Joint Uplink and Downlink Optimization for Wireless Powered NOMA OFDM Communication Systems

Mengshu Zhang[1], Zhenyu Na[1], Mei Yang[1](✉), Weidang Lu[2], and Xin Liu[3]

[1] Dalian Maritime University, Dalian 116026, China
yangmei@dlmu.edu.cn
[2] Zhejiang University of Technology, Hangzhou 310023, China
[3] Dalian University of Technology, Dalian 116024, China

Abstract. In this paper, an Orthogonal Frequency Division Multiplexing (OFDM) wireless communication system is investigated. For downlink, users perform Information Decoding (ID) and Energy Harvesting (EH) simultaneously. For uplink, users transmit information to Base Station (BS), while BS performs the Non-Orthogonal Multiple Access (NOMA) to decode information from users. In order to maximize the total uplink ID rate in the condition that the total downlink ID rate is ensured, a joint uplink and downlink optimization method based on power and subcarrier allocation is proposed. As shown in simulation results, compared with the existing method, the proposed method can implement the maximum harvested energy for users in the downlink and achieve higher total uplink ID rate.

Keywords: OFDM · Energy harvesting · Information decoding · NOMA

1 Introduction

Driven by the rapid evolvement of mobile networks and the growing demands for the Internet of Things (IoT) services, higher capacity, higher transmission rate, denser network deployment and lower time delay become necessary for the 5th Generation (5G) communication [1]. In that case, it will inevitably lead to the scarcity of resource, which may cause serious economic and environmental problems in use of traditional schemes. Thus, new schemes for increasing resource utilization becomes the precondition for implementing these technical requirements.

On the one hand, the Wireless Powered Communication (WPC) attracts broad attention, in which the energy can be harvested from environmental Radio Frequency (RF) signals [2]. So far, plenty of optimization methods are designed for WPC-based systems, such as [3] and [4]. However, most of the designed schemes for WPC only keep eyes on uplink or downlink without taking joint uplink and downlink optimization into account.

On the other hand, as an effective method for improving spectrum efficiency, Non-Orthogonal Multiple Access (NOMA) has received much attention recently. The core

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idea of NOMA is that different proportion of transmit power multiple are allocated to users to achieve the simultaneously access [5]. Many researches focus on the combination of NOMA and other techniques, such as Sparse Code Multiple Access (SCMA), Pattern Division Multiple Access (PDMA) [6] and Mobile Edge Computing (MEC) [7]. But there are few works for WPC NOMA.

In this paper, an OFDM wireless system based on WPC NOMA is studied to optimize the total uplink Information Decoding (ID) rate. Unlike conventional methods, the proposed method can obtain the maximum energy in the downlink and higher total uplink ID rate.

2 System Model and Problem Formulation

2.1 System Model

An OFDM-based wireless communication system with one BS and N users is studied and shown in Fig. 1. In the downlink, ID and Energy Harvesting (EH) are simultaneously performed by users. In the uplink, ID is performed by BS based on NOMA. The user set is represented by $\mathbf{N} = \{1, 2, \ldots, N\}$. The total bandwidth is equally split into K subchannels for K subcarriers. The subcarrier set is represented by $\mathbf{K} = \{1, 2, \ldots, K\}$. For subcarrier k assigned to user n, the channel gain coefficient is represented by $h_{k,n}$. The factor for subcarrier allocation is represented by $a_{k,n}$. It is set that $a_{k,n} = 1$ if subcarrier k is assigned to user n, otherwise, $a_{k,n} = 0$. The total transmit power is represented by P. The power assigned to subcarrier k for user n is represented by $p_{k,n}$.

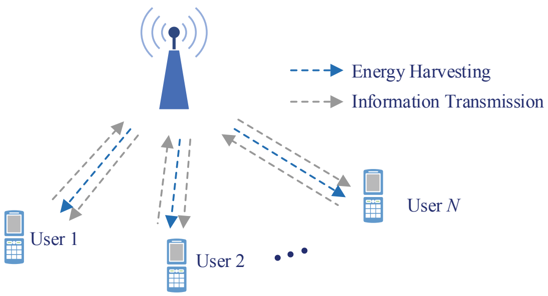

Fig. 1. System model.

2.2 Problem Formulation

In the downlink, subcarriers for ID is allocated to group $\mathbf{K^I}$ and others for EH is allocated to group $\mathbf{K^E}$, where $\mathbf{K^I}, \mathbf{K^E} \subseteq \mathbf{K}$ and $\mathbf{K^I} + \mathbf{K^E} = \mathbf{K}$. $\mathbf{K^I}$ is used for ID while $\mathbf{K^E}$ is used for EH. Each subcarrier is only utilized for ID or EH.

The downlink ID rate on subcarrier k is formulated by

$$R_k = \sum_{n=1}^{N} a_{k,n} \ln(1 + \frac{h_{k,n}^2 p_{k,n}}{\sigma_{k,n}^2}), k \in \mathbf{K_I}, n \in \mathbf{N} \tag{1}$$

Where $\sigma_{k,n}^2$ represents the noise on subcarrier k to user n. The EH on subcarrier k is given by

$$E_k = \eta \sum_{n=1}^{N} a_{k,n} \left(h_{k,n}^2 p_{k,n} + \sigma_{k,n}^2 \right), k \in \mathbf{K_E}, n \in \mathbf{N} \tag{2}$$

Where $\eta \in (0, 1)$ represents the receiver's energy conversion efficiency.

After EH is performed in the downlink, energy obtained by users is available to perform information transmission to BS in the uplink. Then, BS can perform ID based on NOMA. For simplicity, subcarriers in $\mathbf{K^E}$ can be sorted as a fixed decoding order, which is assumed to be the ascending order of $h_{k,n}$, and renumbered from 1 to M. In use of SIC, when the signal from one subcarrier is decoded, signals from who have higher decoding order than the decoded one are treated as noise. The transmit power on subcarrier m for user n is represented by $p_{m,n} = E_{m,n}$. Thus, the ID rate on subcarrier m can be given by

$$R_m = \sum_{n=1}^{N} a_{m,n} \ln(1 + \frac{h_{m,n}^2 p_{m,n}}{\sum\limits_{j=m+1}^{M} h_{j,n}^2 p_{j,n} + \sigma_{m,n}^2}), n \in \mathbf{N} \tag{3}$$

After the ID of M-1 subcarriers, the ID rate on subcarrier M can be given by

$$R_M = \sum_{n=1}^{N} a_{M,n} \ln(1 + \frac{h_{M,n}^2 p_{M,n}}{\sigma_{M,n}^2}), n \in \mathbf{N} \tag{4}$$

The optimization objective of this paper is to maximize the total uplink ID rate while the threshold of total downlink ID rate can be ensured. Thus, the optimization objective can be formulated as

$$\max_{R_m} \sum_{m=1}^{M} R_m \tag{5}$$

Subject to

$$\sum_{n=1}^{N} \sum_{k \in \mathbf{K^I}} a_{k,n} \ln(1 + \frac{h_{k,n}^2 p_{k,n}}{\sigma_{k,n}^2}) \geq R_T \tag{6}$$

Where R_{T} represents the threshold of total downlink ID rate, so that the total ID rate must be more than or equal to R_{T}. As known that one subcarrier is only used for ID or

EH, so that $\sum_{n=1}^{N} a_{k,n} = 1$. It is noted that, in (3) and (4), the ID rate on subcarrier m in the uplink is only determined by $p_{m,n}$. Thus, the original optimization objective can be regarded as a maximization of EH in the downlink. The optimization objective can be arranged as

$$\begin{aligned}
&\max_{\varphi_{k,n},p_{k,n}} \eta \sum_{n=1}^{N} \sum_{k\in\mathbf{K^E}} a_{k,n}(h_{k,n}^2 p_{k,n} + \sigma_{k,n}^2) \\
&\quad \text{s.t.} \sum_{n=1}^{N} \sum_{k\in\mathbf{K^I}} a_{k,n} \ln(1 + \frac{h_{k,n}^2 p_{k,n}}{\sigma_{k,n}^2}) \geq R_T \\
&\quad\quad \sum_{n=1}^{N} a_{k,n} = 1,\ a_{k,n} = 0, 1 \\
&\quad\quad \sum_{n}^{N} \sum_{k=1}^{K} a_{k,n} p_{k,n} \leq P \\
&\quad\quad \mathbf{K^I} + \mathbf{K^E} = \mathbf{K}
\end{aligned} \tag{7}$$

3 Optimal Solution

An iteration method based on Lagrange Multiplier is designed to achieve the optimization objective proposed in Sect. 2. Obviously, the optimization problem in (7) is nonconvex that requires to be broken down into parts to solve. It is set that $p_{k,n}$, $\mathbf{K^I}$ and $\mathbf{K^E}$ are given first. Taking no account of fairness, subcarrier k is allocated to user n by finding the maximum $h_{k,n}$ for it, so that $a_{k,n}$= 1. Thus, (7) is arranged as

$$\begin{aligned}
&\max_{p_{k,n}} \eta \sum_{n=1}^{N} \sum_{k\in\mathbf{K^E}} a_{k,n}(h_{k,n}^2 p_{k,n} + \sigma_{k,n}^2) \\
&\text{s.t.} \quad \sum_{n=1}^{N} \sum_{k\in\mathbf{K^I}} a_{k,n} \ln(1 + \frac{h_{k,n}^2 p_{k,n}}{\sigma_{k,n}^2}) \geq R_T \\
&\quad\quad\ \sum_{n=1}^{N} \sum_{k=1}^{K} a_{k,n} p_{k,n} \leq P
\end{aligned} \tag{8}$$

The optimization problem in (8) is convex so that it can be settled based on the Lagrange Multiplier. Then, the Lagrange dual function of (8) can be formulated as

$$g(\mathbf{\Lambda}) = \max_{\mathbf{P},\mathbf{K}} \mathcal{L}(\mathbf{P}, \mathbf{K}) \tag{9}$$

Where $\mathbf{P} = \{p_{1,n}, p_{2,n}, \ldots, p_{k,n}\}$ is the allocated power set and $\mathbf{K} = \{\mathbf{K^I}, \mathbf{K^E}\}$ is the subcarrier set. The expression of $\mathcal{L}(\mathbf{P}, \mathbf{K})$ is given by

$$\mathcal{L}(\mathbf{P},\mathbf{K}) = \eta\sum_{n=1}^{N}\sum_{k\in\mathbf{K}^{\mathbf{E}}} a_{k,n}(h_{k,n}^{2}p_{k,n}+\sigma_{k,n}^{2}) + \lambda_1(\sum_{n=1}^{N}\sum_{k\in\mathbf{K}^{\mathbf{I}}} a_{k,n}\ln(1+\frac{h_{k,n}^{2}p_{k,n}}{\sigma_{k,n}^{2}}) - R_T) \\ + \lambda_2(P-\sum_{n=1}^{N}\sum_{k=1}^{K} a_{k,n}p_{k,n}) \tag{10}$$

Where $\mathbf{\Lambda} = (\lambda_1, \lambda_2)$ is the non-negative dual variable depending on P and total ID rate. Then, the dual optimization problem is able to be transformed to

$$\min_{\mathbf{\Lambda}} g(\mathbf{\Lambda}) \tag{11}$$

Based on the subgradient method, (11) can be obtained owing to the differentiability of $g(\mathbf{\Lambda})$. The subgradients can be expressed as

$$\Delta\lambda_1 = \sum_{n=1}^{N}\sum_{k\in\mathbf{K}^{\mathbf{I}}} a_{k,n}\ln(1+\frac{h_{k,n}^{2}p_{k,n}}{\sigma_{k,n}^{2}}) - R_T \tag{12}$$

$$\Delta\lambda_2 = P-\sum_{n=1}^{N}\sum_{k=1}^{K} a_{k,n}p_{k,n} \tag{13}$$

$\mathbf{\Lambda}$ can be update by iteration in use of $\mathbf{\Lambda}(t+1) = \mathbf{\Lambda}(t) + \mathrm{v}(t)\cdot\Delta\mathbf{\Lambda}$, where $\Delta\mathbf{\Lambda} = (\Delta\lambda_1,\Delta\lambda_2)$, t represents iterations and v represents negative step size. With the increase of t, $\mathbf{P}$ and $\mathbf{K}$ can be optimized by iteration until $\mathbf{\Lambda}$ converges. In this case, the objective of (11) can be achieved.

The optimization of $\mathbf{P}$ and $\mathbf{K}$ can be performed based on the variable control method. $\mathbf{P}$ can be maximized first with a fixed $\mathbf{K}$ so that $p_{k,n}$ can be obtained by partial derivatives of (10), which are expressed as

$$\frac{\partial\mathcal{L}(\mathbf{P},\mathbf{K})}{\partial p_{k,n}} = \frac{\sum_{n=1}^{N}\lambda_1 a_{k,n}h_{k,n}^{2}}{\sigma_{k,n}^{2}+h_{k,n}^{2}p_{k,n}} - \lambda_2, k\in\mathbf{K}^{\mathbf{I}} \tag{14}$$

$$\frac{\partial\mathcal{L}(\mathbf{P},\mathbf{K})}{\partial p_{k,n}} = \sum_{n=1}^{N} a_{k,n}h_{k,n}^{2}\eta - \lambda_2, k\in\mathbf{K}^{\mathbf{E}} \tag{15}$$

According to the Karush-Kuhn-Tucker condition, the desired $p_{k,n}$ can be obtained when (14) and (15) equal to 0. Therefore, when $k\in\mathbf{K}^{\mathbf{I}}$, the desired $p_{k,n}$ can be formulated by

$$p_{k,n} = \frac{\lambda_1}{\lambda_2} - \frac{\sum_{n=1}^{N} a_{k,n}\sigma_{k,n}^2}{h_{k,n}^2} \tag{16}$$

Obviously, (15) can not be set to zero unless $h_{k,n}\eta = \lambda_2$. For the sake of improving power utilization and obtaining more energy, the linear water-filling method can be utilized to reassign the power not be used for ID. For simplicity, $a_{k,n}$ is not participated in following derivation. Thus, the Lagrange function is expressed as

$$\mathcal{L}(\lambda_2, p_i) = \ln(1 + \frac{h_i^2 p_i}{\sigma_i^2}) + \lambda_2(P_E - \sum_{i \in \mathbf{K^E}} p_i) \tag{17}$$

Where subcarrier i belongs to $\mathbf{K^E}$. P_{E} represents the power unutilized for ID. Thus, the following derivation based on the partial derivative of (17) is expressed by

$$\begin{aligned} p_i &= (\frac{1}{\lambda_2} - \frac{\sigma_i^2}{h_i^2})^+ \Rightarrow \frac{\sigma_i^2}{h_i^2} + p_i = \frac{\sigma_k^2}{h_k^2} + p_k \Rightarrow p_i = p_k + \frac{\sigma_k^2}{h_k^2} - \frac{\sigma_i^2}{h_i^2} \\ &\Rightarrow N_E(p_k + \frac{\sigma_k^2}{h_k^2}) - \sum_{i \in \mathbf{K^E}} \frac{\sigma_i^2}{h_i^2} = P_E \end{aligned} \tag{18}$$

Where subcarrier k is another one of $\mathbf{K^E}$ except subcarrier i. N_{E} represents the number of subcarriers in $\mathbf{K^E}$. The desired p_k for subcarrier k in $\mathbf{K^E}$ can be obtained as

$$p_k = \frac{1}{N_E}(P_E - \frac{N_E\sigma_k^2}{h_k^2} + \sum_{i \in \mathbf{K^E}} \frac{\sigma_i^2}{h_i^2}) \tag{19}$$

Afterwards, the optimized $\mathbf{K^I}$ and $\mathbf{K^E}$ can be obtained by substituting (16) and (19) into (10). The simplification process is given by

$$\begin{aligned} \mathcal{L} &= \eta \sum_{n=1}^{N} \sum_{k \in \mathbf{K^E}} a_{k,n}(h_{k,n}^2 p_{k,n} + \sigma_{k,n}^2) + \lambda_1[\sum_{n=1}^{N} \sum_{k \in \mathbf{K^I}} a_{k,n} \ln(1 + \frac{h_{k,n}^2 p_{k,n}}{\sigma_{k,n}^2}) - R_T] + \lambda_2(P - \sum_{n=1}^{N}\sum_{k=1}^{K} a_{k,n}p_{k,n}) \\ &= \sum_{k \in \mathbf{K^I}} Y_k + \sum_{n=1}^{N}\sum_{k=1}^{K} a_{k,n}[\eta(h_{k,n}^2 p_{k,n} + \sigma_{k,n}^2) - \lambda_2 p_{k,n}] - \lambda_1 R_T + \lambda_2 P \end{aligned} \tag{20}$$

Where

$$Y_k = \sum_{n=1}^{N} a_{k,n}[\lambda_1 \ln(1 + \frac{h_{k,n}^2 p_{k,n}}{\sigma_{k,n}^2}) - \eta(h_{k,n}^2 p_{k,n} + \sigma_{k,n}^2)] \tag{21}$$

Obviously, Y_k is the only part relative to $\mathbf{K^I}$. By finding subcarriers making Y_k positive, the optimized $\mathbf{K^I}$ can be obtained. Other subcarriers are allocated to $\mathbf{K^E}$.

Afterwards, the update of $\Delta\mathbf{\Lambda}$ for the next iteration can be achieved by substituting the optimized $\mathbf{P}$ and $\mathbf{K}$ into (12) and (13). Based on iteration, the maximum EH can be achieved until $\mathbf{\Lambda}$ converges.

Afterwards, the desired transmit power $p_{m,n}$ in the uplink can be obtained based on the optimal harvested energy discussed above. For simplicity, $a_{k,n}$ is not considered in the following discussion. It is assumed that σ_m^2 is set to 1. The maximum sum ID rate in the uplink can be given by

$$R_u = \sum_{m=1}^{M-1} \ln(1 + \frac{h_m^2 p_m}{\sum\limits_{j=m+1}^{M} h_k^2 p_k + \sigma_m^2}) + \ln(1 + \frac{h_M^2 p_M}{\sigma_M^2}) = \ln(2 + \sum_{m=1}^{M} h_m^2 p_m) \tag{22}$$

4 Simulation

The performance of the proposed method is investigated based on simulation results. It is set that $N = 4$, $K = 16$, $\sigma_{k,n}^2 = 1$, $\eta = 0.8$, and $h_{k,n}$ are known at all receivers. The total bandwidth is set to 1 MHz. The signals are assumed to be perfectly synchronized. For iteration, it is set that $\lambda_1 = 2.2$ and $\lambda_2 = 0.6$. The step sizes are set to 0.02 and 0.002, respectively. The threshold of total downlink ID rate R_{T} is set to 6Mbps.

The method proposed is considered as Method 1. The other method defined as Method 2 is considered in which P is equally allocated to subcarriers. When two methods are performed in the downlink, the results of total uplink ID rate are shown in Fig. 2. With the increase of P, the total ID rate based on Method 1 is higher than that based on Method 2.

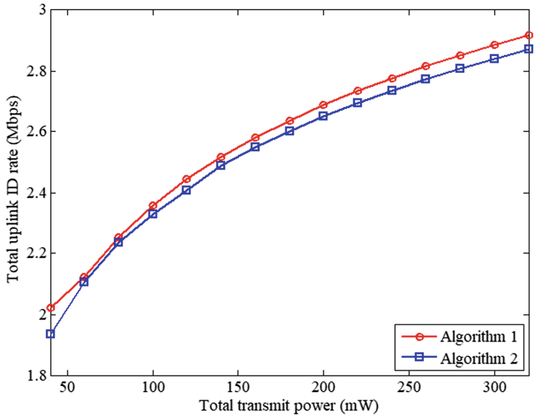

Fig. 2. Total uplink ID rate based on Method 1 and Method 2.

For uplink, the performance based on NOMA is contrasted with that based on Time Division Multiple Access (TDMA) which is a common type of orthogonal multiple access (OMA). While EH is constantly performed for downlink, the results of total uplink ID rate based on NOMA and TDMA are shown in Fig. 3 Obviously, the performance of total ID rate based on NOMA is much better than that based on TDMA.

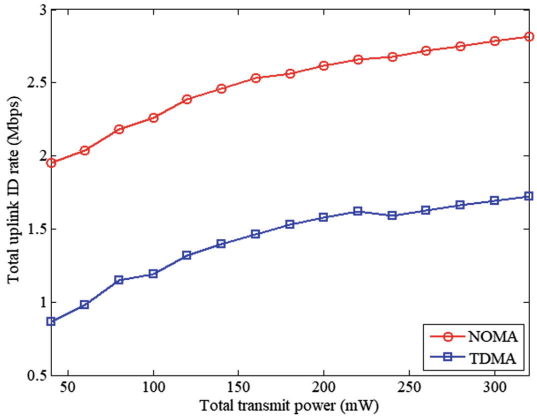

Fig. 3. Total uplink ID rate based on NOMA and TDMA

5 Conclusion

In this paper, a joint uplink and downlink optimization method for wireless powered NOMA OFDM communication system is proposed. Owing to that the total uplink ID rate is only influenced by downlink EH, for achieving the objective, an iteration algorithm based on Lagrange Multiplier is designed. In the downlink, the energy obtained by users can be optimized based on the joint power and subcarrier allocation optimization by iteration. Afterwards, NOMA and SIC are used for uplink at BS to perform ID and improve the total uplink ID rate. As shown in simulation results, in the same condition, the proposed method can increase the energy harvested for uplink and obtain a higher uplink ID rate than traditional methods.

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