Note that the iterative procedure in Algorithm 1 is based on the ellipsoid method, whose convergence behavior has been proven in [24].

The computational complexity of Algorithm 1 can be computed as follows: The complexity of the loop inside the step 2 is $\mathcal{O}(KN)$, and the convergence rate of it, which is based on the ellipsoid method, is given by $\mathcal{O}(K^2)$ [24]. Since the overall complexity is dominated by the loop in step 2, the final computational complexity of Algorithm 1 becomes $\mathcal{O}(K^3N)$.

Algorithm 1. Joint subcarrier scheduling and power allocation algorithm for perfect SIC

1. Initialize $\{\lambda_k > 0\}$ and $\mu > 0$.
2. **Repeat**
   Compute $\{\hat{P}_{U,k}[n]\}$ and $\{\hat{P}_D[n]\}$ in (15).
   Obtain the scheduling function $\Pi(n)$ in (14).
   Calculate $\{P_{U,\Pi(n)}[n]\}$ and $\{P_D[n]\}$ in (16).
   Update $\{\lambda_k\}$ and μ by using the ellipsoid method.
3. **Until** convergence
4. Set $\Pi^\star(n) = \Pi(n)$ for $\forall n$.
5. Compute the set $\mathcal{D}_1$, $\mathcal{D}_2$, and $\mathcal{D}_3$.
6. Set $P_D^\star[n] = \begin{cases} P_{peak}, & \text{if } n \in \mathcal{D}_2 \\ 0, & \text{if } n \in \mathcal{D}_3 \end{cases}$
7. Obtain $\{P_{U,k}^\star[n]\}$ and $\{P_D^\star[n]\}$ for $n \in \mathcal{D}_1$ by solving (18).

[4]Considering the property of the OFDMA user scheduling function $\Pi[n]$ and the fact that the total amount of the harvested energy in (2) is a linear function of $\{P_D[n]\}$, we can readily verify that $|\mathcal{D}_1|$ is less than K. For the sake of brevity, we omit the proof.

[5]It is possible to happen that the subcarrier n which satisfies $P_{U,\Pi^\star(n)}^\star[n] = 0$ can be used as the downlink energy harvesting for user $\Pi^\star(n)$, and overall performance will increase. One possible solution for this case can be obtained by solving problem (18) with $S(k) = \{n|P_{U,k}^\star[n] \neq 0\}$.

IV. Imperfect SIC Case

Next, we consider a more practical case where SI is not totally canceled at the H-AP, i.e., $\beta > 0$ in problem (5). Unlike the previous perfect SIC case, problem (5) is generally non-convex even when the subcarrier scheduling function $\{S(k)\}$ is fixed, since the objective function is non-convex with respect to $\{P_D[n]\}$. Thus, it is more difficult to find the globally optimal solution for problem (5) in an efficient manner. In this case, we identify a local optimal solution by alternatively updating $\{P_{U,k}[n]\}$, $\{S(k)\}$, and $\{P_D[n]\}$. To be specific, we first update $\{P_{U,k}[n]\}$ and $\{S(k)\}$ with given $\{P_D[n]\}$, similar to the perfect SIC case, utilizing the Lagrangian duality method. Then, $\{P_D[n]\}$ are updated with fixed $\{P_{U,k}[n]\}$ and $\{S(k)\}$ based on the projected gradient method. The above procedure is alternated until the sum-rate converges.

Let us denote $P_{U,k}^{(i)}[n]$ and $P_D^{(i)}[n]$ as the uplink and downlink power allocation obtained at the i-th iteration, respectively. Given $\{P_D^{(i-1)}[n]\}$, problem (5) is simplified as

$$\max_{\{S(k)\},\{P_{U,k}\}} \sum_{k=1}^{K} R_k \tag{19}$$

$$\text{s.t.} \quad \sum_{n\in S(k)} P_{U,k}[n] \le E_k, \quad \forall k, \tag{20}$$

$$P_{U,k}[n] \ge 0, \quad \forall n,k.$$

With fixed $\{P_D^{(i-1)}[n]\}$, the above problem (19) is similar to that of the perfect SIC case. Although problem (19) is non-convex due to the subcarrier scheduling function $\{\Pi(n)\}$, we can solve it by exploiting the Lagrange duality method with the zero duality gap. The Lagrangian of problem (19) is written by

$$\begin{aligned}&\mathcal{L}_{SI}(\{S(k)\},\{P_{U,k}[n]\},\{\upsilon_k\})\\ &= \sum_{k=1}^{K} R_k - \sum_{k=1}^{K} \upsilon_k \left(\sum_{n\in S(k)} P_{U,k}[n] - E_k \right),\end{aligned} \tag{21}$$

where υ_k denotes non-negative dual variable associated with the constraint (20).

The dual function $g(\{\upsilon_k\})$ can be obtained by solving the following problem

$$\max_{\{S(k)\},\{P_{u,k}[n]\}} \mathcal{L}_{SI}(\{S(k)\},\{P_{u,k}[n]\},\{\upsilon_k\}) \tag{22}$$

Next, we will compute the optimal $\{S(k)\}$ and $\{P_{U,k}[n]\}$ of problem (22). First, we provide the optimal subcarrier scheduling function of problem (22) with given $\{P_D^{(i-1)}[n]\}$ in the following lemma.

Lemma 2: With a given set of $\{P_D^{(i-1)}[n]\}$ and $\{\upsilon_k\}$, the optimal subcarrier scheduling function $\Pi(n)$ that maximizes the Lagrangian (21) can be calculated as

$$\begin{aligned}\Pi^{(i)}(n) = \arg\max_k \log&\left(1 + \frac{|h_{U,k}[n]|^2 \hat{P}_{U,k}^{(i)}[n]}{\Gamma(\sigma^2 + \beta P_D^{(i-1)}[n])}\right)\\ &- \upsilon_k \hat{P}_{U,k}^{(i)}[n] + P_D^{(i-1)}[n]\left(\zeta \sum_{s\neq k} \upsilon_s |h_{D,s}[n]|^2\right),\end{aligned} \tag{23}$$

where $\hat{P}_{U,k}^{(i)}[n]$ is

$$\hat{P}_{U,k}^{(i)}[n] = \left(\frac{1}{\upsilon_k} - \frac{\Gamma(\sigma^2 + \beta P_D^{(i-1)}[n])}{|h_{U,k}[n]|^2}\right)^+, \quad \forall n,k. \tag{24}$$

Proof: The proof is similar as that of Lemma 1, and thus is omitted. ∎

With the subcarrier scheduling function $\Pi^{(i)}(n)$ determined in (23), $\{P_{u,k}^{(i)}[n]\}$ maximizing the Lagrangian (21) can be found by setting $\frac{\partial}{\partial P_{U,\Pi(n)}^{(i)}[n]}\mathcal{L} = 0$. Then, the optimal uplink power allocation is given by

$$P_{U,k}^{(i)}[n] = \begin{cases} \hat{P}_{U,k}^{(i)}[n], & \text{for } k = \Pi^{(i)}(n),\\ 0, & \text{else.}\end{cases} \tag{25}$$

Subsequent to identifying the dual function $g(\{\upsilon_k\})$ by using Lemma 2 and (25), the dual problem is then defined as $\min_{\{\upsilon_k\}} g(\{\upsilon_k\})$ and this can be solved by the ellipsoid method where the sub-gradient of the dual function can be computed as $\nu = [\nu_{\upsilon_1}, \dots, \nu_{\upsilon_K}]^T$ with

$$\nu_{\upsilon_k} = \zeta \sum_{n\notin S^{(i)}(k)} P_D^{(i-1)}[n]|h_{D,k}[n]|^2 - \sum_{n\in S^{(i)}(k)} P_{U,k}^{(i)}[n], \quad \forall k.$$

After the ellipsoid method converges, the optimal $\{S^{(i)}(k)\}$ and $\{P_{U,k}^{(i)}[n]\}$ of problem (22) is obtained corresponding to the optimal dual variable $\{\upsilon_k^\star\}$.

Once $\{S^{(i)}(k)\}$ and $\{P_{U,k}^{(i)}[n]\}$ are found, $\{P_D^{(i)}[n]\}$ can be identified by exploiting the projected gradient method [22]. The gradient of the objective function $R(\{P_D^{(i-1)}[n]\})$ is expressed as $\nabla\mathbf{r} = [r_1^{(i)}, \dots, r_N^{(i)}]^T$, where

$$R(\{P_D^{(i-1)}[n]\}) = \sum_{k=1}^{K} \sum_{n\in S^{(i)}(k)} \log\left(1 + \frac{|h_{U,k}[n]|^2 P_{U,k}^{(i)}[n]}{\Gamma(\sigma^2+\beta P_D^{(i-1)}[n])}\right)$$

and

$$r_n^{(i)} = \frac{\dfrac{-P_{U,\Pi^{(i)}(n)}^{(i)}[n]|h_{U,\Pi^{(i)}(n)}|^2\beta}{\Gamma(\sigma^2+\beta P_D^{(i-1)}[n])^2}}{1 + \dfrac{P_{U,\Pi^{(i)}(n)}^{(i)}[n]|h_{U,\Pi^{(i)}(n)}|^2}{\Gamma(\sigma^2+\beta P_D^{(i-1)}[n])}}, \quad \forall n. \tag{26}$$

For simplicity, we denote $\mathbf{P}_D^{(i)} = [P_D^{(i)}[1], \dots, P_D^{(i)}[N]]^T$. Then, by applying the above gradient in (26) as a descent direction, $\mathbf{P}_D^{(i)}$ can be updated as

$$\mathbf{P}_D^{(i)} = \mathcal{P}_{\mathcal{E}}(\mathbf{P}_D^{(i-1)} + t^{(i)}\nabla\mathbf{r}) \tag{27}$$

where $t^{(i)}$ is a small step size and $\mathcal{P}_{\mathcal{E}}(x)$ represents the projection operation of x onto a feasible set $\mathcal{E} = \{\mathbf{P}_D | \sum_{n=1}^{N} P_D[n] = P_T \text{ and } 0 \le P_D[n] \le P_{peak}, \forall n\}$.[6]

[6]In general, the total power constraint (6) may not hold with equality at the optimal $\{P_D[n]\}$, but this is usually desirable since there is no energy waste at the H-AP [13].

Algorithm 2. Subcarrier scheduling and power allocation algorithm of WPCN for imperfect SIC

Set $i = 0$ and $\{P_D^{(0)}[n]\} = 0, \quad \forall n$.
Repeat
  Set $i \leftarrow i + 1$ and initialize the dual variables $\{\upsilon_k\}$.
  Repeat
    Compute $\{\hat{P}_{U,k}[n]\}$ in (24).
    Obtain the scheduling function $\Pi^{(i)}(n)$ in (23).
    Compute $\{P^{(i)}_{U,\Pi^i(n)}\}$ for $n = 1, \ldots, N$ in (25).
    Update $\{\upsilon_k\}$ by using the ellipsoid method.
  Until $\{\upsilon_k\}$ converges.
  Update $\{P_D^{(i)}[n]\}$ by applying the projected gradient method (27).
Until $R(\{P^{(i)}_{U,k}[n]\}, \{S^{(i)}(k)\}, \{P_D^{(i)}[n]\})$ converges.

For the imperfect SIC case, the above procedure is repeated until the sum-rate

$$R(\{P_{U,k}[n]\}, \{P_D[n]\}, \{S(k)\})$$

converges. Note that this method yields a local optimum solution, depending on the choice of initial values of $\{P_D^{(0)}[n]\}$. To improve the performance of the solution, we randomly generate M feasible $\{P_D^{(0)}[n]\}$ as the initialization points, and the final solution can be chosen as the one that achieves the best sum-rate. We summarize the proposed algorithm which solves problem (5) for the imperfect SIC case in Algorithm 2.

It is worthwhile to note that the proposed Algorithm 2 guarantees convergence since the sum rate is upper bounded by a certain value and increases monotonically in each step where an outer loop is based on the projected gradient method [24]. We will further verify the convergence of Algorithm 2 in Section V from numerical results. Next, we briefly examine the complexity issue. In a similar manner as in Algorithm 1, the complexity of the inner loop of Algorithm 2 can be expressed as $\mathcal{O}(K^3N)$. Also, $\mathcal{O}(N^2)$ computations is required for the outer loop where the projected gradient method is applied. Considering M initialization points, the total computational complexity of Algorithm 2 becomes $\mathcal{O}(K^3NM + N^2M)$.

V. Simulation Results

In this section, we evaluate the average sum-rate performance of the WPCN for OFDM systems in the perfect and imperfect SIC cases. Throughout simulations, the total bandwidth is set to be 10 MHz, which is equally divided by N subcarriers. The frequency selective uplink and downlink channels for different users are independently generated by the 6 tap exponentially distributed power profile. Also, the distance from the H-AP to all users is 1 meter which results in -30 dB path-loss for all subcarrier channels and the noise power spectral density equals -112 dBm/Hz as in [6]. In addition, the energy harvesting efficiency, the MCS gap, and the number of initializations M are set to be $\zeta = 0.5$, $\Gamma = 9$ dB, and $M = 20$,[7] respectively.

[7]We confirm through our simulation that $M = 20$ is sufficient for achieving good performance.

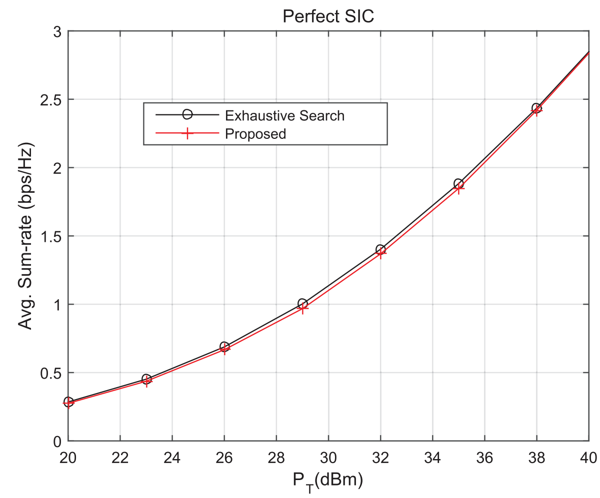

Fig. 2. Average sum-rate of the proposed algorithm and the exhaustive search for the perfect SIC with $K = 2$, $N = 16$, and $P_{peak} = \frac{2P_T}{N}$.

In this section, we compare the average sum-rate performance with the following two conventional schemes.

- **Equal downlink power allocation**: the downlink power is evenly assigned, i.e., $P_D[n] = \frac{P_T}{N}$, $\forall n$. Then, the subcarrier scheduling function $\{\Pi(n)\}$ is obtained by applying our solution with given $\{P_D[n]\}$, and the uplink power allocation is computed by the water-filling algorithm.
- **Channel-based subcarrier scheduling**: the subcarrier scheduling function $\{\Pi(n)\}$ is chosen by selecting the user with the largest uplink channel gain at subcarrier n, i.e., $\Pi(n) = \arg\max_k h_{U,k}[n]$, $\forall n$. Then, the downlink and uplink power allocations are implemented by employing the proposed algorithms.

Figure 2 illustrates the average sum-rate of the WPCN for OFDM systems in the perfect SIC case with $K = 2$, $N = 16$ and $P_{Peak} = \frac{2P_T}{N}$. Here, we also plot the performance of the optimal scheme which finds the optimal subcarrier scheduling function $\{\Pi^\star(n)\}$ by the exhaustive search. Then, the downlink and uplink power allocation can be identified from the proposed algorithm with given $\{\Pi^\star(n)\}$. As shown in Figure 2, no performance difference is observed between the exhaustive search and the proposed algorithm, which verifies the zero duality gap. Note that the exhaustive search method requires K^N comparison for the subcarrier scheduling, while the proposed algorithm only compares KN candidates. Therefore, when $N = 16$, the number of candidates for the subcarrier scheduling for the proposed algorithm and the exhaustive search become 2^{16} and 2×16, respectively, which indicates that the proposed scheme requires only 0.05% of the number of candidates compared to the exhaustive search. It is clear that our proposed algorithm exhibits a near-optimal performance with dramatically reduced complexity.

In Figure 3, the average sum-rate of WPCN for OFDM systems with $N = 64$ is demonstrated for the perfect SIC case. We can observe that the proposed algorithm outperforms the conventional equal downlink power allocation schemes, and the performance gap increases as the available total power at the H-AP grows. With $P_T = 35$ dBm, the proposed algorithm

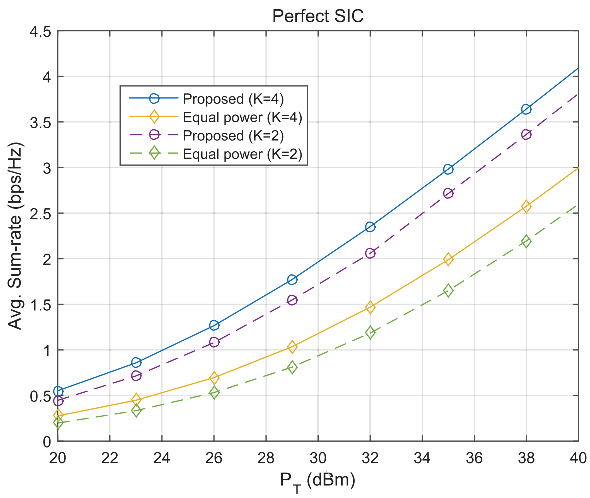

Fig. 3. Average sum-rate comparison for the perfect SIC with $P_{peak} = \frac{2P_T}{N}$ and $N = 64$.

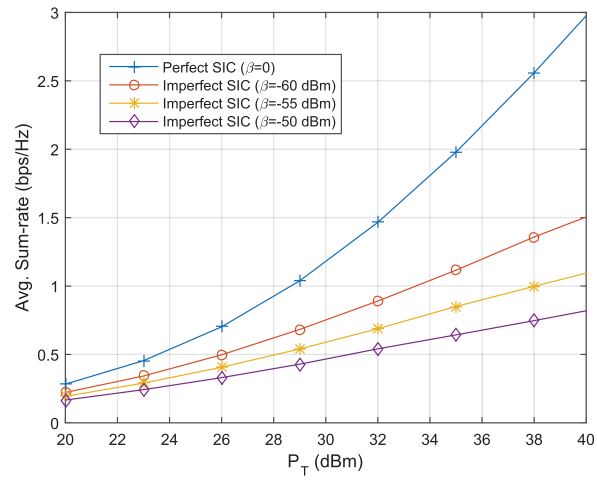

Fig. 5. Average sum-rate of the proposed algorithm for different values of β with $K = 2$, $N = 64$, and $P_{peak} = \frac{2P_T}{N}$.

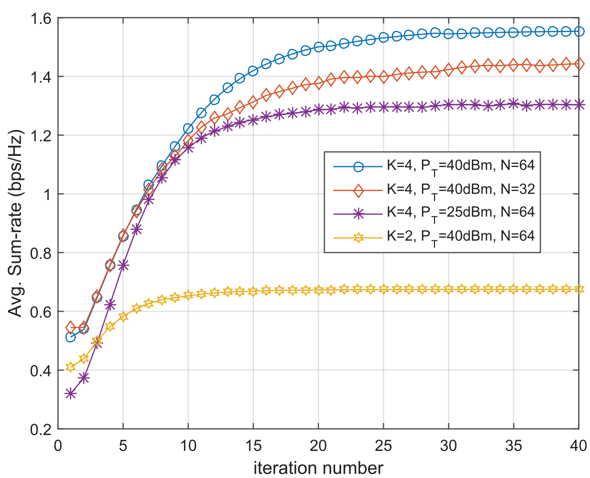

Fig. 4. Average sum-rate with respect to the iteration number of the proposed algorithm for the imperfect SIC case.

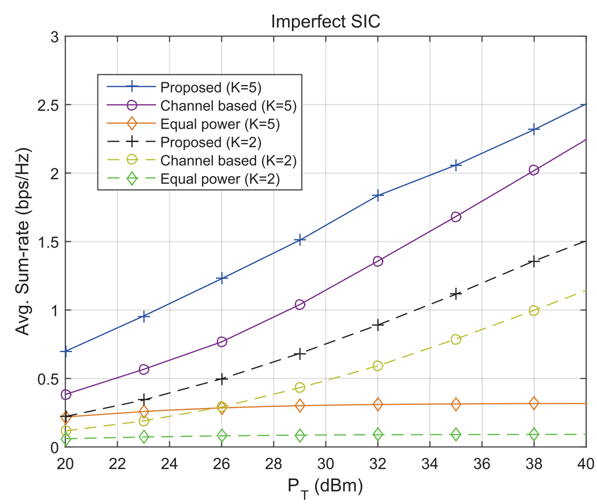

Fig. 6. Average sum-rate of WPCN for OFDM systems with $\beta = -60$ dBm, $N = 64$, and $P_{peak} = \frac{2P_T}{N}$.

provides 64% and 50% gains over the downlink equal power allocation scheme at $K = 2$ and $K = 4$, respectively.

In Figure 4, we illustrate the convergence behavior of the proposed algorithm for the imperfect SIC case with different system parameters. We can see that for all cases, the average sum-rate converges within 30 iterations. In addition, it is shown that the average sum-rate converges faster for small K and P_T, while N does not affect the number of iterations for the convergence.

Next, by fixing $K = 2$, $P_{Peak} = \frac{2P_T}{N}$, and $N = 64$, Figure 5 depicts the average sum-rate performance for the imperfect SIC case with different β, which indicates the level of the SIC. The performance of our proposed algorithm for perfect SIC is plotted for $\beta = 0$ case. It is observed that the average sum-rate increases as β decreases and the performance gap between the perfect and imperfect SIC cases increases as P_T grows, since SI significantly degrades the achievable sum-rate performance at a high P_T regime.

Figure 6 compares the average sum-rate of the proposed algorithm with conventional schemes in the imperfect SIC case. First, we can see that the proposed algorithm exhibits a 41% performance gain at $K = 5$ and $P_T = 32$ dBm compared to the channel-based subcarrier scheduling scheme, which does not consider SI when determining subcarrier scheduling. In addition, it is observed that our proposed algorithm provides a significant performance enhancement compared to the equal downlink power allocation scheme. The performance of the equal downlink power allocation scheme does not improve as P_T increases, which is different compared to the perfect SIC case in Figure 3. This is due to the fact that the SI has more impact on the sum-rate than the uplink power allocation.

VI. Conclusion

In this paper, we have investigated joint subcarrier scheduling and power allocation algorithms of WPCN for OFDM systems where a FD H-AP is employed. We have considered two different scenarios according to the level of the SIC. First, for the perfect SIC case, a joint subcarrier scheduling, downlink and uplink power allocation algorithm has been proposed based on the Lagrange duality method, and we have proven that it achieves the near-optimal performance with much reduced complexity. Next, for the practical imperfect SIC case, an iterative algorithm has been introduced by using the projected gradient method. Simulation results have confirmed that the proposed algorithm outperforms the conventional schemes, and shown that the downlink power allocation plays a key role when maximizing the sum-rate of WPCN for OFDM systems with the FD H-AP.

Appendix A
Proof of Lemma 1

To obtain the dual function of problem (13), we consider the following Lagrangian maximization problem as

$$\begin{aligned}
&\max_{\{S(k)\},\{P_D[n]\},\{P_{U,k}[n]\}} \mathcal{L}(\{S(k)\},\{P_D[n]\},\{P_{U,k}[n]\},\{\lambda\},\mu)\\
&= \max_{\{\Pi(n)\},\{P_D[n]\},\{P_{U,k}[n]\}} \sum_{n=1}^{N}\left(\log\left(1+\frac{|h_{U,\Pi(n)}[n]|^2 P_{U,\Pi(n)}[n]}{\Gamma\sigma^2}\right)\right.\\
&\quad \left. -\lambda_{\Pi(n)}P_{U,\Pi(n)} + P_D[n]\left(\zeta\sum_{k\neq\Pi(n)}^{K}\lambda_k|h_{D,k}[n]|^2-\mu\right)\right)\\
&\quad +\mu P_T\\
&= \sum_{n=1}^{N}\max_k\left\{\max_{\{P_D[n]\},\{P_{U,k}[n]\}}\log\left(1+\frac{|h_{U,k}[n]|^2P_{U,k}[n]}{\Gamma\sigma^2}\right)\right.\\
&\quad \left. +P_D[n]\left(\zeta\sum_{s\neq k}^{K}\lambda_s|h_{D,s}[n]|^2-\mu\right)-\lambda_kP_{U,k}[n]\right\}+\mu P_T\\
&= \sum_{n=1}^{N}\max_k\left(\max_{\{P_D[n]\},\{P_{U,k}[n]\}}\tilde{\mathcal{L}}_{n,k}\right)+\mu P_T\\
&= \sum_{n=1}^{N}\max_k \mathcal{L}_{n,k}+\mu P_T\\
&= \sum_{n=1}^{N}\mathcal{L}_n+\mu P_T,
\end{aligned}$$

where $\tilde{\mathcal{L}}_{n,k}$, $\mathcal{L}_{n,k}$, and $\mathcal{L}_n$ are defined as

$$\begin{aligned}
\tilde{\mathcal{L}}_{n,k} &\triangleq \log\left(1+\frac{|h_{U,k}[n]|^2P_{U,k}[n]}{\Gamma\sigma^2}\right)-\lambda_kP_{U,k}\\
&\quad + P_D[n]\left(\zeta\sum_{s\neq k}^{K}\lambda_s|h_{D,s}[n]|^2-\mu\right),\\
\mathcal{L}_{n,k} &\triangleq \max_{\{P_D[n]\},\{P_{U,k}[n]\}}\tilde{\mathcal{L}}_{n,k}\\
\mathcal{L}_n &\triangleq \max_k \mathcal{L}_{n,k}.
\end{aligned}$$

As we can see, Lagrangian (12) can be expressed as a sum of individual $\mathcal{L}_n$ which is determined by finding the maximum value of $\mathcal{L}_{n,k}$ over $\forall k$. To calculate $\mathcal{L}_{n,k}$, we first set $\Pi(n)=k$, and then applying the zero gradient condition $\frac{\partial}{\partial P_{U,k}[n]}\tilde{\mathcal{L}}_{n,k}=0$, and $\frac{\partial}{\partial P_D[n]}\tilde{\mathcal{L}}_{n,k}=0$. Finally, we can respectively identify $\hat{P}_{U,k}[n]$ and $\hat{P}_D[n]$ that maximize $\tilde{\mathcal{L}}_{n,k}$ as shown in (15).

References

[1] C. K. Ho and R. Zhang, "Optimal energy allocation for wireless communications with energy harvesting constraints," *IEEE Trans. Signal Process.*, vol. 60, no. 9, pp. 4808–4818, Sep. 2012.

[2] H. Ju and R. Zhang, "Throughput maximization in wireless powered communication networks," *IEEE Trans. Wireless Commun.*, vol. 13, no. 1, pp. 418–428, Jan. 2014.

[3] X. Zhou, R. Zhang, and C. K. Ho, "Wireless information and power transfer: Architecture design and rate-energy tradeoff," *IEEE Trans. Wireless Commun.*, vol. 61, no. 11, pp. 4754–4767, Oct. 2013.

[4] R. Zhang and C. K. Ho, "MIMO broadcasting for simultaneous wireless information and power transfer," *IEEE Trans. Wireless Commun.*, vol. 12, no. 5, pp. 1989–2001, May 2013.

[5] J. Xu, L. Liu, and R. Zhang, "Multiuser MISO beamforming for simultaneous wireless information and power transfer," *IEEE Trans. Wireless Commun.*, vol. 62, no. 18, pp. 4798–4810, Sep. 2014.

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

[7] K. Huang and E. Larsson, "Simultaneous information and power transfer for broadband wireless systems," *IEEE Trans. Signal Process.*, vol. 61, no. 23, pp. 5972–5986, Dec. 2013.

[8] H. Lee, S.-R. Lee, H.-B. Kong, and I. Lee, "Optimal beamforming designs for wireless information and power transfer in MISO interference channels," *IEEE Trans. Wireless Commun.*, vol. 14, no. 9, pp. 4810–4821, Apr. 2015.

[9] X. Zhou, C. K. Ho, and R. Zhang, "Wireless power meets energy harvesting: A joint energy allocation approach," in *Proc. IEEE Global Conf. Signal Inf. Process.*, Dec. 2014, pp. 198–202.

[10] X. Zhou, C. K. Ho, and R. Zhang, "Wireless power meets energy harvesting: A joint energy allocation approach in OFDM-based system," *IEEE Trans. Wireless Commun.*, to be published.

[11] L. Liu, R. Zhang, and K.-C. Chua, "Multi-antenna wireless powered communication with energy beamforming," *IEEE Trans. Wireless Commun.*, vol. 62, no. 12, pp. 4649–4361, Dec. 2014.

[12] X. Kang, C. K. Ho, and S. Sun, "Full-duplex wireless-powered communication network with energy causality," *IEEE Trans. Wireless Commun.*, vol. 14, no. 10, pp. 5539–5551, Jun. 2015.

[13] H. Ju and R. Zhang, "Optimal resource allocation in full-duplex wireless-powered communication network," *IEEE Trans. Commun.*, vol. 62, no. 10, pp. 3528–3540, Oct. 2014.

[14] C. Zhong, H. A. Suraweera, G. Zheng, I. Krikidis, and Z. Zhang, "Wireless information and power transfer with full duplex relaying," *IEEE Trans. Commun.*, vol. 62, no. 10, pp. 3447–3461, Oct. 2014.

[15] B. P. Day, A. R. Margetts, D. W. Bliss, and P. Schniter, "Full-duplex bidirectional MIMO: Achievable rates under limited dynamic range," *IEEE Trans. Signal Process.*, vol. 60, no. 7, pp. 3702–3713, Apr. 2012.

[16] K. Lee, S.-H. Moon, S.-R. Lee, and I. Lee, "Low complexity pilot assisted carrier frequency offset estimation for OFDMA uplink systems," *IEEE Trans. Wireless Commun.*, vol. 11, no. 8, pp. 2690–2695, Aug. 2012.

[17] K. Lee, S.-R. Lee, S.-H. Moon, and I. Lee, "MMSE-based CFO compensation for uplink OFDMA systems with conjugate gradient," *IEEE Trans. Wireless Commun.*, vol. 11, no. 8, pp. 2767–2775, Aug. 2012.

[18] K. Lee, S.-H. Moon, and I. Lee, "A pilot-aided frequency offset estimation algorithm for OFDMA uplink systems," in *Proc. IEEE Veh. Technol. Conf.*, Sep. 2012, pp. 1–5.

[19] H. Kim, H. Lee, M. Ahn, H.-B. Kong, and I. Lee, "Joint subcarrier and power allocation method in wireless powered communication networks for OFDM systems," in *Proc. IEEE Global Commun. Conf. (Globecom)*, Dec. 2015, pp. 1–6.

[20] W. Li, J. Lilleberg, and K. Rillinen, "On rate region analysis of half-and full-duplex OFDM communication links," *IEEE J. Sel. Areas Commun.*, vol. 32, no. 9, pp. 1688–1698, Jun. 2014.

[21] W. Yu and R. Lui, "Dual methods for nonconvex spectrum optimization of multicarrier systems," *IEEE Trans. Commun.*, vol. 54, no. 7, pp. 1310–1322, Jul. 2006.

[22] S. Boyd and L. Vandenberghe, *Convex Optimization*. Cambridge, U.K.: Cambridge Univ. Press, 2004.

[23] M. Grant and S. Boyd. (2014). *CVX: Matlab Software for Disciplined Convex Programming, Version 2.1* [Online]. Available: http://cvxr.com/cvx

[24] S. Boyd. *EE364b Lecture Notes* [Online]. Available: http://www.stanford.edu/class/ee364b/lectures.html

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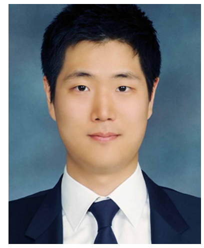

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