Optimal Transceiver Design for SWIPT in Interference Alignment Network

Yan CHEN, Chen LIU*, Youhua FU，Yunchao SONG，Mujun QIAN
National and Local Joint Engineering Laboratory of RF Integration and Micro-Assembly Technology, Nanjing University of Posts and Telecommunications, Nanjing, 210003，China
corresponding.liuch@njupt.edu.cn

***Abstract*—This paper studies simultaneous wireless information and power transfer in a K-user multiple-input multiple-output interference channel. A new scheme jointly designing interference alignment (IA) and wireless energy harvesting is proposed. Firstly, the character of each receiver is determined according to the maximum achievable rate and maximum harvested power. The receiving users are used as either energy harvesting (EH) users or information decoding (ID) users, where EH users are used to harvest energy, and ID users are used to transmit information. Secondly, the double-objective problem is established by maximizing both the total power harvested by EH users and the total signal-to-interference-noise ratio (SINR) of the ID users. The problem is solved by the weighted sum method. Moreover, the transmit precoding matrices and the receive interference suppression matrices are solved by iterative optimization algorithm based on a complete IA constraint (IOA-CIA). Simulation results show that the proposed IOA-CIA algorithm provides higher sum rate and harvested power than the existing algorithm.**

***Index Terms*—energy harvesting, interference channels, iterative methods, MIMO, optimization.**

I. Introduction

In wireless communication, interference makes wireless transmission challenging [1]. Interference alignment (IA) [2] is a widely acknowledged interference management technology, which can obtain the Shannon capacity of interference network at high signal-to-noise ratio (SNR). The research of IA technology [3] considering 3 aspects: dimension, network topology and application. IA technology can be achieved in time dimension, frequency dimension and space dimension. Network topologies of IA technology conclude interference channel [4], X channel [5], interference broadcast channel [6] etc. IA technology can be applied to cognition wireless network [7], massive multiple-input multiple-output systems [8], device-to-device (D2D) network [9] and so on. IA can achieve good performance in interference networks, but it is difficult to obtain its closed-form solution especially when the number of users is large. Current research focuses on the design of iterative algorithms [10-11] to obtain the optimal IA matrices with low computational complexity.

In recent years, the influence of interference in wireless communication has shifted from a disadvantageous to an advantageous one because of the research of wireless energy harvesting (WEH) technology [12-13]. There are three transmission schemes in WEH networks. The first scheme is called wireless power transfer (WPT) [14], which only transmits power to energy harvesting (EH) receivers without information exchange. The second scheme is called wireless power communication network (WPCN) [15], which uses the power harvested to transmit information. The third scheme is called simultaneous wireless information and power transfer (SWIPT) [16], where information and energy are transferred by the same radio frequency signal. The paper adopts the third one in an interference channel where the interference is reasonably utilized as power source for energy receivers. When interference is reasonably used in WEH, energy can be saved and green communication can be achieved.

In order to implement SWIPT, the received signal should be used for information decoding and energy harvesting. There are two common receiver structures: time switching (TS) [17] and power splitting (PS) [18-19]. The former one is simple to implement since it only requires a switch between the information decoding receiver and the energy harvesting receiver. But it requires strict time synchronization. The latter one splits the received signal into two streams which are for ID and EH, respectively. It is more complicate but can provide better compromise between transmission rate and harvested power. The receiver structure in this paper adopts PS mode. And the PS ratio in this paper can only be 0 or 1 in a transmission, which means that each user on the receiving side can only be ID user or EH user.

Currently, the research work on EH and IA is mainly separated. In multiuser system, some users want to transmit information at high speed, while others want to harvest wireless energy when the battery is low. Therefore, it is reasonable for some IA receivers to harvest wireless energy from the transmitting side at a certain time slot. The literature combining EH technique and IA technique were mainly [20-26]. A diversity IA technique was derived in [20]. In [21-22], two easy-to-implement SWIPT user selection algorithms were designed: Round-Robin Selection (RRS) algorithm and Power-to-Rate Ratio Selection (PRRS) algorithm. The PRRS algorithm used the iterative algorithm [10] to obtain the transmit precoding matrices and the receive interference suppression matrices. Then a power-to-rate ratio (PRR) parameter was defined as the criterion for judging the characters of the receiving side users. The results showed that PRRS algorithm outperformed RRS algorithm under the same number of ID receivers. In [23], an anti-jamming opportunistic IA scheme for SWIPT was

This work was supported by the National Natural Science Foundation of China under Grant No. 61771257, No. 61901232, Jiangsu Higher Education Institutions under Grant No. 18KJB510027, Jiangsu Postgraduate Research and Practice Innovation Program under Grant No.KYLX160646.

Digital Object Identifier 10.4316/AECE.2020.02003

proposed. Two schemes for the SWIPT in relay interference channels were studied in [24]. An artificial noise assisted IA scheme with WEH was proposed in [25]. The performance of cognitive relay network was studied in [26]. In these literature, interference alignment was first performed before energy harvesting and information transmission were carried out. This motivates us to propose a new scheme.

The main idea of this paper is to design transmit precoding matrices and receive interference suppression matrices by first determining EH and ID users, then maximizing the total power harvested by EH users and the total signal-to-interference-to-noise ratio (SINR) of ID users. Compared to joint EH-IA researches in [20-26], the main contributions of this paper are summarized as follows,

1) In the limited works of joint EH-IA research, IA is performed first, and then energy harvesting and information transmission are carried out. The innovation of this paper is that user selection is carried out first, and the receiver side users are divided into two types: EH users to harvesting energy and ID users to decoding information. Then only ID users are jammed and aligned, while EH users harvest the energy transferred by ID users.

2) After users selection, we develop a double-objective optimization problem based on a complete IA constraint, i.e. maximization both the total power harvested by EH users and the total SINR of ID users under complete interference alignment. For this double-objective optimization problem, the weighted objective sum method is used to quantify the double-objective problem in this paper.

3) We propose an iterative optimization algorithm based on a complete IA constraint (IOA-CIA) for solving the non-convex problem. When fixing the transmit precoding matrix or the receive interference suppression matrix, the non-convex problem can be transformed to a Rayleigh entropy maximization problem. The optimality of the designs of the transmit precoding matrix and the received interference suppression matrix is verified by simulations. Results show that the proposed scheme can improve the performance of the system and outperform the scheme being compared.

The rest of this paper is organized as follows. Section II describes the system model along with the users selection method. The objective function and constraints of the new algorithm based on complete IA is proposed in Section III. Section IV gives the optimization solution of the proposed IOA-CIA algorithm. Numerical results and discussions are provided and analyzed in Section V, and finally, Section VI concludes the paper.

Notations: $\mathbf{I}_d$ is the $d \times d$ identity matrix. $\mathbf{A}^{\mathrm{H}}$ represents the conjugate transpose of matrix $\mathbf{A}$. $\mathrm{Tr}(\mathbf{A})$ is trace of matrix $\mathbf{A}$. $\mathrm{Rank}(\mathbf{A})$ and $\mathbb{E}[\mathbf{A}]$ denote rank and statistical expectation of matrix $\mathbf{A}$, respectively. $\|\boldsymbol{a}\|$ is the Euclidean norm of vector $\boldsymbol{a}$. $\|\mathbf{A}\|_{\mathrm{F}}$ denotes the Frobenius norm of matrix $\mathbf{A}$. $\lambda_{\max}(\mathbf{A})$ is the largest eigenvalue of $\mathbf{A}$. $\boldsymbol{\gamma}_{\max}(\mathbf{A})$ is the eigenvector corresponding to the largest eigenvalue of $\mathbf{A}$. $\mathcal{CN}(\boldsymbol{\mu},\mathbf{C})$ is used to express circularly symmetric complex gaussian (CSCG) distribution which has mean $\boldsymbol{\mu}$ and covariance matrix $\mathbf{C}$.

II. SYSTEM MODEL

Consider a K-user multiple-input multiple-output (MIMO) interference channel where the transmitter TX-k and receiver RX-$k\left(k \in \kappa \triangleq \{1,2,\ldots,K\}\right)$ are equipped with N_t and N_r antennas respectively. d_k is the number of data streams sent by TX-k. Each receiver is equipped with an ID terminal and an EH terminal, but can only be either ID receiver or EH receiver at a certain transmission. In this model, ID and EH users are selected first, then IA is implemented on ID users, and EH users receive energy from ID users. This system model is shown in Fig. 1.

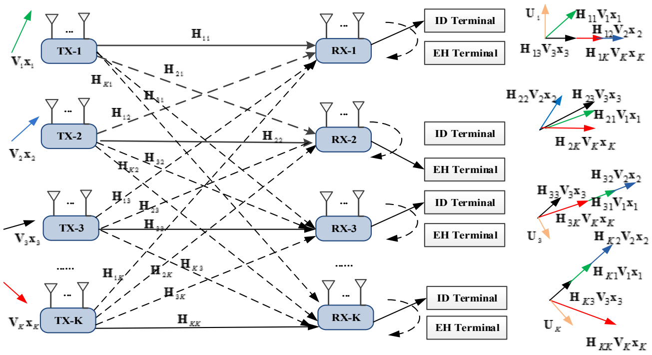

Figure 1. A MIMO SWIPT system, where ID user pairs transmit information and EH user pairs harvest energy.

In the n-th time slot, the received signal at RX-k can be represented as:

$$\mathbf{r}_k(n) = \mathbf{H}_{kk}(n)\mathbf{V}_k(n)\mathbf{x}_k(n) + \sum_{j=1, j\neq k}^{K} \mathbf{H}_{kj}(n)\mathbf{V}_j(n)\mathbf{x}_j(n) + \mathbf{z}_k(n),\ k \in \kappa, \tag{1}$$

where $\mathbf{H}_{kj}(n)$ denotes channel gain matrix from the TX-j to the RX-k, with all its entries being independent and identically (i.i.d.) zero-mean and w_{kj}^2-variance CSCG random variables. For the convenience of the subsequent analysis, the time slot n is henceforth suppressed unless to avoid heavy notation. $\mathbf{x}_k$ is the information symbols transmitted by TX-k which is composed of the d_k data streams. The transmit power at TX-k is $\mathbb{E}\left[\|\mathbf{x}_k\|^2\right] = P$. The transmit precoding matrix $\mathbf{V}_k$ of TX-k satisfies $\mathbf{V}_k^{\mathrm{H}}\mathbf{V}_k = \mathbf{I}_{d_k}$. Channel state information (CSI) is available throughout this paper. $\mathbf{z}_k$ is the received noise vector, and it obeys the CSCG distribution $\mathcal{CN}\left(\mathbf{0},\sigma^2\mathbf{I}_{N_r}\right)$ [15].

The expected harvested power at RX-k denoted by Q_k is equal to:

$$Q_k = \zeta\mathbb{E}\left(\|\mathbf{r}_k\|^2\right) = \zeta\mathbb{E}\left(\left\|\sum_{j=1}^{K}\mathbf{H}_{kj}\mathbf{V}_j\mathbf{x}_j + \mathbf{z}_k\right\|^2\right) \approx \zeta P\sum_{j=1}^{K}\left\|\mathbf{H}_{kj}\mathbf{V}_j\right\|_{\mathrm{F}}^2,\ k \in \kappa, \tag{2}$$

where $\zeta \in (0,1)$ is a constant for a particular system, indicating the power conversion efficiency from the harvested energy to the electric energy. We have used the following assumptions: $\mathbb{E}\left[\mathbf{x}_k\mathbf{x}_j^{\mathrm{H}}\right] = \mathbf{0}, \forall k \neq j$, $\mathbb{E}\left[\mathbf{x}_k\mathbf{z}_j^{\mathrm{H}}\right] = \mathbf{0}$, due to i.i.d. characteristics. The noise power $\zeta\sigma^2$ being much smaller than the harvested power can be omitted in (2). All the receivers in this paper have the same power conversion efficiency.

According to [21], the lower bound of the harvested power is obtained when the desired signal and the total interferences have the same length with the angle equal to π between them. The upper bound of the harvested power is obtained when the desired signal is in the same direction as all interferences. The range of power harvested can be expressed as:

$$0 \le Q_k \le \zeta P \sum_{j=1}^{K} \lambda_{\max}\left(\mathbf{H}_{kj}^{\mathrm{H}}\mathbf{H}_{kj}\right), \tag{3}$$

where 0 and $\zeta P \sum_{j=1}^{K} \lambda_{\max}\left(\mathbf{H}_{kj}^{\mathrm{H}}\mathbf{H}_{kj}\right)$ represent the lower and upper bounds of the harvested power at RX-k, respectively.

When the interference suppression matrix $\mathbf{U}_k$ of the received signal is processed, the estimate of $\mathbf{x}_k$ can be obtained as follows:

$$\begin{aligned}\hat{\mathbf{x}}_k &= \mathbf{U}_k^{\mathrm{H}}\left(\mathbf{H}_{kk}\mathbf{V}_k\mathbf{x}_k + \sum_{j=1, j\neq k}^{K}\mathbf{H}_{kj}\mathbf{V}_j\mathbf{x}_j + \mathbf{z}_k\right) \\ &= \mathbf{U}_k^{\mathrm{H}}\mathbf{H}_{kk}\mathbf{V}_k\mathbf{x}_k + \mathbf{U}_k^{\mathrm{H}}\sum_{j=1, j\neq k}^{K}\mathbf{H}_{kj}\mathbf{V}_j\mathbf{x}_j + \mathbf{U}_k^{\mathrm{H}}\mathbf{z}_k,\ k\in\kappa.\end{aligned} \tag{4}$$

If there exist transmit precoding matrix $\mathbf{V}_k$ and receive interference suppression matrix $\mathbf{U}_k$ which satisfy

$$\begin{aligned}&\mathbf{U}_k^{\mathrm{H}}\mathbf{H}_{kj}\mathbf{V}_j = \mathbf{0}, k, j\in\kappa, j\neq k, \\ &\mathrm{Rank}\left(\mathbf{U}_k^{\mathrm{H}}\mathbf{H}_{kk}\mathbf{V}_k\right) = d_k,\ k\in\kappa,\end{aligned} \tag{5}$$

with $\mathbf{V}_k^{\mathrm{H}}\mathbf{V}_k = \mathbf{I}_{d_k}$, $\mathbf{U}_k^{\mathrm{H}}\mathbf{U}_k = \mathbf{I}_{d_k}$, we say that IA is feasible, then the interference between users is completely deleted. The first condition in (5) indicates that the interference signal is aligned to the null space of the interference suppression matrix, and the second condition indicates that the degree of freedom d_k of the desired signal is maintained.

If the interference between users is completely deleted, the estimate of $\mathbf{x}_k$ is simplified as follows:

$$\hat{\mathbf{x}}_k = \mathbf{U}_k^{\mathrm{H}}\mathbf{H}_{kk}\mathbf{V}_k\mathbf{x}_k + \mathbf{U}_k^{\mathrm{H}}\mathbf{z}_k,\ k\in\kappa. \tag{6}$$

Then the achievable rate of RX-k is:

$$R_k = \log_2\left|\mathbf{I}_{d_k} + \frac{P\left(\mathbf{U}_k^{\mathrm{H}}\mathbf{H}_{kk}\mathbf{V}_k\right)\left(\mathbf{U}_k^{\mathrm{H}}\mathbf{H}_{kk}\mathbf{V}_k\right)^{\mathrm{H}}}{\sigma^2}\right|. \tag{7}$$

Since this paper focuses on information transmission and energy harvesting, we set the number of data streams d_k to 1, (7) can be simplified as:

$$\begin{aligned}R_k &= \log_2\left|1 + \frac{P\left|\mathbf{u}_k^{\mathrm{H}}\mathbf{H}_{kk}\mathbf{v}_k\right|^2}{\sigma^2}\right| \\ &= \log_2\left|1 + \frac{Ps_k^2\cos^2\varphi_k}{\sigma^2}\right|,\end{aligned} \tag{8}$$

where $s_k = \left\|\mathbf{H}_{kk}\mathbf{v}_k\right\|^2$ and φ_k is the angle between the interference suppression vector $\mathbf{u}_k$ and the signal $\mathbf{H}_{kk}\mathbf{v}_k$. When interference suppression vector $\mathbf{u}_k$ is in the same direction as the signal $\mathbf{H}_{kk}\mathbf{v}_k$, the achievable rate of RX-k reaches its upper bound. When the interference suppression vector $\mathbf{u}_k$ is orthogonal to the signal $\mathbf{H}_{kk}\mathbf{v}_k$, the achievable rate of RX-k reaches its lower bound. The range of RX-k achievable rate is as follows:

$$0 \le R_k \le \log_2\left(1 + \frac{P\left\|\mathbf{H}_{kk}\mathbf{v}_k\right\|^2}{\sigma^2}\right). \tag{9}$$

According to the definitions of induction norm and spectral norm, we have

$$\left\|\mathbf{H}_{kk}\mathbf{v}_k\right\| \le \left\|\mathbf{H}_{kk}\right\| = \sqrt{\lambda_{\max}\left(\mathbf{H}_{kk}^{\mathrm{H}}\mathbf{H}_{kk}\right)}, \tag{10}$$

Thus Eq. (9) can be rewritten as:

$$0 \le R_k \le \log_2\left[1 + \frac{P}{\sigma^2}\lambda_{\max}\left(\mathbf{H}_{kk}^{\mathrm{H}}\mathbf{H}_{kk}\right)\right], \tag{11}$$

Let β_k denotes the ratio between the upper bound of the harvested power and the upper bound of the achievable rate, then β_k can be denoted as:

$$\beta_k = \frac{\zeta P \sum_{j=1}^{K}\lambda_{\max}\left(\mathbf{H}_{kj}^{\mathrm{H}}\mathbf{H}_{kj}\right)}{\log_2\left[1 + \frac{P}{\sigma^2}\lambda_{\max}\left(\mathbf{H}_{kk}^{\mathrm{H}}\mathbf{H}_{kk}\right)\right]}, \tag{12}$$

here β_k is sorted under a time slot. If the value is large, the user pair is more likely to be an EH user. If the value is small, the user pair is more likely to be an ID user. This paper chooses the users with larger β_k as the EH users, whereas the remaining users as the ID users. The number of ID users is set to be $K_{\mathrm{ID}}\left(1 \le K_{\mathrm{ID}} \le K\right)$, and the number of EH users is $K_{\mathrm{EH}}\left(0 \le K_{\mathrm{EH}} < K\right)$.

The EH user set of n-th time slot is recorded as E, the ID user set is recorded as I, $E \cap I = \varnothing$. In our scheme, EH users do not send messages for the convenience of analysis.

Note that the received signal of ID receiver RX-$i\left(i\in I\right)$ can be represented as:

$$\mathbf{r}_i = \mathbf{H}_{ii}\mathbf{v}_i x_i + \sum_{\substack{j\in I \\ j\neq i}}\mathbf{H}_{ij}\mathbf{v}_j x_j + \mathbf{z}_i, i\in I, \tag{13}$$

where $\mathbf{H}_{ii}\mathbf{v}_i x_i$ represents information-bearing signal of RX-i, $\sum_{\substack{j\in I \\ j\neq i}}\mathbf{H}_{ij}\mathbf{v}_j x_j$ represents the interferences from other ID users. The transmit power of TX-i is set to $\frac{KP}{K_{\mathrm{ID}}}$. To recover the desired information symbol x_i, the ID signal flow is passed to the receive interference suppression vector $\mathbf{u}_i$, then the estimate of x_i is given by

$$\hat{x}_i^{\mathrm{ID}} = \mathbf{u}_i^{\mathrm{H}}\mathbf{H}_{ii}\mathbf{v}_i x_i + \mathbf{u}_i^{\mathrm{H}}\sum_{\substack{j\in I \\ j\neq i}}\mathbf{H}_{ij}\mathbf{v}_j x_j + \mathbf{u}_i^{\mathrm{H}}\mathbf{z}_i, i\in I. \tag{14}$$

The achievable rate of RX-i can be calculated as:

$$R_i = \log_2\left(1 + \frac{\frac{KP}{K_{\mathrm{ID}}}\left|\mathbf{u}_i^{\mathrm{H}}\mathbf{H}_{ii}\mathbf{v}_i\right|^2}{\frac{KP}{K_{\mathrm{ID}}}\sum_{\substack{j\in I \\ j\neq i}}\left|\mathbf{u}_i^{\mathrm{H}}\mathbf{H}_{ij}\mathbf{v}_j\right|^2 + \sigma^2}\right), i\in I, \tag{15}$$

and the SINR of RX-i can be expressed as:

$$\mathrm{SINR}_i = \frac{\dfrac{KP}{K_{\mathrm{ID}}}\left|\mathbf{u}_i^{\mathrm{H}}\mathbf{H}_{ii}\mathbf{v}_i\right|^2}{\dfrac{KP}{K_{\mathrm{ID}}}\sum\limits_{\substack{j\in I\\ j\neq i}}\left|\mathbf{u}_i^{\mathrm{H}}\mathbf{H}_{ij}\mathbf{v}_j\right|^2+\sigma^2}, i\in I. \quad (16)$$

The harvested power of EH users comes from the signal broadcasted by the transmitters of the ID user pairs. The received signals of EH receiver RX- $e(e\in E)$ can be expressed as:

$$\mathbf{r}_e = \sum_{i\in I}\mathbf{H}_{ei}\mathbf{v}_i x_i + \mathbf{z}_e, e\in E, \quad (17)$$

and the expected harvested power of user e is equal to

$$Q_e = \zeta\mathbb{E}\left(\left\|\mathbf{r}_e\right\|^2\right) \approx \zeta\frac{KP}{K_{\mathrm{ID}}}\sum_{i\in I}\left\|\mathbf{H}_{ei}\mathbf{v}_i\right\|^2, e\in E \quad (18)$$

The sum of harvested power of EH users is represented as:

$$Q_{sum\_e} = \sum_{e\in E}Q_e = \sum_{e\in E}\zeta\frac{KP}{K_{\mathrm{ID}}}\sum_{i\in I}\left\|\mathbf{H}_{ei}\mathbf{v}_i\right\|^2, e\in E. \quad (19)$$

III. Problem Formulation

In our paper, the proposed optimization problem takes the complete IA constraint into consideration. Subject to the constraint that all interference of ID users are aligned, we aim to maximize the total SINR of ID users and the total harvested power of EH users. The joint transceiver design problem can be formulated as:

$$\begin{aligned}&\max_{\{\mathbf{u}_i,\mathbf{v}_i\}}\left\{\sum_{i\in I}\mathrm{SINR}_i, \sum_{e\in E}Q_e\right\}\\ &s.t.\quad \mathbf{u}_i^{\mathrm{H}}\mathbf{H}_{ij}\mathbf{v}_j = 0, i, j\in I, j\neq i,\\ &\qquad \left\|\mathbf{u}_i\right\|^2 = 1, i\in I,\\ &\qquad \left\|\mathbf{v}_i\right\|^2 = 1, i\in I.\end{aligned} \quad (20)$$

The problem (20) is a double-objective optimization problem. When maximizing the total SINR of ID users, the power harvested by EH users will inevitably not reach the maximum. The total SINR of ID users will not be maximized when the total harvested power of EH users is maximized. Therefore, it is necessary to coordinate and trade-off between the two objective functions. The two objective functions can reach the approximate optimal as far as possible, that is, to seek its Pareto optimal solution. Next, we will scalarize the double-objective optimization scheme by using the weighted sum of SINR and harvested power, and get the following problem:

$$\begin{aligned}&\max_{\{\mathbf{u}_i,\mathbf{v}_i\}}\left\{\mu\sum_{i\in I}\mathrm{SINR}_i + (1-\mu)\sum_{e\in E}Q_e\right\}\\ &s.t.\quad \mathbf{u}_i^{\mathrm{H}}\mathbf{H}_{ij}\mathbf{v}_j = 0, i, j\in I, j\neq i,\\ &\qquad \left\|\mathbf{u}_i\right\|^2 = 1, i\in I,\\ &\qquad \left\|\mathbf{v}_i\right\|^2 = 1, i\in I,\end{aligned} \quad (21)$$

where we define a weighted value μ to satisfy $0<\mu\le 1$, μ and $1-\mu$ respectively denote the weights for the SINR of ID users and harvested power of EH users. Considering that EH users do not send information, the harvested energy mainly comes from ID users, so the value μ can not be 0. If μ is set to 1, all users are ID users. When μ becomes larger, it means the SINR of ID users will be dominant in the objective function in (21). When μ is smaller, it means that the harvested power of EH users will be dominant. Substituting SINR of RX- i and harvested power of RX- e into the problem (21), the optimization problem (21) is reformulated as follows:

$$\begin{aligned}&\max_{\{\mathbf{u}_i,\mathbf{v}_i\}}\left\{\mu\sum_{i\in I}\frac{\dfrac{KP}{K_{\mathrm{ID}}}\left|\mathbf{u}_i^{\mathrm{H}}\mathbf{H}_{ii}\mathbf{v}_i\right|^2}{\dfrac{KP}{K_{\mathrm{ID}}}\sum\limits_{\substack{j\in I\\ j\neq i}}\left|\mathbf{u}_i^{\mathrm{H}}\mathbf{H}_{ij}\mathbf{v}_j\right|^2+\sigma^2} + (1-\mu)\frac{KP}{K_{\mathrm{ID}}}\sum_{e\in E}\zeta\sum_{i\in I}\left\|\mathbf{H}_{ei}\mathbf{v}_i\right\|^2\right\}\\ &s.t.\quad \mathbf{u}_i^{\mathrm{H}}\mathbf{H}_{ij}\mathbf{v}_j = 0, i, j\in I, j\neq i,\\ &\qquad \left\|\mathbf{u}_i\right\|^2 = 1, i\in I,\\ &\qquad \left\|\mathbf{v}_i\right\|^2 = 1, i\in I.\end{aligned} \quad (22)$$

In problem (22), using the first constraint (i.e. complete IA constraint), the optimization problem (22) can be simplified as:

$$\begin{aligned}&\max_{\{\mathbf{u}_i,\mathbf{v}_i\}}\left\{\frac{\mu}{\sigma^2}\frac{KP}{K_{\mathrm{ID}}}\sum_{i\in I}\left|\mathbf{u}_i^{\mathrm{H}}\mathbf{H}_{ii}\mathbf{v}_i\right|^2 + (1-\mu)\frac{KP}{K_{\mathrm{ID}}}\sum_{e\in E}\zeta\sum_{i\in I}\left\|\mathbf{H}_{ei}\mathbf{v}_i\right\|^2\right\}\\ &s.t.\quad \mathbf{u}_i^{\mathrm{H}}\mathbf{H}_{ij}\mathbf{v}_j = 0, i, j\in I, j\neq i,\\ &\qquad \left\|\mathbf{u}_i\right\|^2 = 1, i\in I,\\ &\qquad \left\|\mathbf{v}_i\right\|^2 = 1, i\in I.\end{aligned} \quad (23)$$

Once we get the solution of (23), the interferences among the ID users can be perfectly eliminated. Considering a symmetric K -user MIMO interference system, where each user has 1 data stream, and each transmitter and receiver has N_t and N_r antennas, respectively, the symmetric system is proper [27], if and only if $N_t + N_r \ge K+1$.

IV. Alternating Optimization Solution Based on Complete IA Constraint

The optimization problem (23) is non-convex since the variables $\mathbf{u}_i$ and $\mathbf{v}_i$ are coupled together, and thus it is difficult to obtain the optimal solution. In this part, an efficient IOA-CIA algorithm to solve (23) is proposed which utilizes the alternating optimization method based on complete IA.

A. Optimization of $\mathbf{v}_i$

With variables $\mathbf{u}_i$ fixed and $\left\|\mathbf{u}_i\right\|^2 = 1$, problem (23) is degenerated to

$$\begin{aligned}&\max_{\{\mathbf{v}_i\}}\left\{\frac{\mu}{\sigma^2}\frac{KP}{K_{\mathrm{ID}}}\sum_{i\in I}\left|\mathbf{u}_i^{\mathrm{H}}\mathbf{H}_{ii}\mathbf{v}_i\right|^2 + (1-\mu)\frac{KP}{K_{\mathrm{ID}}}\sum_{e\in E}\zeta\sum_{i\in I}\left\|\mathbf{H}_{ei}\mathbf{v}_i\right\|^2\right\}\\ &s.t.\quad \mathbf{u}_i^{\mathrm{H}}\mathbf{H}_{ij}\mathbf{v}_j = 0, i, j\in I, j\neq i,\\ &\qquad \left\|\mathbf{v}_i\right\|^2 = 1, i\in I.\end{aligned} \quad (24)$$

In solving (24), we classify the solution into the following two cases.

1). The number of ID users in the system is 1

If the number of ID users equals 1, then there is no interference signal and no interference alignment is required. Problem (24) can be simplified as:

$$\max_{\mathbf{v}_i}\left\{\frac{\mu}{\sigma^2}\frac{KP}{K_{\mathrm{ID}}}\left|\mathbf{u}_i^{\mathrm{H}}\mathbf{H}_{ii}\mathbf{v}_i\right|^2+(1-\mu)\frac{\zeta KP}{K_{\mathrm{ID}}}\sum_{e\in E}\left\|\mathbf{H}_{ei}\mathbf{v}_i\right\|^2\right\}$$
$$=\max_{\mathbf{v}_i}\left\{\mathbf{v}_i^{\mathrm{H}}\left[\frac{\mu}{\sigma^2}\frac{KP}{K_{\mathrm{ID}}}\mathbf{H}_{ii}^{\mathrm{H}}\mathbf{u}_i\mathbf{u}_i^{\mathrm{H}}\mathbf{H}_{ii}+(1-\mu)\frac{\zeta KP}{K_{\mathrm{ID}}}\sum_{e\in E}\mathbf{H}_{ei}^{\mathrm{H}}\mathbf{H}_{ei}\right]\mathbf{v}_i\right\}$$
$$s.t.\quad \left\|\mathbf{v}_i\right\|^2=1. \tag{25}$$

The objective function of (25) has the form of Rayleigh entropy. Then, the optimal $\mathbf{v}_i$ is obtained in a closed form as (26) :

$$\mathbf{v}_i=\boldsymbol{\gamma}_{\max}\left(\frac{\mu}{\sigma^2}\frac{KP}{K_{\mathrm{ID}}}\mathbf{H}_{ii}^{\mathrm{H}}\mathbf{u}_i\mathbf{u}_i^{\mathrm{H}}\mathbf{H}_{ii}+(1-\mu)\frac{KP}{K_{\mathrm{ID}}}\zeta\sum_{e\in E}\mathbf{H}_{ei}^{\mathrm{H}}\mathbf{H}_{ei}\right). \tag{26}$$

2). The number of ID users is greater than 1

If there are K_{ID} ID users in the system, each ID user must satisfy $K_{\mathrm{ID}}-1$ interference alignment conditions to completely cancel out the interference. For ID user i, the first constraint in problem (24) can be rewritten as follows, $\mathbf{u}_j^{\mathrm{H}}\mathbf{H}_{ji}\mathbf{v}_i=0, i, j\in I, j\neq i$. The $K_{\mathrm{ID}}-1$ row vectors $\left\{\overline{\mathbf{v}}_i=\mathbf{u}_j^{\mathrm{H}}\mathbf{H}_{ji}\right\}, i, j\in I, j\neq i$ are constructed into a new matrix $\overline{\mathbf{V}}_i$. Denote the Singular Value Decomposition (SVD) of $\overline{\mathbf{V}}_i$ as:

$$\overline{\mathbf{V}}_i=\mathbf{G}_i\boldsymbol{\Lambda}_i\mathbf{W}_i^{\mathrm{H}}=\mathbf{G}_i\left[\boldsymbol{\Lambda}_{i1}\ \ \mathbf{0}\right]\begin{bmatrix}\mathbf{W}_{i1}^{\mathrm{H}}\\ \mathbf{W}_{i2}^{\mathrm{H}}\end{bmatrix} \tag{27}$$

where $\mathbf{G}_i$ is a left singular vector matrix. $\boldsymbol{\Lambda}_i=\left[\boldsymbol{\Lambda}_{i1}\ \mathbf{0}\right]$, $\boldsymbol{\Lambda}_{i1}$ is a diagonal matrix composed of $K_{\mathrm{ID}}-1$ nonzero singular values. $\mathbf{W}_i^{\mathrm{H}}=\begin{bmatrix}\mathbf{W}_{i1}^{\mathrm{H}}\\ \mathbf{W}_{i2}^{\mathrm{H}}\end{bmatrix}$, $\mathbf{W}_{i1}$ and $\mathbf{W}_{i2}$ denote the right singular vectors corresponding to nonzero singular values and zero singular values, respectively. Substituting them into the first constraint, and we have:

$$\overline{\mathbf{V}}_i\mathbf{v}_i=0\Rightarrow\mathbf{G}_i\left[\boldsymbol{\Lambda}_{i1}\ \ \mathbf{0}\right]\begin{bmatrix}\mathbf{W}_{i1}^{\mathrm{H}}\\ \mathbf{W}_{i2}^{\mathrm{H}}\end{bmatrix}\mathbf{v}_i=0\Rightarrow\mathbf{v}_i=\mathbf{W}_{i2}\mathbf{m}_i, \tag{28}$$

where $\mathbf{m}_i$ is a vector, satisfying $\left\|\mathbf{m}_i\right\|^2=1$. $\mathbf{v}_i$ is in the orthogonal space of $\mathrm{span}\left(\overline{\mathbf{V}}_i\right)$ which can be represented by the base vector of the orthogonal space, and the base vector is $\mathbf{W}_{i2}$.

Substituting Eq. (28) into objective function in (24) yields:

$$\max_{\{\mathbf{v}_i\}}\left\{\frac{\mu}{\sigma^2}\frac{KP}{K_{\mathrm{ID}}}\sum_{i\in I}\left|\mathbf{u}_i^{\mathrm{H}}\mathbf{H}_{ii}\mathbf{v}_i\right|^2+(1-\mu)\frac{KP}{K_{\mathrm{ID}}}\sum_{e\in E}\zeta\sum_{i\in I}\left\|\mathbf{H}_{ei}\mathbf{v}_i\right\|^2\right\}$$
$$=\max_{\{\mathbf{m}_i\}}\left\{\sum_{i\in I}\mathbf{m}_i^{\mathrm{H}}\left[\mu\Phi_i+(1-\mu)\Psi_i\right]\mathbf{m}_i\right\}. \tag{29}$$

where $\Phi_i=\frac{KP}{K_{\mathrm{ID}}\sigma^2}\mathbf{W}_{i2}^{\mathrm{H}}\mathbf{H}_{ii}^{\mathrm{H}}\mathbf{u}_i\mathbf{u}_i^{\mathrm{H}}\mathbf{H}_{ii}\mathbf{W}_{i2}$

and $\Psi_i=\zeta\frac{KP}{K_{\mathrm{ID}}}\sum_{e\in E}\mathbf{W}_{i2}^{\mathrm{H}}\mathbf{H}_{ei}^{\mathrm{H}}\mathbf{H}_{ei}\mathbf{W}_{i2}$.

The objective function (29) can be decomposed into K_{ID} sub-problems. The i -th sub-problem is:

$$\max_{\mathbf{m}_i}\left\{\mathbf{m}_i^{\mathrm{H}}\left[\mu\Phi_i+(1-\mu)\Psi_i\right]\mathbf{m}_i\right\}$$
$$s.t.\quad \left\|\mathbf{m}_i\right\|^2=1 \tag{30}$$

(30) is the Rayleigh entropy maximization form, and its maximum value is the maximum eigenvalue of $\mu\Phi_i+(1-\mu)\Psi_i$, then $\mathbf{m}_i$ is the eigenvector corresponding to the maximum eigenvalue, i.e.,

$$\mathbf{m}_i=\boldsymbol{\gamma}_{\max}\left(\mu\Phi_i+(1-\mu)\Psi_i\right), \tag{31}$$

where $\mathbf{v}_i$ can be obtained by substituting (31) in problem (28).

B. OPTIMIZATION OF $\mathbf{u}_i$

With variables $\mathbf{v}_i$ fixed and $\left\|\mathbf{v}_i\right\|^2=1$, the maximization of the objective in problem (23) means maximizing the total SINR of ID users, so problem (23) is reduced to:

$$\max_{\{\mathbf{u}_i\}}\left\{\frac{\mu}{\sigma^2}\frac{KP}{K_{\mathrm{ID}}}\sum_{i\in I}\left|\mathbf{u}_i^{\mathrm{H}}\mathbf{H}_{ii}\mathbf{v}_i\right|^2\right\}$$
$$s.t.\quad \mathbf{u}_i^{\mathrm{H}}\mathbf{H}_{ij}\mathbf{v}_j=0, i, j\in I, j\neq i,$$
$$\left\|\mathbf{u}_i\right\|^2=1, i\in I. \tag{32}$$

Similar as the solution of $\mathbf{v}_i$, we classify the solution into two cases.

1). The number of ID users in the system is 1

Once the number of ID users equals 1, there is no interference signal and no interference alignment is required. Problem (32) can be simplified to the following:

$$\max_{\mathbf{u}_i}\left\{\frac{\mu}{\sigma^2}\frac{KP}{K_{\mathrm{ID}}}\left|\mathbf{u}_i^{\mathrm{H}}\mathbf{H}_{ii}\mathbf{v}_i\right|^2\right\}$$
$$=\max_{\mathbf{u}_i}\left\{\mathbf{u}_i^{\mathrm{H}}\left[\frac{\mu}{\sigma^2}\frac{KP}{K_{\mathrm{ID}}}\mathbf{H}_{ii}\mathbf{v}_i\mathbf{v}_i^{\mathrm{H}}\mathbf{H}_{ii}^{\mathrm{H}}\right]\mathbf{u}_i\right\} \tag{33}$$
$$s.t.\quad \left\|\mathbf{u}_i\right\|^2=1.$$

The objective function of (33) has the form of Rayleigh entropy that is a Rayleigh entropy maximization problem. Then, the optimal $\mathbf{v}_i$ is obtained in a closed form as (34) :

$$\mathbf{u}_i=\boldsymbol{\gamma}_{\max}\left(\frac{\mu}{\sigma^2}\frac{KP}{K_{\mathrm{ID}}}\mathbf{H}_{ii}\mathbf{v}_i\mathbf{v}_i^{\mathrm{H}}\mathbf{H}_{ii}^{\mathrm{H}}\right). \tag{34}$$

2). The number of ID users in the system is greater than 1

For ID user i, the first constraint of problem (32) can be rewritten as $\mathbf{v}_j^{\mathrm{H}}\mathbf{H}_{ij}^{\mathrm{H}}\mathbf{u}_i=0, i, j\in I, j\neq i$. If there are K_{ID} ID users in the system, each ID user must satisfy $K_{\mathrm{ID}}-1$ interference alignment conditions for complete interference alignment. The $K_{\mathrm{ID}}-1$ row vectors $\left\{\overline{\mathbf{u}}_i=\mathbf{v}_j^{\mathrm{H}}\mathbf{H}_{ij}^{\mathrm{H}}\right\}, i, j\in I, j\neq i$ are constructed into a new matrix $\overline{\mathbf{U}}_i$. Denote the SVD of $\overline{\mathbf{U}}_i$ as:

$$\overline{\mathbf{U}}_i=\mathbf{D}_i\boldsymbol{\Sigma}_i\mathbf{F}_i^{\mathrm{H}}=\mathbf{D}_i\left[\boldsymbol{\Sigma}_{i1}\ \ \mathbf{0}\right]\begin{bmatrix}\mathbf{F}_{i1}^{\mathrm{H}}\\ \mathbf{F}_{i2}^{\mathrm{H}}\end{bmatrix}, \tag{35}$$

where $\mathbf{D}_i$ is a left singular vector matrix. $\boldsymbol{\Sigma}_i=\left[\boldsymbol{\Sigma}_{i1}\ \mathbf{0}\right]$, $\boldsymbol{\Sigma}_{i1}$ is a diagonal matrix composed of $K_{\mathrm{ID}}-1$ nonzero singular values. $\mathbf{F}_i^{\mathrm{H}} = \begin{bmatrix} \mathbf{F}_{i1}^{\mathrm{H}} \\ \mathbf{F}_{i2}^{\mathrm{H}} \end{bmatrix}$, $\mathbf{F}_{i1}$ and $\mathbf{F}_{i2}$ denote the right singular vectors corresponding to nonzero singular values and zero singular values, respectively. Substituting them into the first constraint, we have:

$$\overline{\mathbf{U}}_i\mathbf{u}_i = 0 \Rightarrow \mathbf{D}_i\left[\Sigma_{i1}\ \ \mathbf{0}\right]\begin{bmatrix} \mathbf{F}_{i1}^{\mathrm{H}} \\ \mathbf{F}_{i2}^{\mathrm{H}} \end{bmatrix}\mathbf{u}_i = 0 \Rightarrow \mathbf{u}_i = \mathbf{F}_{i2}\mathbf{g}_i. \quad (36)$$

where $\mathbf{g}_i$ is a vector, satisfying $\|\mathbf{g}_i\|^2 = 1$. $\mathbf{u}_i$ is on the orthogonal space of $\mathrm{span}\left(\overline{\mathbf{U}}_i\right)$ which can be represented by the base vector of the orthogonal space, and the base vector is $\mathbf{F}_{i2}$.

Substituting (36) into objective function in (32) yields:

$$\begin{aligned} &\max_{\{\mathbf{u}_i\}}\left\{\frac{\mu}{\sigma^2}\frac{KP}{K_{\mathrm{ID}}}\sum_{i\in I}\left|\mathbf{u}_i^{\mathrm{H}}\mathbf{H}_{ii}\mathbf{v}_i\right|^2\right\} \\ &= \max_{\{\mathbf{u}_i\}}\left\{\frac{\mu}{\sigma^2}\frac{KP}{K_{\mathrm{ID}}}\sum_{i\in I}\mathrm{Tr}\left(\mathbf{u}_i^{\mathrm{H}}\mathbf{H}_{ii}\mathbf{v}_i\mathbf{v}_i^{\mathrm{H}}\mathbf{H}_{ii}^{\mathrm{H}}\mathbf{u}_i\right)\right\} \\ &= \max_{\{\mathbf{g}_i\}}\left\{\sum_{i\in I}\mathbf{g}_i^{\mathrm{H}}\left(\frac{\mu}{\sigma^2}\frac{KP}{K_{\mathrm{ID}}}\mathbf{F}_{i2}^{\mathrm{H}}\mathbf{H}_{ii}\mathbf{v}_i\mathbf{v}_i^{\mathrm{H}}\mathbf{H}_{ii}^{\mathrm{H}}\mathbf{F}_{i2}\right)\mathbf{g}_i\right\}. \end{aligned} \quad (37)$$

Problem (37) can be decomposed into K_{ID} sub-problems where the i -th sub-problem is as follows:

$$\begin{aligned} &\max_{\mathbf{g}_i}\left\{\mathbf{g}_i^{\mathrm{H}}\left(\frac{\mu}{\sigma^2}\frac{KP}{K_{\mathrm{ID}}}\mathbf{F}_{i2}^{\mathrm{H}}\mathbf{H}_{ii}\mathbf{v}_i\mathbf{v}_i^{\mathrm{H}}\mathbf{H}_{ii}^{\mathrm{H}}\mathbf{F}_{i2}\right)\mathbf{g}_i\right\} \\ &\text{s.t. } \|\mathbf{g}_i\|^2 = 1 \end{aligned} \quad (38)$$

Eq. (38) is a Rayleigh entropy maximization form, and its maximum value is the maximum eigenvalue of $\frac{\mu}{\sigma^2}\frac{KP}{K_{\mathrm{ID}}}\mathbf{F}_{i2}^{\mathrm{H}}\mathbf{H}_{ii}\mathbf{v}_i\mathbf{v}_i^{\mathrm{H}}\mathbf{H}_{ii}^{\mathrm{H}}\mathbf{F}_{i2}$, then $\mathbf{g}_i$ is the eigenvector corresponding to maximum eigenvalue. It can be expressed as follows:

$$\mathbf{g}_i = \boldsymbol{\gamma}_{\max}\left(\frac{\mu}{\sigma^2}\frac{KP}{K_{\mathrm{ID}}}\mathbf{F}_{i2}^{\mathrm{H}}\mathbf{H}_{ii}\mathbf{v}_i\mathbf{v}_i^{\mathrm{H}}\mathbf{H}_{ii}^{\mathrm{H}}\mathbf{F}_{i2}\right), \quad (39)$$

where $\mathbf{u}_i$ can be obtained by substituting (39) in problem (36).

Note that, the harvested power becomes 0 provided that all users in the system are ID users. This is because all receivers decode information, and the second item in formula (23) is 0.

The solution to the problem (23) is summarized as the proposed complete IA algorithm in Table I.

TABLE I. PROPOSED IOA-CIA ALGORITHM

Input: channel matrix $\mathbf{H}_{ij}$, receive interference suppression vector initial value $\mathbf{u}_i(1)$, a weighted value μ Output: $\mathbf{u}_i(t)$, $\mathbf{v}_i(t)$
1) Initialize: When the time slot starts, the user properties are determined according to (12), the maximum number of iterations $T_{\max}$, and an initial value $\mathbf{u}_i(1)$, μ . 2) repeat 3) By $\mathbf{u}_i(t)$, the solution of problem (31) is used to get $\mathbf{m}_i(t+1)$. It is substituted (28) to get $\mathbf{v}_i(t+1)$. 4) By $\mathbf{v}_i(t+1)$, the solution of problem (39) is used to get $\mathbf{g}_i(t+1)$. It is substituted (36) to get $\mathbf{u}_i(t+1)$. 5) $t=t+1$. 6) Until $t = T_{\max}$. 7) Output: $\mathbf{v}_i^*(t) = \mathbf{v}_i(t)$, $\mathbf{u}_i^*(t) = \mathbf{u}_i(t)$.

V. NUMERICAL RESULTS

In this section, we provide some simulation results to validate our proposed IOA-CIA algorithm. The simulation environment is as follows. Considering a five-user IA interference channel, the number of data streams by each user is set to 1, the number of antennas at each user is the same $N_t = N_r = N$, and the number of antennas is greater than or equal to the number of users. The above parameters satisfy the feasibility condition of symmetric network interference alignment [27]. The channel adopts Rayleigh block fading channel, each element in the channel coefficient matrix follows $\mathcal{CN}(0, 0.2/N)$ and the perfect CSI is assumed to be known. The energy conversion efficiency ζ is set to 0.5 and the time slot number is set to be 10000 using the linear EH model. In this section, we compare the performance of our proposed IOA-CIA algorithm with that of PRRS algorithm in [21-22]. The total transmit power of the PRRS algorithm is assumed to be KP, and the average power of each user is assigned. In the proposed IOA-CIA algorithm, the total transmit power of the ID users of is set to KP, and each ID user allocates power equally.

1). Pareto curve of the proposed IOA-CIA algorithm under different μ values

Under different μ values, the Pareto curve of the proposed IOA-CIA algorithm is shown in Fig. 2. The star label in Fig. 2 represents the average sum achievable rate of ID users and the average sum power harvested by EH users of PRRS algorithm.

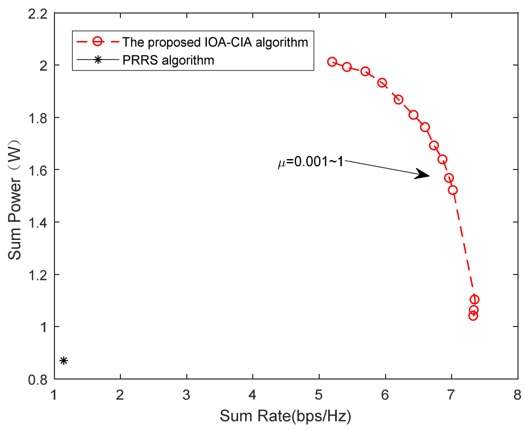

Figure 2. Sum harvested power versus sum rate with different μ with $\sigma^2 = 0.1$, $P = 1$, and $N = 6$.

From this figure, we can see that the sum reachable rate of ID users and the sum power harvested by EH users vary with μ in the proposed IOA-CIA algorithm. The sum reachable rate of ID users increases with the increase of μ , while the sum of the power harvested by EH users decreases with the increase of μ . According to the objective function in (23), the increase μ shows that the rate demand of ID users is higher or the demand to harvest energy of EH users is lower; while the decrease of μ means the requirement to harvest energy of EH users is high or the rate requirement of ID users is low which is consistent with the theory. When μ varies from 0.001 to 1, the sum rate of ID users and the sum power harvested by EH users of the proposed IOA-CIA algorithm are greater than PRRS algorithm. For convenient of analysis, μ is set to 0.04.

2). Comparison of the proposed IOA-CIA algorithm and the PRRS algorithm with different SNR

Under different number of users K, the sum rate of ID users and the sum power harvested by EH users of the proposed IOA-CIA algorithm and PRRS algorithm with different SNR are shown in Fig. 3 and Fig. 4, respectively.

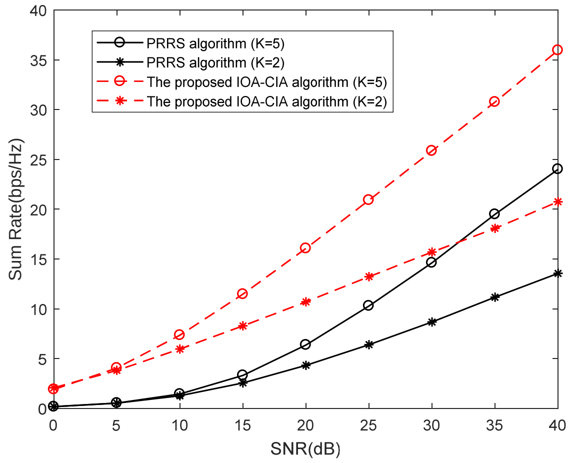

Figure 3. Sum rate versus SNR under different number of users K.

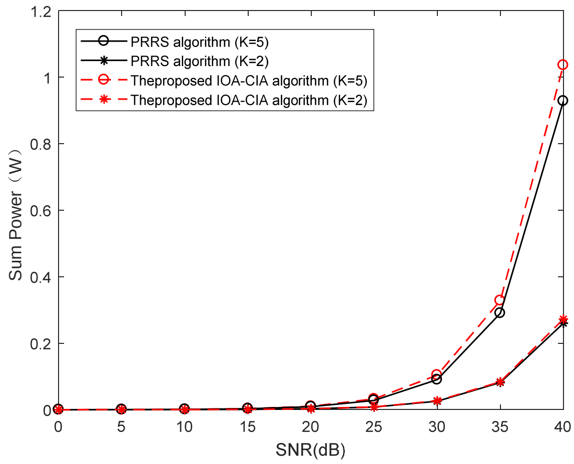

Figure 4. Sum harvested power versus SNR under different number of users K.

The number of transmit and receive antennas of the two algorithms is set to 6, and the noise power in the two algorithms is $\sigma^2 = 10^{-4}$. From Fig. 3, we can see that the sum rate of PRRS algorithm and the proposed IOA-CIA algorithm increase with the increase of SNR under different number of users, yet the sum rate of the proposed IOA-CIA algorithm is obviously superior to the PRRS algorithm under the same SNR and number of users. From Figure 4, we can see that the more users means the more harvested power for the same algorithm. Since the curves of the two comparison algorithms are close to each other, we provide Table II to show the performance improvement of the proposed algorithm comparing with the PRRS algorithm.

From the above two figures and Table II, it can be seen that the performance of proposed IOA-CIA algorithm is superior to PRRS algorithm.

TABLE II. THE PERFORMANCE IMPROVEMENT OF THE PROPOSED ALGORITHM COMPARING WITH THE PRRS ALGORITHM

SNR (dB)	Sum rate		Sum power	
	K=2	K=5	K=2	K=5
0	10.4dB	10.2dB	0.49dB	0.71dB
10	6.7dB	7.1dB	0.63dB	0.72dB
20	4dB	4dB	0.31dB	0.69dB
30	2.6dB	2.5dB	0.25dB	0.61dB
40	1.8dB	1.8dB	0.2dB	0.48dB

3). Comparison of the proposed IOA-CIA algorithm and the PRRS algorithm with different number of ID users

In the proposed IOA-CIA algorithm and PRRS algorithm, the sum rate of ID users and sum power harvested by the EH users with different number of ID users under different SNR are shown in Fig. 5 and Fig. 6.

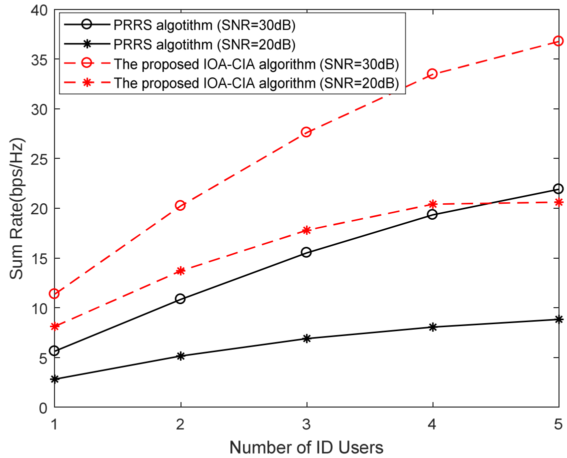

Figure 5. Sum rate versus number of ID users under different SNR.

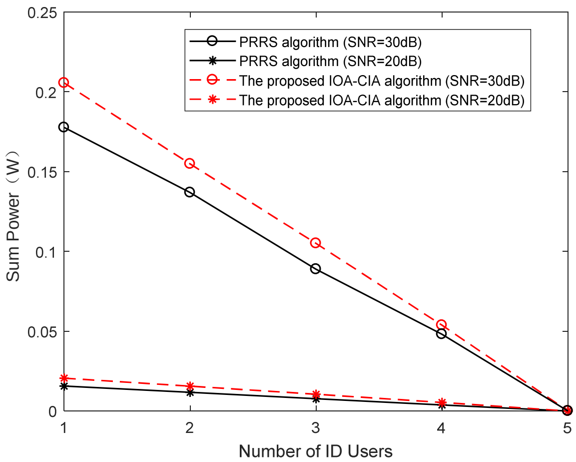

Figure 6. Sum harvested power versus number of ID users under different SNR.

The number of transmit and receive antennas of the two algorithms is set to 6, the SNR is set to 20 dB and 30 dB, and the noise power in the two algorithms is $\sigma^2 = 10^{-4}$. From Fig. 5, it can be seen that the sum rate of PRRS algorithm and the proposed IOA-CIA algorithm increase gradually with number of ID users, while the sum rate of the proposed IOA-CIA algorithm is obviously higher than that of PRRS algorithm under the same number of ID users. We find that the larger SNR brings the greater sum achievable rate of the two algorithms. From Fig. 6, it can be seen that with the increase number of ID users in the system, the sum power harvested by EH users in PRRS algorithm and proposed IOA-CIA algorithm decrease gradually. We find that larger SNR brings larger sum power harvested by EH users in the two algorithms.When the SNR is small, the performance of the two algorithms is similar. The proposed algorithm harvests more power at high SNR. Moreover, we can see that the proposed IOA-CIA algorithm with an increase of the number of ID users, the rate of the proposed algorithm increases, and the sum power decreases which is consistent with the analysis above. From these results it can be seen that the performance of proposed IOA-CIA algorithm is superior to PRRS algorithm.

VI. Conclusion

In our paper, a new scheme combining energy harvesting and interference alignment is investigated. Different from the existing algorithms where interference alignment was performed before energy harvesting and information transmission, the proposed scheme performs user selection first and studies the user selection criteria to determine which users should be ID users and which users should be EH users. The optimization objective of the new model is to maximize the sum power harvested by EH users and the sum SINR of ID users under complete IA constraint. For this double-objective optimization problem, a weighted sum objective method is used. We adopt a new IOA-CIA algorithm to solve the non-convex problem. Simulation results show that the proposed IOA-CIA algorithm is superior to the existing PRRS algorithm in terms of harvested power and reachable rate when the weighting coefficient is set reasonably.

References

[1] D. Tse and P. Viswanath, Fundamentals of Wireless Communication. Cambridge, U.K.: Cambridge Univ. Press, 2005.

[2] V. R. Cadambe and S. A. Jafar, “Interference alignment and degrees of freedom of the K-user interference channel,” IEEE Trans. Inf. Theory, vol. 54, no. 8, pp. 3425–3441, Aug. 2008. doi:10.1109/TIT.2008.926344

[3] N. Zhao, S. Zhang, F. Richard Yu, Y. F. Chen, A. Nallanathan, V.C. M. Leung, “Exploiting interference for energy harvesting: a survey, research issues and challenges,” IEEE Access, vol. 5, pp. 10403–10421, May. 2017. doi:10.1109/ACCESS.2017.2705638

[4] X. Q. Miao, S. S. Yang, C. H. Wang, S. Wang, L. Hanzo,“On the energy efficiency of interference alignment in the K -user interference channel,” IEEE Access, vol. 7, pp. 97253 - 97263, Jul. 2019. doi:10.1109/ACCESS.2019.2929085

[5] Y. Wei, T. M. Lok, “An iterative interference alignment algorithm for the general MIMO X channel,” IEEE Trans. Wireless Commun, vol. 18, no. 3, pp. 1847 - 1859, Mar. 2019. doi:10.1109/TWC.2019.2897676

[6] L. Suo, J. D. Li, H. Y. Li, S. Zhang, T. N. Davidson, “Achievable sum rate and degrees of freedom of opportunistic interference alignment in MIMO interfering broadcast channels,” IEEE Trans. Commun, vol. 67, no. 6, pp. 4062 - 4073, Jun. 2019. doi:10.1109/TCOMM.2019.2903250

[7] M. Rong, “Achievement of interference alignment in general underlay cognitive radio networks: scenario classification and adaptive spectrum sharing,” China Communications, vol. 15, no. 6, pp. 98–108, Jun. 2018. doi:10.1109/CC.2018.8398507

[8] J. Ma, S. Zhang, H. Li, N. Zhao, V. C. M. Leung, “Interference-alignment and soft-space-reuse based cooperative transmission for multi-cell massive MIMO networks,” IEEE Trans. Wireless Commun, vol. 17, no. 3, pp. 1907-1922, Mar. 2018. doi: 10.1109/TWC.2017.2786722

[9] X. Y. Li, C. He, H. S. Shen, J. D. Li, J. Wang, “Feasibility-aware partial interference alignment for hybrid D2D and cellular communication networks,” IEEE Access, vol. 6, pp. 71069 - 71083, Nov. 2018. doi:10.1109/ACCESS.2018.2880478

[10] K. Gomadam, V. R. Cadambe, S.A. Jafar, “A distributed numerical approach to interference alignment and applications to wireless networks,” IEEE Trans. Inf. Theory, vol. 57, no. 6, pp. 3309–3322, Jun. 2011. doi:10.1109/TIT.2011.2142270

[11] D. A. Schmidt, C. X. Shi, R. A. Berry, M. L. Honig, W. Utschick, “Minimum mean squared error interference alignment,” in IEEE 43th Asilomar Conference on Signals, Systems and Computers, 2009, pp. 1106-1110. doi:10.1109/ACSSC.2009.5470055

[12] 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. doi:10.1109/TWC.2013.031813.120224

[13] X. Lu, P. Wang, D. Niyato, D. I. Kim, and Z. Han, “Wireless networks with RF energy harvesting: a contemporary survey,” IEEE Commun. Surv. Tutor, vol. 17, no. 2, pp. 757–789, Nov. 2015. doi:10.1109/COMST.2014.2368999

[14] P. Grover, A. Sahai, “Shannon meets Tesla: wireless information and power transfer,” in 2010 IEEE International Symposium on Information Theory, 2010, pp. 2363–2367. doi:10.1109/ISIT.2010.5513714

[15] S. Z. Bi, C. K. Ho, R. Zhang, “Wireless powered communication: opportunities and challenges,” IEEE Commun. Mag, vol.53, no. 4, pp. 117–125, Apr. 2015. doi:10.1109/MCOM.2015.7081084

[16] D. X. Wang, R. Q. Zhang, X. Cheng, L. Q. Yang, “Capacity-Enhancing full-duplex relay networks based on Power-Splitting(PS-) SWIPT,” IEEE Transactions on Vehicular Technology, vol. 66, no. 6, pp. 5445–5450, Jun. 2017. doi:10.1109/TVT.2016.2616147

[17] H. Lee, K. J. Lee, H. Kim, I. Lee, “Joint transceiver optimization for MISO SWIPT systems with time switching,” IEEE Trans. Wireless Commun, vol. 17, no. 5, pp. 3298–3312, May. 2018. doi:10.1109/TWC.2018.2809734

[18] Y. Q. Xu, C. Shen, Z. G. Ding, X. F. Sun, S. Yan, G. Zhu, et al., “Joint beamforming and power-splitting control in downlink cooperative SWIPT NOMA systems,” IEEE Trans. Sig. Process, vol. 65, no. 18, pp. 4874–4886, Sep. 2017. doi:10.1109/TSP.2017.2715008

[19] M. Abedi, H. Masoumi, M. J. Emadi, “Power splitting-based SWIPT systems with decoding cost,” IEEE Wireless Communications Letters, vol. 8, no. 2, pp. 432-435, Apr. 2019. doi:10.1109/LWC.2018.2874886

[20] Z. Y. Zong, H. Feng, F. R. Yu, N. Zhao, T. Yang, B. Hu, “Optimal transceiver design for SWIPT in K-user MIMO interference channels,” IEEE Trans. Wireless Commun, vol. 15, no. 1, pp. 430–445, Jan. 2016. doi:10.1109/TWC.2015.2474857

[21] N. Zhao, F. R. Yu, V. C. M. Leung, “Simultaneous wireless information and power transfer in interference alignment networks,” in 2014 International Wireless Communications and Mobile Computing Conference (IWCMC), 2014, pp. 7–11. doi:10.1109/IWCMC.2014.6906324

[22] N. Zhao, F. R. Yu, V. C. M. Leung, “Wireless energy harvesting in interference alignment networks,” IEEE Communications Magazine, vol. 53, no. 6, pp. 72–78, Jun. 2015. doi:10.1109/MCOM.2015.7120020

[23] J. Guo, N. Zhao, F. R. Yu, X. Liu, V. C. M. Leung, “Exploiting adversarial jamming signals for energy harvesting in interference networks,” IEEE Transactions on Wireless Communications, vol. 16, no. 2, pp. 1267–1280, Feb. 2017. doi:10.1109/TWC.2016.2643658

[24] M. Chu, B. He, X. W. Liao, Z. Z. Gao, V. C. M. Leung, “On the design of power splitting relays with interference alignment,” IEEE Trans. on Commun, vol. 66, no. 4, pp. 1411–1424, Apr. 2018. doi:10.1109/TCOMM.2017.2785319

[25] N. Zhao, Y. Cao, F. R. Yu, Y. F. Chen, M. L. Jin, V. C. M. Leung, “Artificial noise assisted secure interference networks with wireless power transfer,” IEEE Transactions on Vehicular Technology, vol. 67, no. 2, pp. 1087–1098, Feb. 2018. doi: 10.1109/TVT.2017.2700475

[26] S. Arzykulov, G. Nauryzbayev, T.A. Tsiftsiso, M. Abdallah, “On the performance of wireless powered cognitive relay network with interference alignment,” IEEE Trans. Commun, vol. 66, no. 9, pp. 3825- 3836, Sept. 2018. doi: 10.1109/TCOMM.2018.2833104

[27] C. M. Yetis, T. G. Gou, S. A. Jafar, A. H. Kayran, “On feasibility of interference alignment in MIMO interference networks,” IEEE Trans. Sig. Process, vol. 58, no. 9, pp. 4771–4782, Sep. 2010. doi:10.1109/TSP.2010.2050480