Int. J. Electron. Commun. (AEÜ) 90 (2018) 171–174

Contents lists available at ScienceDirect

Int. J. Electron. Commun. (AEÜ)

journal homepage: www.elsevier.com/locate/aeue

Regular paper

Optimization of wireless information and power transfer in multiuser OFDM systems

Ding Xu*, Qun Li

[a] Wireless Communication Key Lab of Jiangsu Province, Nanjing University of Posts and Telecommunications, Nanjing, China
[b] Jiangsu Key Lab of Big Data Security and Intelligent Processing, Nanjing University of Posts and Telecommunications, Nanjing, China

ARTICLE INFO

Keywords:
Simultaneous information and power transfer
Energy harvesting
OFDM

ABSTRACT

Simultaneous wireless information and power transfer (SWIPT), which belongs to energy harvesting techniques, is an important research topic. In existing literature, two SWIPT schemes, namely the time switching (TS) scheme and the power splitting (PS) scheme are adopted. For multiuser orthogonal frequency division multiple (OFDM) systems, this paper proposes a new SWIPT scheme named as the subcarrier sharing (SS) scheme. Resource allocation algorithms for the SS scheme are then proposed for maximizing the sum rate under the minimum harvested energy constraint. We show that the SS scheme outperforms the existing TS and the PS schemes.

1. Introduction

Recently, simultaneous wireless information and power transfer (SWIPT) has been researched a lot for its ability to solve the problem of energy scarcity in wireless communication networks [1–6]. Basically, two SWIPT schemes are adopted in existing literature, i.e., the time switching (TS) scheme and the power splitting (PS) scheme, where the former allocates different time slots for information transfer and power transfer, while the latter splits the received signal into two portions for information transfer and power transfer. For example, Ref. [2] studied the TS scheme in a point-to-point wireless link, Refs. [3,4] studied the PS scheme in a point-to-point wireless link and an interference channel, respectively, and [5] investigated both the TS scheme and the PS scheme in a small cell network. In [6], the TS scheme and the PS scheme in orthogonal frequency division multiple access (OFDMA) systems were investigated.

Different from the TS and the PS schemes for SWIPT adopted in the aforementioned works [2–6], this paper proposes a new scheme for SWIPT in multiuser OFDM systems, namely the subcarrier sharing (SS) scheme, where each user decodes information on the subcarriers that are allocated to it for information transfer and harvests energy on the subcarriers that are allocated to other users for information transfer and the subcarriers dedicated for energy transfer. Resource allocation algorithms for the SS scheme are then proposed for maximizing the sum rate under the minimum harvested energy constraint. The main contribution of this paper is proposing the SS scheme for SWIPT in multiuser OFDMA systems which is shown to outperform the TS and the PS schemes.

The remainder of the paper is organized as follows. In Section 2, we present the system model, propose the SS scheme and formulate the optimization problem. In Section 3, resource allocation algorithms are proposed to solve the optimization problem. In Section 4, simulation results are provided to verify the proposed SS scheme and the resource allocation algorithms. Section 5 concludes the paper.

2. System model and problem formulation

A downlink multiuser OFDM system with K users and N subcarriers is considered. Let $\mathscr{K}$ and $\mathscr{N}$ denote the sets of the users and the subcarriers, respectively. The channel power gain from the base station to user k on subcarrier n is denoted as $h_{k,n}$. All the channels are assumed to be block fading, i.e., the channel power gains are constant within one transmission block and may change from one block to another. The base station is assumed to have knowledge of all the channel power gains. Let p_n denote the downlink transmit power of the base station on subcarrier n. The total transmit power of the base station on all the subcarriers is limited, i.e., $\sum_{n\in\mathscr{N}} p_n \leqslant P_{tot}$, where P_{tot} denotes the total transmit power limit. There is also a peak transmit power limit for each subcarrier written as $p_n \leqslant P_{pk}$, where P_{pk} denotes the peak transmit power limit for each subcarrier. Let $\alpha_{k,n}$ ($\alpha_{k,n} \in \{0,1\}$) denote the binary subcarrier allocation index for user k on subcarrier n. Specifically, $\alpha_{k,n} = 1$ indicates that the subcarrier n is allocated to user k for information transfer and $\alpha_{k,n} = 0$ indicates otherwise. It is assumed that each subcarrier can be allocated to at most one user for information transfer, i.e., $\sum_{n\in\mathscr{N}} \alpha_{k,n} \leq 1$. Note that if $\alpha_{k,n} = 0$ for all $k \in \mathscr{K}$, then

* Corresponding author.
E-mail address: xuding@ieee.org (D. Xu).

https://doi.org/10.1016/j.aeue.2018.04.021
Received 1 November 2017; Accepted 20 April 2018

subcarrier n is dedicated for energy transfer for all the users.

The proposed SS scheme assumes that each user decodes information on its allocated subcarriers for information transfer and harvests energy on the subcarriers that are allocated to other users for information transfer and the subcarriers dedicated for energy transfer [1]. The total energy harvested by user k is given by $E_k = \zeta \sum_{n\in\mathcal{N}} (1-\alpha_{k,n})p_n h_{k,n}$, where ζ $(0<\zeta<1)$ denotes the energy harvesting efficiency. It is assumed that each user is required to harvest a minimum energy denoted by B_k for user k. The proposed SS scheme aims to optimize the subcarrier allocation $\alpha_{k,n}$ and the power allocation p_n to maximize the sum rate under the aforementioned constraints. The optimization problem is formulated as (P1):

$$\max_{\{\alpha_{k,n}\},\{p_n\}} \sum_{n\in\mathcal{N}} \sum_{k\in\mathcal{K}} \alpha_{k,n}\ln\left(1+\frac{p_n h_{k,n}}{\sigma^2}\right) \tag{1}$$

$$\text{s. t.} \sum_{n\in\mathcal{N}} p_n \leqslant P_{tot}, \tag{2}$$

$$0 \leqslant p_n \leqslant P_{pk}, n\in\mathcal{N}, \tag{3}$$

$$E_k \geqslant B_k, k\in\mathcal{K}, \tag{4}$$

$$\alpha_{k,n}\in\{0,1\}, k\in\mathcal{K}, n\in\mathcal{N}, \tag{5}$$

$$\sum_{k\in\mathcal{K}} \alpha_{k,n} \leq 1, n\in\mathcal{N}, \tag{6}$$

where σ^2 denotes the noise power. The problem (P1) is a mixed integer nonlinear programming problem, which is NP-hard in general.

3. Resource allocation algorithms

3.1. Dual design

To solve (P1), we introduce an auxiliary binary variable $\alpha_{0,n}$ indicating whether subcarrier n is allocated exclusively for energy transfer. If $\alpha_{0,n}=1$, then subcarrier n is allocated exclusively for energy transfer, and $\alpha_{0,n}=0$ indicates otherwise. Then, we can rewrite the constraints (3), (6) as

$$p_n\alpha_{k,n} \leqslant P_{pk}, k\in\mathcal{K}\cup\{0\}, n\in\mathcal{N}, \tag{7}$$

$$\sum_{k\in\mathcal{K}\cup\{0\}} \alpha_{k,n} = 1, n\in\mathcal{N}, \tag{8}$$

respectively.

After that, we relax $\alpha_{k,n}$ as $0\leqslant\alpha_{k,n}\leq 1$ and let $p_{k,n}=p_n\alpha_{k,n}$ for all $k\in\mathcal{K}\cup\{0\}$, $n\in\mathcal{N}$. Considering the constraint (8), we can rewrite the constraints (2) and (4) as

$$\sum_{n\in\mathcal{N}} \sum_{k\in\mathcal{K}\cup\{0\}} p_{k,n} \leqslant P_{tot}, \tag{9}$$

$$\sum_{n\in\mathcal{N}} \sum_{k'\in\mathcal{K}\cup\{0\}} p_{k',n}h_{k,n} - p_{k,n}h_{k,n} \geqslant \frac{B_k}{\zeta}, k\in\mathcal{K}, \tag{10}$$

respectively. Then, (P1) is rewritten as (P2):

$$\max_{\{\alpha_{k,n}\},\{p_{k,n}\}} \sum_{n\in\mathcal{N}} \sum_{k\in\mathcal{K}} \alpha_{k,n}\ln\left(1+\frac{p_{k,n} h_{k,n}}{\alpha_{k,n}\sigma^2}\right) \tag{11}$$

$$\text{s. t.}\ 0 \leqslant p_{k,n} \leqslant P_{pk}, k\in\mathcal{K}\cup\{0\}, n\in\mathcal{N}, \tag{12}$$

$$0 \leqslant \alpha_{k,n} \leqslant 1, k\in\mathcal{K}\cup\{0\}, n\in\mathcal{N}, \tag{13}$$

$$\sum_{k\in\mathcal{K}\cup\{0\}} \alpha_{k,n} = 1, n\in\mathcal{N}, \tag{14}$$

$$\text{and constraints (9),(10).} \tag{15}$$

It can be verified that (P2) is convex. From convex optimization theory [8], the duality gap of (P2) is thus zero and we can optimally solve (P2) using the Lagrange duality method, i.e., (P2) can be solved equivalently by solving the Lagrange dual problem associated with (P2).

The Lagrangian of (P2) can be written as

$$L(\{\alpha_{k,n}\},\{p_{k,n}\},\lambda,\{\mu_k\}) = \sum_{n\in\mathcal{N}} \sum_{k\in\mathcal{K}} \alpha_{k,n}\ln\left(1+\frac{p_{k,n}h_{k,n}}{\alpha_{k,n}\sigma^2}\right) - \lambda\left(\sum_{n\in\mathcal{N}} \sum_{k\in\mathcal{K}\cup\{0\}} p_{k,n} - P_{tot}\right) + \sum_{k\in\mathcal{K}} \mu_k \times \left(\sum_{n\in\mathcal{N}} \sum_{k'\in\mathcal{K}\cup\{0\}} p_{k',n}h_{k,n} - p_{k,n}h_{k,n} - \frac{B_k}{\zeta}\right), \tag{16}$$

where λ and $\mu_k, k\in\mathcal{K}$ are the non-negative dual variables associated with the constraints (9) and (10), respectively. The Lagrange dual function $G(\lambda,\{\mu_k\})$ is then obtained by solving the following problem as given by (P2.1)

$$\max_{\{\alpha_{k,n}\},\{p_{k,n}\}} L(\{\alpha_{k,n}\},\{p_{k,n}\},\lambda,\{\mu_k\}) \tag{17}$$

s. t. constraints (12)–(14).

It is observed that the above problem can be decoupled into N parallel subproblems with the same structure, each for one subcarrier, as given by (P2.2):

$$G_n(\lambda,\{\mu_k\}) = \max_{\{\alpha_{k,n}\},\{p_{k,n}\}} \sum_{k\in\mathcal{K}} \alpha_{k,n}\ln\left(1+\frac{p_{k,n}h_{k,n}}{\alpha_{k,n}\sigma^2}\right) - \lambda \sum_{k\in\mathcal{K}\cup\{0\}} p_{k,n} + \sum_{k\in\mathcal{K}} \mu_k \left(\sum_{k'\in\mathcal{K}\cup\{0\}} p_{k',n} - p_{k,n}\right) h_{k,n} \tag{18}$$

s. t. constraints(12)–(14),

for $n\in\mathcal{N}$. Recall that each subcarrier can be allocated to at most one user for information transfer. Therefore, the subcarrier allocation of (P2.2) can be obtained by first finding $K+1$ optimal power allocations and then choosing the one that achieves the maximum objective function value of (P2.2). On one hand, assuming that subcarrier n is allocated to user k, i.e., $\alpha_{k,n}=1, \alpha_{k',n}=0, \forall k'\neq k, k'\in\mathcal{K}\cup\{0\}$, and considering $p_n=\frac{p_{k,n}}{\alpha_{k,n}}$, the problem (P2.2) reduces to the following problem as

$$G_{k,n}(\lambda,\{\mu_k\}) = \max_{0\leqslant p_n\leqslant P_{pk}} \ln\left(1+\frac{p_n h_{k,n}}{\sigma^2}\right) - \lambda p_n + \sum_{k'\neq k, k'\in\mathcal{K}} \mu_{k'}h_{k',n}p_n. \tag{19}$$

It is easily seen that the objective function in (19) is concave and thus, without considering the constraint $0\leqslant p_n\leqslant P_{pk}$, the derivative of the objective function in (19) at the optimal point p_n^* must be zero according to (4.22) in [8], i.e.,

$$\frac{\partial \ln\left(1+\frac{p_n h_{k,n}}{\sigma^2}\right) - \lambda p_n + \sum_{k'\neq k, k'\in\mathcal{K}} \mu_{k'}h_{k',n}p_n}{\partial p_n}\Big|_{p_n=p_n^*} = 0. \tag{20}$$

After some easy mathematical manipulations, the above equation can be rewritten as $p_n^* = \frac{1}{\lambda - \sum_{k'\neq k, k'\in\mathbb{K}} \mu_{k'}h_{k',n}} - \frac{\sigma^2}{h_{k,n}}$. Since the objective function in (19) is concave, the objective function in (19) increases as p_n increases for $p_n<p_n^*$ and decreases as p_n increases for $p_n>p_n^*$. Then, taking the constraint $0\leqslant p_n\leqslant P_{pk}$ into consideration, the optimal power allocation on subcarrier n that is allocated to user k for the problem (19) can be obtained as

[1] It is noted that harvesting energy and receiving information on different subcarriers can be implemented by the OFDMA receiver with band-pass filters [7]. It is also noted that the proposed SS scheme is applicable for multiuser multicarrier systems regardless whether the systems are unicast or broadcast. Although the system model discussed in this paper is unicast, the proposed scheme is applicable for broadcast systems where some subcarriers will be allocated for dedicated energy transfer.