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Resource allocation in OFDM-based wireless powered communication networks with SWIPT

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A B S T R A C T

This paper considers a multiuser orthogonal frequency division multiplexing (OFDM)-based wireless powered communication networks (WPCNs) with simultaneous wireless information and power transfer (SWIPT). In particular, both uplink and downlink communications are considered by dividing the time for transmission into downlink and uplink communication phases. In the downlink, SWIPT is adopted at the users with nonlinear energy harvesting model, and in the uplink, users use the harvested energy to perform uplink data transmission. We propose a suboptimal resource allocation scheme to maximize the weighted downlink and uplink sum rate by optimizing the time, subcarrier and power allocation. It is shown that the proposed scheme can well balance between the downlink rate and the uplink rate.

1. Introduction

Energy harvesting in wireless networks has drawn a lot of attention recently due to its ability to provide perpetual energy to wireless devices [1]. Since conventional renewable energy sources such as solar and wind are intermittent and unpredictable, wireless power transfer is preferred as it allows energy to be harvested in a more controlled manner. Basically, there are three classes of wireless power transfer technologies, i.e., inductive coupling, magnetic resonant coupling and RF-based electromagnetic radiation [2,3]. The inductive coupling and magnetic resonant coupling belong to near-field wireless transmission and their charging distance is very limited. Besides, they also require very strict calibration and alignment. Thus, both inductive coupling and magnetic resonant are not suitable for mobile and remote charging. On the contrary, RF-based wireless power transfer uses the far-field radiative properties of electromagnetic waves to power devices distributed in a wide area [4]. Thus, RF-based wireless power transfer is suitable for powering mobile devices. In this paper, we consider RF-based wireless power transfer.

In wireless powered communication networks (WPCNs), users first harvest energy from RF signals transmitted from dedicated power stations and then use the harvested energy for information transmission [5]. In [6], a "harvest-then-transmit" protocol was proposed to let users first harvest energy broadcast by a hybrid access point (HAP) in the downlink, and then transmit data to the HAP in the uplink. In [7], joint optimal power allocation of the HAP and time allocation among the users was optimized to maximize the sum rate of the users. In [8,9], the problems of resource allocation for a cognitive WPCN under the constraint that the primary user's quality of service was unaffected or even improved were investigated. In [10], both the secondary user and the primary user in a cognitive WPCN were assumed to be wirelessly powered and the problem of joint time allocation, subcarrier allocation and power allocation was investigated and solved with a heuristic scheme. In [11], the authors considered an orthogonal frequency division multiplexing (OFDM)-based WPCN and investigated subcarrier allocation and power allocation to maximize the sum rate of the users. In [12], a cognitive small cell-based WPCN was considered to offload data traffic from a macrocell and iterative data traffic offloading schemes were proposed to maximize the small cell throughput under the constraint that the required minimum macrocell throughput is satisfied. In [13], by considering that users are capable of harvesting energy from uplink signals of other users in a WPCN, the optimal time allocations to maximize the weighted sum rate and minimize the total transmission time were derived. In [14], the achievable throughput of a multiuser WPCN under non-identical Nakagami fading environments was derived in closed-form and maximized by obtaining the optimal time allocation. In [15], resource allocation in a cognitive WPCN for guaranteeing secure primary communication was investigated. Besides, energy efficiency [16], defined as the ratio of the achieved throughput to the consumed energy is also a hot research topic in

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WPCNs. Specifically, in [17], the problem of maximizing achievable system energy efficiency of a WPCN by jointly optimizing time and power allocation was investigated with and without the minimum system throughput constraint. In [18], the weighted sum of the user energy efficiency of a WPCN was maximized by jointly optimizing time and power allocation with and without the minimum user throughput constraint. In [19], the energy efficiency of a WPCN based on nonorthogonal multiple access was investigated.

Meanwhile, simultaneous wireless information and power transfer (SWIPT) was proposed to transmit energy and information at the same time [20]. A time switching scheme was proposed in [20] to switch between the mode of energy harvesting and information decoding for SWIPT. In [21], the optimal design for both the time switching scheme and the power splitting scheme in an OFDM system with SWIPT was investigated. In [22], the channel allocation, power allocation and power splitting ratio were jointly optimized in a cognitive radio network with SWIPT. In [23,24], the effective capacity and effective energy efficiency of an OFDM-based SWIPT system based on the time switching and the power splitting schemes were maximized subject to the minimum harvested energy, the average sum transmit power and the delay quality of service constraints. In [25], a new SWIPT scheme was proposed for multiuser OFDM systems and was shown to outperform the time switching and the power splitting schemes.

Note that WPCN is usually used for uplink information transmission, while SWIPT is usually used for downlink energy and information transmission. Naturally, if WPCN and SWIPT can be considered together, both downlink and uplink information transmission can be achieved. Although considering both WPCN and SWIPT may degrade uplink/downlink rate compared to solo WPCN/SWIPT, WPCN with SWIPT is appealing due to the fact that both downlink information transmission and uplink information transmission can be realized, rather than only uplink/downlink information transmission for WPCN/SWIPT. However, to our best knowledge, no existing work has jointly considered WPCN and SWIPT.

Motivated by above discussions, this paper considers a multiuser OFDM-based WPCN with SWIPT. Specifically, both uplink and downlink communications are considered, and the time for transmission is assumed to be divided into the downlink and the uplink communication phases. In the downlink communication phase, the SWIPT scheme proposed in [25] is adopted at the users, where each user decodes information on its allocated subcarriers for data transmission and harvests energy on other subcarriers. Specifically, the energy harvesting at each user is assumed to be nonlinear. In the uplink communication phase, users use the harvested energy to perform uplink data transmission. Then, we propose a suboptimal resource allocation scheme to maximize the weighted downlink and uplink sum rate by optimizing the time, subcarrier and power allocation. It is shown that the proposed scheme can well balance between the downlink rate and the uplink rate.

The rest of the paper is organized as follows. Section 2 presents the system model and the investigated problem. The resource allocation scheme is proposed in Section 3. Simulation results to verify the proposed resource allocation scheme are provided in Section 4. Section 5 concludes the paper.

2. System model and problem formulation

We consider a multiuser OFDM system with K users and N subcarriers, as shown in Fig. 1. The sets of the users and the subcarriers are denoted by $\mathbb{K}$ and $\mathbb{N}$, respectively. We assume that the channels experience quasi-static flat fading, i.e., channels stay constant during each transmission block and are different among blocks. Without loss of generality, the time for each transmission block is assumed to be unitary. Both uplink (users to base station) and downlink (base station to users) communications are considered, and each transmission block consists of two phases, i.e., the downlink communication phase with time duration τ^D and the uplink communication phase with time duration τ^U. The channel power gain on subcarrier n between the base station and user k is denoted by $h_{k,n}$. In order to focus on the main contribution of this paper to combine WPCN and SWIPT to achieve both uplink and downlink transmission, we assume that channel state information on the channel power gains is perfectly known. Such assumption of perfect channel state information can be realized by traditional channel training, estimation and feedback mechanisms. Imperfect channel state information will degrade the performance of WPCN and SWIPT, and investigating it is out of the scope of this paper. Interested readers can refer to [26] and references therein for the work on imperfect channel state information in energy harvesting wireless networks.

For the downlink communication, the SWIPT scheme in [25] is adopted at the users. Specifically, each user decodes information on its allocated subcarriers for data transmission and harvests energy on other subcarriers. For dealing with the case when some subcarriers are allocated exclusively for energy harvesting, a virtual user is introduced with index 0. If the subcarriers are allocated to the virtual user for data transmission, then these subcarriers are used by all the real users for energy harvesting. The channel power gains related to the virtual user are assumed to be zero. In the rest of the paper, the virtual user is assumed to be included in the user

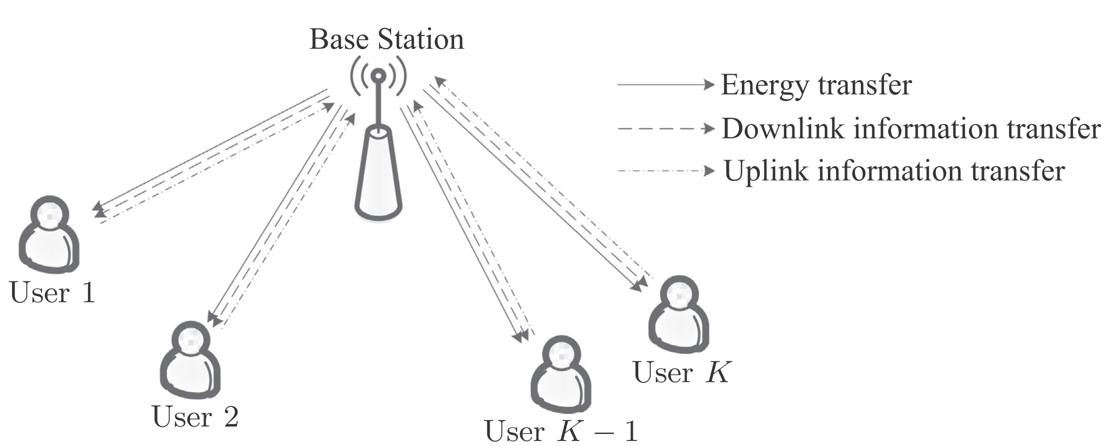

Fig. 1. System model.

set $\mathbb{K}$. Let $p^D_{k,n}$ denote the transmit power from the base station to user k on subcarrier n for downlink data transmission. Exclusive downlink subcarrier allocation is adopted, i.e., each subcarrier can be allocated to only one user for data transmission and we have $p^D_{k',n}p^D_{k,n}=0, \forall k' \neq k, k' \in \mathbb{K}, k \in \mathbb{K}$. Besides, the total transmit power of the base station is restricted as $\sum_{k\in\mathbb{K}}\sum_{n\in\mathbb{N}}p^D_{k,n} \leqslant P$, and the transmit power allocated to each subcarrier is restricted as $p^D_{k,n} \leqslant P_{pk}$. Let ζ $(0<\zeta<1)$ denotes the energy harvesting efficiency. In most literature, the harvested energy is linear as given by $\zeta\tau^D\sum_{k'\neq k,k'\in\mathbb{K}}\sum_{n\in\mathbb{N}}p^D_{k',n}h_{k,n}$. However, it has been noted that such linear model is not accurate and practical harvested energy is nonlinear and shows saturation behavior [27,28]. In this paper, a nonlinear energy harvesting model named as piece-wise linear model is adopted. The piece-wise linear energy harvesting model is analytically tractable and captures the saturation character of practical energy harvesting, which has been widely used in literature such as [29–31]. According to the piece-wise linear model [29], the energy harvested by user k can be written as

$$E_k = \begin{cases} \zeta\tau^D \sum\limits_{k'\neq k,k'\in\mathbb{K}}\sum\limits_{n\in\mathbb{N}} p^D_{k',n}h_{k,n}, & \sum\limits_{k'\neq k,k'\in\mathbb{K}}\sum\limits_{n\in\mathbb{N}} p^D_{k',n}h_{k,n} \leqslant \bar{P}_k \\ \zeta\tau^D\bar{P}_k, & \text{otherwise} \end{cases}, \tag{1}$$

where $\bar{P}_k$ is the saturation threshold. Similar to [17,18], the harvested energy is assumed to be stored in a rechargeable battery with an initial energy of Q_k.

For the uplink communication, users use the harvested energy to perform uplink data transmission. Let $p^U_{k,n}$ denote the transmit power from user k to the base station on subcarrier n for uplink data transmission. Exclusive uplink subcarrier allocation is adopted, i.e., $p^U_{k',n}p^U_{k,n}=0, \forall k'\neq k, k'\in\mathbb{K}, k\in\mathbb{K}$. Since the used energy cannot exceed total available energy consisting of the harvested energy E_k and the initial energy Q_k, we have $\tau^U\sum_{n\in\mathbb{N}}p^U_{k,n} \leqslant E_k+Q_k$, for $\forall k\in\mathbb{K}$.

To maximize the weighted downlink and uplink sum rate, the time, subcarrier and power allocation scheme shall be properly designed. The optimization problem is formulated as

$$\max_{\tau^D,\tau^U,\{p^D_{k,n}\},\{p^U_{k,n}\}} \frac{\omega^D\tau^D}{N}\sum_{k\in\mathbb{K}}\sum_{n\in\mathbb{N}}\ln\left(1+\frac{p^D_{k,n}h_{k,n}}{\sigma^2}\right) + \frac{\omega^U\tau^U}{N}\sum_{k\in\mathbb{K}}\sum_{n\in\mathbb{N}}\ln\left(1+\frac{p^U_{k,n}h_{k,n}}{\sigma^2}\right) \tag{2}$$

$$\text{s.t.} \sum_{k\in\mathbb{K}}\sum_{n\in\mathbb{N}}p^D_{k,n} \leqslant P, \tag{3}$$

$$0 \leqslant p^D_{k,n} \leqslant P_{pk}, p^U_{k,n} \geqslant 0, \forall k\in\mathbb{K}, \forall n\in\mathbb{N}, \tag{4}$$

$$p^D_{k',n}p^D_{k,n}=0, \forall k'\neq k, k'\in\mathbb{K}, k\in\mathbb{K}, \tag{5}$$

$$p^U_{k',n}p^U_{k,n}=0, \forall k'\neq k, k'\in\mathbb{K}, k\in\mathbb{K}, \tag{6}$$

$$\tau^U\sum_{n\in\mathbb{N}}p^U_{k,n} \leqslant E_k+Q_k, \forall k\in\mathbb{K}, \tag{7}$$

$$\tau^D+\tau^U=1, \tau^D\geqslant 0, \tau^U\geqslant 0, \tag{8}$$

where $\omega^D \geqslant 0$ and $\omega^U \geqslant 0$ $(\omega^D+\omega^U=1)$ are the weights of downlink and uplink transmissions, respectively, and σ^2 is the noise power.

3. Resource allocation scheme

The problem in (2) is highly nonlinear and the optimal solution is hard to obtain. Thus, in what follows, we propose a heuristic suboptimal scheme. From (8), we can have $\tau^D=1-\tau^U$. Then, by inserting $\tau^D=1-\tau^U$ and (1) into the problem in (2), we have

$$\max_{\tau^U,\{p^D_{k,n}\},\{p^U_{k,n}\}} \frac{\omega^D(1-\tau^U)}{N}\sum_{k\in\mathbb{K}}\sum_{n\in\mathbb{N}}\ln\left(1+\frac{p^D_{k,n}h_{k,n}}{\sigma^2}\right) + \frac{\omega^U\tau^U}{N}\sum_{k\in\mathbb{K}}\sum_{n\in\mathbb{N}}\ln\left(1+\frac{p^U_{k,n}h_{k,n}}{\sigma^2}\right) \tag{9}$$

$$\text{s.t. } \tau^U\sum_{n\in\mathbb{N}}p^U_{k,n} \leqslant \zeta(1-\tau^U)\min\left(\sum_{k'\neq k,k'\in\mathbb{K}}\sum_{n\in\mathbb{N}}p^D_{k',n}h_{k,n}, \bar{P}_k\right) + Q_k, \forall k\in\mathbb{K}, \tag{10}$$

$$0 \leqslant \tau^U \leq 1, \tag{11}$$

and constraints (3)–(6).

We can further rewrite the constraint in (10) as two constraints given by

$$\tau^U\sum_{n\in\mathbb{N}}p^U_{k,n} \leqslant \zeta(1-\tau^U)\sum_{k'\neq k,k'\in\mathbb{K}}\sum_{n\in\mathbb{N}}p^D_{k',n}h_{k,n}+Q_k, \forall k\in\mathbb{K}, \tag{12}$$

$$\tau^U\sum_{n\in\mathbb{N}}p^U_{k,n} \leqslant \zeta(1-\tau^U)\bar{P}_k+Q_k, \forall k\in\mathbb{K}. \tag{13}$$

For a given τ^U, the problem of optimizing $\{p^D_{k,n}\},\{p^U_{k,n}\}$ is nonconvex due to the constraints in (5) and (6). Thus, the optimal solution is hard to be obtained. Fortunately, OFDM systems usually employ a large number of subcarriers and it has been shown in [32] that the duality gap is virtually zero for a large number of subcarriers for the problem of optimizing $\{p^D_{k,n}\},\{p^U_{k,n}\}$. Therefore, we can solve the problem of optimizing $\{p^D_{k,n}\},\{p^U_{k,n}\}$ given τ^U using the Lagrange duality method. As shown in [32], although such solution is not optimal in general case, the solution is close to optimal when N is large. The Lagrangian is given by

$$\begin{aligned} L(\{p^D_{k,n}\},\{p^U_{k,n}\},\lambda,\{\mu_k\},\{\nu_k\}) &= \frac{\omega^D(1-\tau^U)}{N}\sum_{k\in\mathbb{K}}\sum_{n\in\mathbb{N}}\ln\left(1+\frac{p^D_{k,n}h_{k,n}}{\sigma^2}\right) \\ &+ \frac{\omega^U\tau^U}{N}\sum_{k\in\mathbb{K}}\sum_{n\in\mathbb{N}}\ln\left(1+\frac{p^U_{k,n}h_{k,n}}{\sigma^2}\right) - \lambda\left(\sum_{k\in\mathbb{K}}\sum_{n\in\mathbb{N}}p^D_{k,n}-P\right) \\ &- \sum_{k\in\mathbb{K}}\mu_k\left(\tau^U\sum_{n\in\mathbb{N}}p^U_{k,n}-\zeta(1-\tau^U)\sum_{k'\neq k,k'\in\mathbb{K}}\sum_{n\in\mathbb{N}}p^D_{k',n}h_{k,n}-Q_k\right) \\ &- \sum_{k\in\mathbb{K}}\nu_k\left(\tau^U\sum_{n\in\mathbb{N}}p^U_{k,n}-\zeta(1-\tau^U)\bar{P}_k-Q_k\right), \end{aligned} \tag{14}$$

where λ, $\{\mu_k, k\in\mathbb{K}\}$ and $\{\nu_k, k\in\mathbb{K}\}$ are the non-negative dual variables associated with the constraints in (3), (12) and (13), respectively. The Lagrange dual function $G(\lambda,\{\mu_k\},\{\nu_k\})$ is obtained by solving the following problem as

$$G(\lambda,\{\mu_k\},\{\nu_k\}) = \max_{\{p^D_{k,n}\},\{p^U_{k,n}\}} L(\{p^D_{k,n}\},\{p^U_{k,n}\},\lambda,\{\mu_k\},\{\nu_k\}) \tag{15}$$

s.t. constraints(4)–(6).

To solve the problem in (15), we can rewrite (14) as

$$\begin{aligned} L(\{p^D_{k,n}\},\{p^U_{k,n}\},\lambda,\{\mu_k\},\{\nu_k\}) &= \sum_{n\in\mathbb{N}}\sum_{k\in\mathbb{K}}L^D_{k,n}(p^D_{k,n},\lambda,\{\mu_k\}) \\ &+ L^U_{k,n}(p^U_{k,n},\mu_k,\nu_k)+\lambda P+\sum_{k\in\mathbb{K}}\mu_kQ_k+\sum_{k\in\mathbb{K}}\nu_k(\zeta(1-\tau^U)\bar{P}_k+Q_k), \end{aligned} \tag{16}$$

where

$$L^D_{k,n}(p^D_{k,n},\lambda,\{\mu_k\}) = \frac{\omega^D(1-\tau^U)}{N}\ln\left(1+\frac{p^D_{k,n}h_{k,n}}{\sigma^2}\right) - \left(\lambda-\zeta(1-\tau^U)\sum_{k'\neq k,k'\in\mathbb{K}}\mu_{k'}h_{k',n}\right)p^D_{k,n}, \tag{17}$$

and

$$L_{k,n}^U(p_{k,n}^U,\mu_k,\nu_k)=\frac{\omega^U\tau^U}{N}\ln\left(1+\frac{p_{k,n}^U h_{k,n}}{\sigma^2}\right)-\tau^U(\mu_k+\nu_k)p_{k,n}^U. \quad (18)$$

Thus, the problem in (15) can be decoupled into $2N$ parallel subproblems as given by

$$G_n^D(\lambda,\{\mu_k\})=\max_{\{0\leqslant p_{k,n}^D\leqslant P_{pk}\}}\sum_{k\in\mathbb{K}}L_{k,n}^D(p_{k,n}^D,\lambda,\{\mu_k\}) \quad (19)$$

s.t. constraint (5),

and

$$G_n^U(\lambda,\{\mu_k\},\{\nu_k\})=\max_{\{p_{k,n}^U\geqslant 0\}}\sum_{k\in\mathbb{K}}L_{k,n}^U(p_{k,n}^U,\mu_k,\nu_k) \quad (20)$$

s.t. constraint (6),

for $n\in\mathbb{N}$. Since each subcarrier can be allocated to only one user for downlink and uplink information transfer from the constraints in (5) and (6), both the problems in (19) and (20) can be solved by first solving K subproblems, each for one user, and then choosing the one with the maximum objective function value. Assume that subcarrier n is allocated to user k for downlink and uplink information transfer. Since the objective functions in (19) and (20) are concave with respect to $p_{k,n}^D$ and $p_{k,n}^U$, respectively, the optimal power allocation can be easily derived by setting the derivatives of the objective functions to zero as given by

$$\tilde{p}_{k,n}^D=\left[\frac{\omega^D(1-\tau^U)}{\lambda N-\zeta(1-\tau^U)N\sum\limits_{k'\neq k,k'\in\mathbb{K}}\mu_{k'}h_{k',n}}-\frac{\sigma^2}{h_{k,n}}\right]_0^{P_{pk}}, \quad (21)$$

$$\tilde{p}_{k,n}^U=\left(\frac{\omega^U}{N(\mu_k+\nu_k)}-\frac{\sigma^2}{h_{k,n}}\right)^+, \quad (22)$$

where $[x]_a^b=\max(a,\min(b,x))$ and $(x)^+=\max(x,0)$. After $\tilde{p}_{k,n}^D$ and $\tilde{p}_{k,n}^U$ has been obtained for all K users for subcarrier n, the values of $G_n^D(\lambda,\{\mu_k\})$ and $G_n^U(\lambda,\{\mu_k\},\{\nu_k\})$ can be obtained as

$$G_n^D(\lambda,\{\mu_k\})=L_{\tilde{k}_n^D,n}^D\left(\tilde{p}_{\tilde{k}_n^D,n}^D,\lambda,\{\mu_k\}\right), \quad (23)$$

$$G_n^U(\lambda,\{\mu_k\},\{\nu_k\})=L_{\tilde{k}_n^U,n}^U\left(\tilde{p}_{\tilde{k}_n^U,n}^U,\mu_{\tilde{k}_n^U},\nu_{\tilde{k}_n^U}\right), \quad (24)$$

where

$$\tilde{k}_n^D=\arg\max_{k\in\mathbb{K}}L_{k,n}^D(\tilde{p}_{k,n}^D,\lambda,\{\mu_k\}), \quad (25)$$

$$\tilde{k}_n^U=\arg\max_{k\in\mathbb{K}}L_{k,n}^U(\tilde{p}_{k,n}^U,\mu_k,\nu_k). \quad (26)$$

Thus, the downlink power allocation for subcarrier n is $p_{\tilde{k}_n^D,n}^D=\tilde{p}_{\tilde{k}_n^D,n}^D$, $p_{k,n}^D=0$ for all $k\neq\tilde{k}_n^D$, and the uplink power allocation for subcarrier n is $p_{\tilde{k}_n^U,n}^U=\tilde{p}_{\tilde{k}_n^U,n}^U$, $p_{k,n}^U=0$ for all $k\neq\tilde{k}_n^U$. After (23) and (24) has been derived for all subcarriers $n\in\mathbb{N}$, the dual function $G(\lambda,\{\mu_k\})$ is obtained as

$$G(\lambda,\{\mu_k\},\{\nu_k\})=\sum_{n\in\mathbb{N}}G_n^D(\lambda,\{\mu_k\})+G_n^U(\lambda,\{\mu_k\},\{\nu_k\})+\lambda P$$
$$+\sum_{k\in\mathbb{K}}\mu_k Q_k+\sum_{k\in\mathbb{K}}\nu_k(\zeta(1-\tau^U)\bar{P}_k+Q_k). \quad (27)$$

To obtain the dual variables $\lambda,\{\mu_k\}$ and $\{\nu_k\}$, the dual problem is defined as

$$\min_{\lambda\geqslant 0,\{\mu_k\}\succeq 0,\{\nu_k\}\succeq 0}G(\lambda,\{\mu_k\},\{\nu_k\}), \quad (28)$$

which can be solved by the ellipsoid method [33].

We denote the above optimized $\{p_{k,n}^D\},\{p_{k,n}^U\}$ with a given τ^U as $\{p_{k,n}^D(\tau^U)\},\{p_{k,n}^U(\tau^U)\}$, which indicates that the values of $\{p_{k,n}^D\},\{p_{k,n}^U\}$ depend on τ^U. Then, using the optimized $\{p_{k,n}^D(\tau^U)\},\{p_{k,n}^U(\tau^U)\}$ obtained above, the problem of optimizing τ^U is formulated as

$$\max_{\tau^U}\frac{\omega^D(1-\tau^U)}{N}\sum_{k\in\mathbb{K}}\sum_{n\in\mathbb{N}}\ln\left(1+\frac{p_{k,n}^D(\tau^U)h_{k,n}}{\sigma^2}\right)$$
$$+\frac{\omega^U\tau^U}{N}\sum_{k\in\mathbb{K}}\sum_{n\in\mathbb{N}}\ln\left(1+\frac{p_{k,n}^U(\tau^U)h_{k,n}}{\sigma^2}\right) \quad (29)$$

$$\text{s.t. }\tau^U\sum_{n\in\mathbb{N}}p_{k,n}^U(\tau^U)\leqslant\zeta(1-\tau^U)\sum_{k'\neq k,k'\in\mathbb{K}}\sum_{n\in\mathbb{N}}p_{k',n}^D(\tau^U)h_{k,n}+Q_k,\forall k\in\mathbb{K}, \quad (30)$$

$$\tau^U\sum_{n\in\mathbb{N}}p_{k,n}^U(\tau^U)\leqslant\zeta(1-\tau^U)\bar{P}_k+Q_k,\forall k\in\mathbb{K}, \quad (31)$$

$$0\leqslant\tau^U\leq 1. \quad (32)$$

The above problem is highly intractable. Luckily, since τ^U lies within the narrow interval $[0,1]$, we can apply a one-dimensional exhaustive search to find the optimal τ^U. The proposed suboptimal resource allocation scheme is summarized in Table 1. The complexity of the proposed scheme is analyzed here. For a given τ^U, the ellipsoid method converges in $\mathcal{O}((2K+1)^2)$ iterations [25]. Calculating $\{p_{k,n}^D\}$ and $\{p_{k,n}^U\}$ from step 3 to 7 requires $\mathcal{O}(2KN)$ operations. Assume that the accuracy of exhaustive search on τ^U is Δ. Thus, the total complexity is $\mathcal{O}\left(\frac{2KN(2K+1)^2}{\Delta}\right)$.

4. Simulation results

This section provides simulation results to verify the performance of the proposed resource allocation scheme. We use a simulation setup similar to the one in [6]. Specifically, the bandwidth of the system is assumed to be 10 MHz with noise spectral density -120 dBm/Hz and is equally divided into $N=8$ subcarriers. The path loss from the base station to the users is assumed to be $30+20\log_{10}(d)$ dB, where d is the distance and is assumed to be uniformly distributed within $5\leqslant d\leq 10$ meter. The small-scale Rayleigh fading with unit mean is also assumed for all the channels. In addition, we set $K=2,\zeta=0.5$ and $P_{pk}=4P/N$. For the purpose of comparison, three reference schemes are proposed. The first reference scheme (denoted as ETRef) assumes equal time allocation, while allocating subcarrier to the user with the highest channel power gain and allocating transmit power following water-filling model. The second reference scheme (denoted as DLRef) sets $\tau^D=1,\tau^U=0$ and thus only considers downlink information transmission. The third reference scheme (denoted as ULRef) is the traditional WPCN scheme that only considers uplink information transmission.

Figs. 2 and 3 show the downlink rate and the uplink rate against ω^D, respectively. It is observed that the downlink rate achieved by the proposed scheme is lower than that of the DLRef scheme, while the uplink rate achieved by the proposed scheme is lower than that of the ULRef scheme. This is as expected as the downlink rate achieved by the DLRef scheme and the uplink rate achieved by the ULRef scheme are the highest achievable rate without considering uplink transmission and downlink transmission, respectively. It is also observed that, as ω^D increases/decreases, the proposed scheme achieves higher downlink/uplink rate and lower uplink/downlink rate, and the downlink/uplink rate achieved by the proposed scheme is closed to that of the DLRef/ULRef scheme when ω^D is relatively large/small. This indicates that the proposed scheme can well balance between the achieved downlink rate and the uplink rate by adjusting the value of ω^D. This also indicates that the proposed scheme can achieve downlink/uplink rate close

Table 1
Proposed suboptimal resource allocation scheme.

for $\tau^U = 0$ to 1 **do**
  repeat
    for all n such that $n \in \mathbb{N}$ **do**
      Calculate $\tilde{p}^D_{k,n}$ and $\tilde{p}^U_{k,n}$ from (21) and (22), respectively, for all $k \in \mathbb{K}$.
      Calculate $\tilde{k}^D_n$ and $\tilde{k}^U_n$ from (25) and (26), respectively.
      Let $p^D_{\tilde{k}^D_n,n} = \tilde{p}^D_{\tilde{k}^D_n,n}, p^D_{k,n} = 0$ for all $k \neq \tilde{k}^D_n$, and $p^U_{\tilde{k}^U_n,n} = \tilde{p}^U_{\tilde{k}^U_n,n}, p^U_{k,n} = 0$ for all $k \neq \tilde{k}^U_n$.
    end for
    Update $\lambda, \{\mu_k\}$ and $\{\nu_k\}$ by the ellipsoid method.
  until $\lambda, \{\mu_k\}$ and $\{\nu_k\}$ converge to a desired accuracy.
end for
Choose the τ^U that maximizes the weighted sum rate.

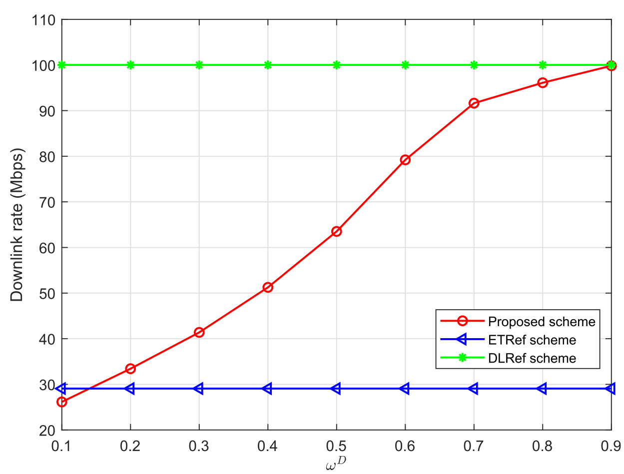

Fig. 2. Downlink rate against ω^D ($P = 10$ W, $Q_k = 0.1$ mJ and $\bar{P}_k = 1$ mW).

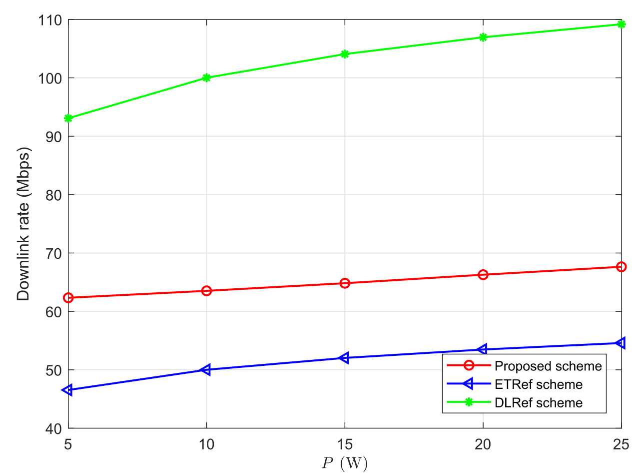

Fig. 4. Downlink rate against P ($\omega^D = 0.5, Q_k = 0.1$ mJ and $\bar{P}_k = 1$ mW).

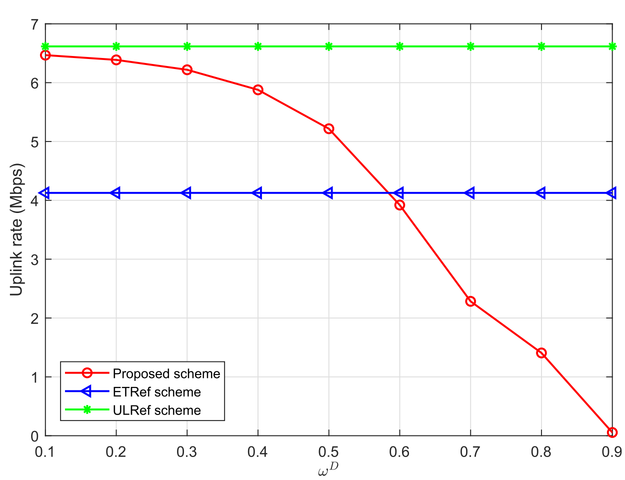

Fig. 3. Uplink rate against ω^D ($P = 10$ W, $Q_k = 0.1$ mJ and $\bar{P}_k = 1$ mW).

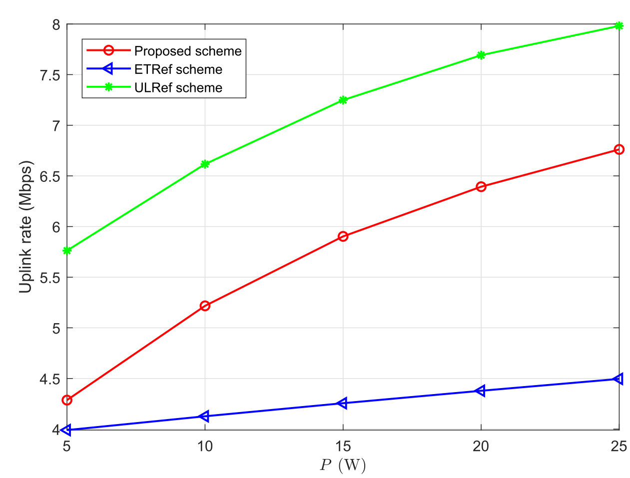

Fig. 5. Uplink rate against P ($\omega^D = 0.5, Q_k = 0.1$ mJ and $\bar{P}_k = 1$ mW).

to that achieved by the DLRef/ULRef scheme while also providing a certain level of uplink/downlink rate. Besides, it is observed that, compared to the proposed scheme, the ETRef scheme is inflexible and mostly achieves much lower downlink rate while may achieve higher uplink rate when ω^D is relatively large. This indicates that equal time allocation is inflexible and may sacrifice downlink rate in exchange for higher uplink rate.

Figs. 4 and 5 show the downlink rate and the uplink rate against P, respectively. It is observed that, as P increases, both downlink rate and uplink rate increases. This is as expected as a higher P can achieve a higher downlink rate and can also let users harvest more energy to be used for uplink transmission. It is also observed that the proposed scheme outperforms the ETRef scheme especially when P is large. This indicates that the proposed scheme is more preferred if P is large.

Figs. 6 and 7 show the downlink rate and the uplink rate against Q_k, respectively. It is shown that the downlink rate achieved by the proposed scheme increases very slowly as Q_k increases, while the uplink rate increases as Q_k increases. This is explained as follows. A higher Q_k means that users have more energy for uplink transmission and thus a higher uplink rate is achieved. Meanwhile, since our aim is to maximize the weighted downlink and uplink sum

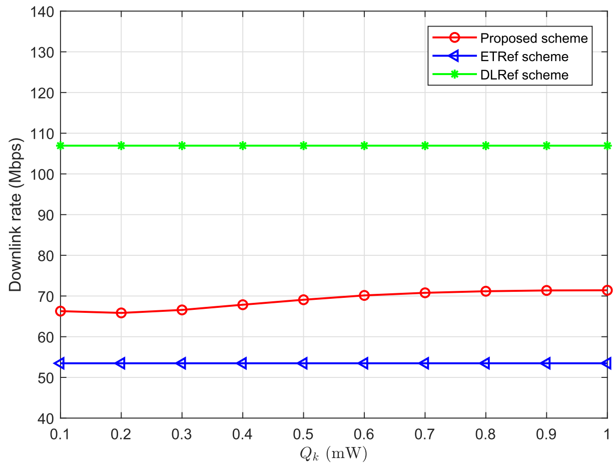

Fig. 6. Downlink rate against Q_k ($\omega^D = 0.5, P = 20$ W and $\bar{P}_k = 1$ mW).

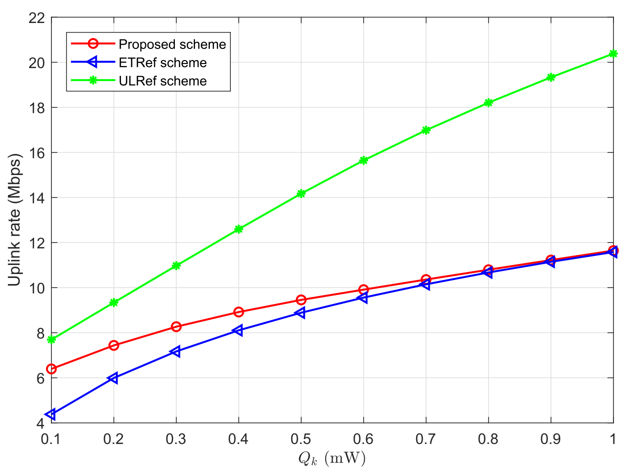

Fig. 7. Uplink rate against Q_k ($\omega^D = 0.5, P = 20$ W and $\bar{P}_k = 1$ mW).

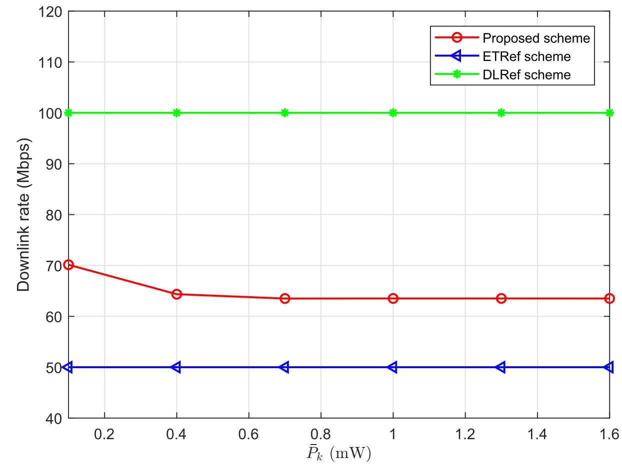

Fig. 8. Downlink rate against $\bar{P}_k$ ($\omega^D = 0.5, P = 10$ W and $Q = 0.1$ mJ).

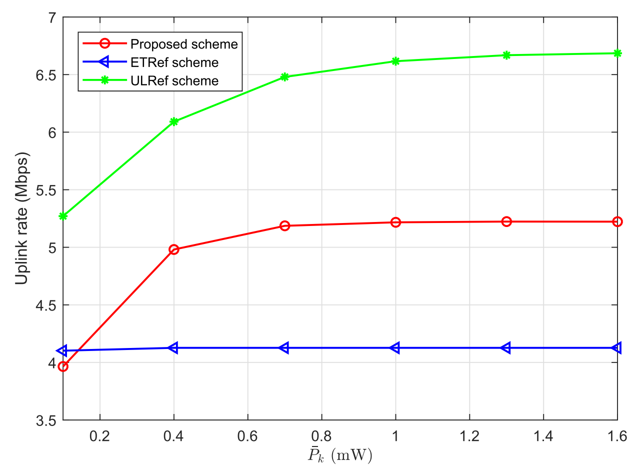

Fig. 9. Uplink rate against $\bar{P}_k$ ($\omega^D = 0.5, P = 10$ W and $Q = 0.1$ mJ).

rate, a higher Q_k thus means that more resources can be allocated for downlink transmission and a higher downlink rate is achieved. Besides, it is shown that the uplink rate achieved by the proposed scheme is higher than that achieved by the ETRef scheme when Q_k is small and the gap gradually vanishes as Q_k increases.

Figs. 8 and 9 show the downlink rate and the uplink rate against $\bar{P}_k$, respectively. It is observed that, as $\bar{P}_k$ increases, the uplink rate achieved by the proposed scheme increases and then saturates as $\bar{P}_k$ increases further. This is because that when $\bar{P}_k$ is small, $\bar{P}_k$ restricts the harvested energy, and thus increasing $\bar{P}_k$ can increase the uplink rate. When $\bar{P}_k$ is large enough, the harvested energy is not restricted by the value of $\bar{P}_k$, and thus increasing $\bar{P}_k$ have no impact on the uplink rate. It is also observed that when $\bar{P}_k$ is small, increasing $\bar{P}_k$ results in a lower downlink rate achieved by the proposed scheme. This indicates that more resources are allocated for uplink transmission by increasing $\bar{P}_k$ when $\bar{P}_k$ is small.

5. Conclusion

We consider a multiuser OFDM system, which jointly considers WPCN and SWIPT. Both downlink and uplink are considered and the time is assumed to be divided into two phases, i.e., the first downlink communication phase and the second uplink communication phase. SWIPT is adopted in the downlink communication phase with nonlinear energy harvesting model, where each user decodes information on its allocated subcarriers for data transmission and harvests energy on other subcarriers. Then, users use the harvested energy to perform uplink data transmission. We propose a suboptimal resource allocation scheme to maximize the weighted downlink and uplink sum rate by optimizing the time, subcarrier and power allocation. It is shown that the proposed scheme can well balance between the downlink rate and the uplink rate.

There are some possible extensions in our future work. Firstly, perfect channel state information is considered in this paper, and our future work will investigate the impact of imperfect channel state information on the system performance. Secondly, single antenna is assumed to be equipped on each node in this paper, and our future work will consider multiple antennas and investigate its impact on the resource allocation. Thirdly, weighted sum rate is maximized in this paper, and our future work will consider energy efficiency as design objective.

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