Joint Transceiver Design for Full-Duplex K-Pair MIMO Interference Channel with Energy Harvesting

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***Abstract*—In this paper, we propose a joint transceiver design algorithm for the full-duplex (FD) K-pair multiple-input multiple-output (MIMO) interference channel with simultaneous wireless information and power transfer (SWIPT). The aim is to minimize the total transmission power under both transmission rate and energy harvesting (EH) constraints. An iterative algorithm based on alternating optimization and with guaranteed monotonic convergence is proposed to successively optimize the transceiver coefficients. The algorithm consists of three main steps, aimed at successively optimizing: 1) the power splitting (PS) vectors of the EH nodes; 2) the receive beamforming vectors; 3) the transmit beamforming vectors. The first step is carried out based on concave-convex procedure (CCCP), the second step is based on the minimum mean square error (MMSE) criterion and the third step resorts to using semidefinite relaxation (SDR). Simulation results are presented to validate the effectiveness of the proposed algorithm.** [1]

***Index Terms*—Transceiver design, full-duplex, energy harvesting, MIMO interference channel.**

I. Introduction

The time switching (TS) and power splitting (PS) schemes are two techniques currently under consideration for SWIPT [1]. In the former, the receiver switches between information decoding (ID) and energy harvesting (EH). In the latter, the received signal is split into two streams, such that a fraction ρ ($0 \leq \rho \leq 1$) of the received signal power is used for ID while the remaining fraction $(1 - \rho)$ is used for EH. PS-based transceiver design algorithms have received significant attention recently [2]–[5], The authors of [2] studied the joint beamforming and power splitting (JBPS) design for a multiuser multiple-input single-output (MISO) broadcast system with SWIPT. The JBPS problem for a K-pair MISO interference channel was considered in [3], where the authors used the SDR technique to address the non-convex problem and proved that the SDR is tight in the case of $K = 2$ or 3. Different from the approach of [3], an alternative second-order-cone-programming (SOCP) relaxation method was proposed in [4]. In order to harvest more power for reliable device operation, the authors of [5] considered multiple antennas at the receiver and proposed a transceiver design algorithm for SWIPT over K-pair MIMO interference channels. However, the studies in [5] only consider a common, identical PS ratio among all the receive antennas for each user, which is not an optimum PS scheme [6]. A vector consisting of different PS ratios from multiple receive antennas, which is referred to as PS vector, needs to be taken into account in the optimization problem rather than a single PS ratio. This problem has not yet been addressed in the literature.

In traditional half-duplex (HD) systems, devices can either transmit or receive on a single frequency band, but not simultaneously. With FD communication system, a device transmits and receives simultaneously on the same channel, which can potentially double its link capacity and increase its spectral efficiency [7]–[10]. Recently, transceiver design algorithms have been developed to deal with interference and improve quality of service (QoS) in different FD communication systems [11]–[14]. To the best of our knowledge, the transceiver design problem with SWIPT has not been investigated in FD systems.

This work studies the joint transceiver design problem for the transmit beamforming, the receive beamforming, and the PS vectors at the EH nodes in a FD K-pair MIMO interference channel with SWIPT. The aim is to minimize the total transmission power under both transmission rate and EH constraints. An iterative algorithm based on alternating optimization is proposed to successively optimize the transceiver coefficients. The algorithm consists of three main steps, aimed at successively optimizing: 1) the PS vectors of the EH nodes; 2) the receive beamforming vectors; 3) the transmit beamforming vectors. The first step is carried out based on CCCP, the second step is based on the MMSE criterion and the third step resorts to using SDR. Since the feasible set for the transmit beamformers is enlarged when optimizing the receive beamforming vectors and PS vectors, the transmission power is guaranteed to be decreasing when optimizing transmit beamformers, implying a monotonic convergence of the proposed algorithm. Simulation results are presented to validate the effectiveness of the proposed algorithm.

II. System Model and Problem Formulation

A. System Model

We consider a FD MIMO interference channel with K pairs, as illustrated in Fig. 1. We assume that the FD nodes

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of the ith pair, where $i \in \mathcal{K} \triangleq \{1,\ldots,K\}$, are equipped with T_i and N_i transmit and receive antennas, respectively. Each pair exchanges information simultaneously in a two way communication. Besides, we assume that the 1st node of each pair only contains an ID receiver, while the 2nd node of each pair has both ID and EH receivers.[2]

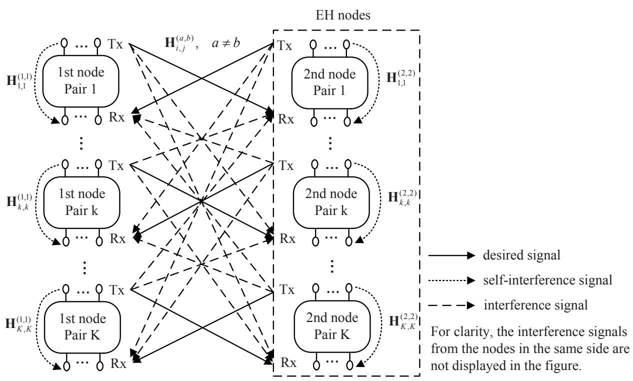

Fig. 1. Full-duplex K-pair MIMO interference channel.

The received data vector at node $a \in \{1,2\}$ of the ith pair is given by

$$\begin{aligned}\mathbf{y}_{a,i} &= \mathbf{H}_{i,i}^{(a,b)} \sum_{s=1}^{M} \mathbf{f}_{s,b,i} x_{s,b,i} + \mathbf{H}_{i,i}^{(a,a)} \sum_{s=1}^{M} \mathbf{f}_{s,a,i} x_{s,a,i} \\ &+ \sum_{j\neq i}^{K} \sum_{c=1}^{2} \mathbf{H}_{i,j}^{(a,c)} \sum_{s=1}^{M} \mathbf{f}_{s,c,j} x_{s,c,j} + \mathbf{n}_{a,i},\ a \neq b,\end{aligned} \tag{1}$$

where $x_{s,a,i}$ denotes the sth transmit symbol (data stream) of the ath node in pair i with zero mean and $E[|x_{s,a,i}|^2] = 1$, where $s \in \mathcal{M} \triangleq \{1,\ldots,M\}$ and $i \in \mathcal{K}$, and $\mathbf{f}_{s,a,i}$ denotes the $T_i \times 1$ transmit beamforming vector for the sth symbol of the ath node in the ith pair. The $N_i \times T_i$ matrix $\mathbf{H}_{i,i}^{(a,b)}$ denotes the desired channel between node a and b of the ith pair, where $a, b \in \{1,2\}$ and $a \neq b$. The $N_i \times T_i$ matrix $\mathbf{H}_{i,i}^{(a,a)}$ denotes the self-interference channel of node a. The $N_i \times T_j$ matrix $\mathbf{H}_{i,j}^{(a,b)}$ denotes the interference channel from the transmit antennas of node b in pair j to the receive antennas of node a in pair i, where $a, b \in \{1,2\}$, and $i, j \in \mathcal{K}$, $i \neq j$. $\mathbf{n}_{a,i} \in \mathcal{C}^{N_i \times 1}$ denotes the additive white Gaussian noise vector at the ath node of pair i with zero mean and $E[\mathbf{n}_{a,i}\mathbf{n}_{a,i}^H] = \sigma_{a,i}^2 \mathbf{I}$, where $\sigma_{a,i}^2$ is the average noise power. We assume $a \neq b$ hereinafter if a and b appear in the same expression.

Let $\rho_{n,i}$ $(0 \le \rho_{n,i} \le 1)$ denote the PS ratio for the nth receive antenna of node 2 in the ith pair, where $n \in \mathcal{N}_i \triangleq \{1,\ldots,N_i\}$, which means that a portion $\rho_{n,i}$ of the nth receive antenna's signal power is used for signal detection and the remaining portion $1-\rho_{n,i}$ of the power is diverted to an energy harvester. By defining $\mathbf{\Lambda}_i = \text{diag}\{[\sqrt{\rho_{1,i}},\ldots,\sqrt{\rho_{N_i,i}}]\}$, where the operator diag$\{.\}$ transforms a vector to a diagonal matrix, the signal for ID at node 2 of the ith pair can be expressed as

$$\begin{aligned}\bar{\mathbf{y}}_i &= \mathbf{\Lambda}_i(\mathbf{H}_{i,i}^{(2,1)} \sum_{s=1}^{M} \mathbf{f}_{s,1,i} x_{s,1,i} + \mathbf{H}_{i,i}^{(2,2)} \sum_{s=1}^{M} \mathbf{f}_{s,2,i} x_{s,2,i} \\ &+ \sum_{j\neq i}^{K} \sum_{c=1}^{2} \mathbf{H}_{i,j}^{(2,c)} \sum_{s=1}^{M} \mathbf{f}_{s,c,j} x_{s,c,j} + \mathbf{n}_{2,i}) + \mathbf{v}_i,\end{aligned} \tag{2}$$

where $\mathbf{v}_i$ is the $N_i \times 1$ additional complex Gaussian circuit noise vector with zero mean and covariance matrix $\omega_i^2 \mathbf{I}$, resulting from the phase offsets and non-linearities during baseband conversion.

The transmission rate of the sth symbol for node a in the ith pair is given by $\log_2\left(1+\Gamma_{s,a,i}\right)$, where $\Gamma_{s,a,i}$ denotes the corresponding signal-to-interference-plus-noise ratio (SINR), which can be expressed as

$$\Gamma_{s,a,i} = \frac{|\mathbf{w}_{s,a,i}^H \bar{\mathbf{H}}_{i,i}^{(a,b)} \mathbf{f}_{s,b,i}|^2}{\mathbf{w}_{s,a,i}^H \mathbf{R}_{a,i} \mathbf{w}_{s,a,i}}, \tag{3}$$

where $\mathbf{w}_{s,a,i} \in \mathcal{C}^{N_i \times 1}$ denotes the receive beamforming vector for the sth symbol of node a in the ith pair and

$$\begin{aligned}\mathbf{R}_{s,a,i} &= \sum_{s'\neq s}^{M} \bar{\mathbf{H}}_{i,i}^{(a,b)} \mathbf{f}_{s',b,i} \mathbf{f}_{s',b,i}^H \bar{\mathbf{H}}_{i,i}^{(a,b)H} \\ &+ \sum_{s'=1}^{M} \bar{\mathbf{H}}_{i,i}^{(a,a)} \mathbf{f}_{s',a,i} \mathbf{f}_{s',a,i}^H \bar{\mathbf{H}}_{i,i}^{(a,a)H} \\ &+ \sum_{j\neq i}^{K} \sum_{c=1}^{2} \sum_{s'=1}^{M} \bar{\mathbf{H}}_{i,j}^{(a,c)} \mathbf{f}_{s',c,j} \mathbf{f}_{s',c,j}^H \bar{\mathbf{H}}_{i,j}^{(a,c)H} + \mathbf{U}_{a,i}.\end{aligned} \tag{4}$$

In particular, for the 1st node we have $\bar{\mathbf{H}}_{i,i}^{(1,2)} = \mathbf{H}_{i,i}^{(1,2)}$, $\bar{\mathbf{H}}_{i,i}^{(1,1)} = \mathbf{H}_{i,i}^{(1,1)}$, $\bar{\mathbf{H}}_{i,j}^{(1,c)} = \mathbf{H}_{i,j}^{(1,c)}$ and $\mathbf{U}_{1,i} = \sigma_{1,i}^2 \mathbf{I}$, where $c \in \{1,2\}$. For the 2nd node, we have $\bar{\mathbf{H}}_{i,i}^{(2,1)} = \mathbf{\Lambda}_i \mathbf{H}_{i,i}^{(2,1)}$, $\bar{\mathbf{H}}_{i,i}^{(2,2)} = \mathbf{\Lambda}_i \mathbf{H}_{i,i}^{(2,2)}$, $\bar{\mathbf{H}}_{i,j}^{(2,c)} = \mathbf{\Lambda}_i \mathbf{H}_{i,j}^{(2,c)}$ and $\mathbf{U}_{2,i} = \sigma_{2,i}^2 \mathbf{\Lambda}_i \mathbf{\Lambda}_i^H + \omega_i^2 \mathbf{I}$.

Besides, the total harvested energy that can be stored by node 2 of the ith pair is given by

$$\begin{aligned}P_i &= \xi_i E[\|\mathbf{\Phi}_i \mathbf{y}_{2,i}\|^2] \\ &= \xi_i(\sum_{s'=1}^{M} \|\mathbf{\Phi}_i \mathbf{H}_{i,i}^{(2,1)} \mathbf{f}_{s',1,i}\|^2 + \sum_{s'=1}^{M} \|\mathbf{\Phi}_i \mathbf{H}_{i,i}^{(2,2)} \mathbf{f}_{s',2,i}\|^2 \\ &+ \sum_{j\neq i}^{K} \sum_{c=1}^{2} \sum_{s'=1}^{M} \|\mathbf{\Phi}_i \mathbf{H}_{i,j}^{(2,c)} \mathbf{f}_{s',c,j}\|^2 + \sigma_{2,i}^2 \|\text{vec}\{\mathbf{\Phi}_i\}\|^2),\end{aligned} \tag{5}$$

where $\mathbf{\Phi}_i = \text{diag}\{\left[\sqrt{1-\rho_{1,i}},\ldots,\sqrt{1-\rho_{N_i,i}}\right]\}$ and $\xi_i \in (0,1]$ denotes the energy conversion efficiency of the EH unit in pair i.

B. Problem Formulation

We formulate the optimization problem for the joint design of $\{\mathbf{w}_{s,a,i}\}$, $\{\mathbf{f}_{s,a,i}\}$ and $\{\mathbf{d}_i\}$ so as to minimize the total power consumption at the 1st and 2nd nodes among the pairs under the constraint that a set of minimum transmission rate and EH targets[3] be satisfied, where $\mathbf{d}_i = [\sqrt{\rho_{1,i}},\ldots,\sqrt{\rho_{N_i,i}}]^T$. The optimization problem can be expressed as follows

$$\begin{aligned}&\min_{\{\mathbf{w}_{s,a,i}\},\{\mathbf{f}_{s,a,i}\},\{\mathbf{d}_i\}} \sum_{i=1}^{K} \sum_{a=1}^{2} \sum_{s=1}^{M} \mathbf{f}_{s,a,i}^H \mathbf{f}_{s,a,i} \\ &\text{s.t. } R_{s,a,i} \ge \varphi_{s,a,i},\ P_i \ge \psi_i, \\ &0 \le \rho_{n,i} \le 1,\ n \in \mathcal{N}_i,\ i \in \mathcal{K},\ s \in \mathcal{M},\ a \in \{1,2\}.\end{aligned} \tag{6}$$

[2]This is a reasonable assumption since if both nodes need to harvest energy, then we can simply reduce their transmission power such that more power can be saved.

[3]In this work, we assume that each data stream supports a different type of service. Therefore, we consider the rate constraint of each data stream.

TABLE I
THE CCCP BASED ITERATIVE ALGORITHM TO SOLVE (10)

1. Define the tolerance of accuracy δ_1 and the maximum number of iteration N^1_{max}. Initialize the algorithm with a feasible point $\mathbf{s}(0)$. Set the iteration number $k = 0$.
2. **Repeat**
   - Compute the affine approximation $\hat{v}_{s,i}(\mathbf{s}^{(k)}, \mathbf{s})$.
   - Solve problem (20), and assign the solution to $\mathbf{s}^{(k+1)}$.
   - Update the iteration number : $k = k + 1$.
3. **Until** $|f(\mathbf{s}^{(k+1)}) - f(\mathbf{s}^{(k)})| \leq \delta$ or the maximum number of iterations is reached, i.e., $k > N_{\max}$.

III. Proposed Alternating Optimization Design Algorithm

We propose an alternating optimization approach for the joint transceiver design. Firstly, by fixing all the transmit beamforming vectors $\{\mathbf{f}_{s,a,i}\}$ and the PS vectors $\{\mathbf{d}_i\}$, we can obtain the receive beamforming vectors using the MMSE criterion as

$$\mathbf{w}_{s,a,i} = \mathbf{R}^{-1}_{s,a,i}\bar{\mathbf{H}}^{(a,b)}_{i,i}\mathbf{f}_{s,b,i}, \tag{7}$$

where $a \in \{1, 2\}$.

Then, let us consider the optimization of $\{\mathbf{f}_{s,a,i}\}$ by fixing $\{\mathbf{d}_i\}$ and $\{\mathbf{w}_{s,a,i}\}$. We resort to the celebrated SDR technique to solve this problem. By introducing a new variable $\mathbf{F}_{s,a,i} = \mathbf{f}_{s,a,i}\mathbf{f}^H_{s,a,i}$ and ignoring the rank-one constraints for all $\mathbf{F}_{s,a,i}$, problem (6) can be reformulated as shown in (8), where $\gamma_{s,a,i} = 2^{\varphi_{s,a,i}} - 1$, $\theta_{1,i} = \sigma^2_{1,i}\mathbf{w}^H_{s,1,i}\mathbf{w}_{s,1,i}$ and $\theta_{2,i} = \sigma^2_{2,i}\mathbf{w}^H_{s,2,i}\mathbf{\Lambda}_i\mathbf{\Lambda}^H_i\mathbf{w}_{s,2,i} + \omega^2_i\mathbf{w}^H_{s,2,i}\mathbf{w}_{s,2,i}$. Therefore, (8) is a convex semidefinite programming (SDP) problem, which can be efficiently solved by off-the-shelf algorithms [15]. It is worth mentioning that, the optimal solution $\{\mathbf{F}^*_{s,a,i}\}$ to problem (8) cannot be proven to be of rank-one in general, however, we have the following lemma to address the rank property of problem (8) when $K = 2$.

Lemma 1. *When $K = 2$, there always exist an optimal rank-one solution to problem (8), which are also optimal to the problem before SDR regardless of the stream number M.*

The proof is relegated to Appendix A. To guarantee a rank one solution when $K \geq 3$, we may use a simple rank-one recovery method based on Gaussian randomization procedure. Interested readers may refer to [16] for details.

Thirdly, let us optimize the PS vectors $\{\mathbf{d}_i\}$ by fixing $\{\mathbf{f}_{s,a,i}\}$ and $\{\mathbf{w}_{s,a,i}\}$. Since the objective function of (6) does not include $\{\mathbf{d}_i\}$, we consider the following equivalent optimization problem:

$$\begin{aligned}&\max_{t,\,\{\mathbf{d}_i\}} \; t\\ &\text{s.t. } \frac{\Gamma_{s,2,i}}{\gamma_{s,2,i}} \geq t, \; \frac{P_i}{\psi_i} \geq t,\\ &0 \leq \rho_{n,i} \leq 1, \; n \in \mathcal{N}_i, i \in \mathcal{K}, s \in \mathcal{M}.\end{aligned} \tag{9}$$

It is readily seen that, once problem (9) is solved, the feasible set for $\{\mathbf{f}_{s,a,i}\}$ becomes larger, implying a decreased transmission power.

Let us define a $(\sum_{i=1}^{K} N_i + 1) \times 1$ vector of parameters $\mathbf{s} = [t, \mathbf{d}^T_1, \ldots, \mathbf{d}^T_K]^T$, then problem (9) can be equivalently rewritten as (10) (at the top of the next page), where the objective function $f(\mathbf{s}) = t$,

$$\begin{aligned}u_{s,i}(\mathbf{s}) = &\sum_{s' \neq s}^{M} |\mathbf{w}^H_{s,2,i}\text{diag}\{\mathbf{H}^{(2,1)}_{i,i}\mathbf{f}_{s',1,i}\}\mathbf{d}_i|^2\\ &+ \sum_{s'=1}^{M} |\mathbf{w}^H_{s,2,i}\text{diag}\{\mathbf{H}^{(2,2)}_{i,i}\mathbf{f}_{s',2,i}\}\mathbf{d}_i|^2\\ &+ \sum_{j \neq i}^{K}\sum_{c=1}^{2}\sum_{s'=1}^{M} |\mathbf{w}^H_{s,2,i}\text{diag}\{\mathbf{H}^{(2,c)}_{i,j}\mathbf{f}_{s',c,j}\}\mathbf{d}_i|^2 + \theta_{2,i}\end{aligned} \tag{11}$$

and $v_{s,i}(\mathbf{s}) = \frac{|\mathbf{w}^H_{s,2,i}\text{diag}\{\mathbf{H}^{(2,1)}_{i,i}\mathbf{f}_{s,1,i}\}\mathbf{d}_i|^2}{t\gamma_{s,2,i}}$. Note that the first constraint is a difference of convex (DC) program, according to the CCCP concept we approximate the convex function $v_{s,i}(\mathbf{s})$ in the kth iteration by its first order Taylor expansion around the current point $\mathbf{s}^{(k)}$, denoted as $\hat{v}_{s,i}(\mathbf{s}^{(k)}, \mathbf{s})$. Based on [17] and [18], $\hat{v}_{s,i}(\mathbf{s}^{(k)}, \mathbf{s})$ is given by

$$\hat{v}_{s,i}(\mathbf{s}^{(k)}, \mathbf{s}) = v_{s,i}(\mathbf{s}^{(k)}) + 2\Re\{\triangledown v^H_{s,i}(\mathbf{s}^{(k)})(\mathbf{s} - \mathbf{s}^{(k)})\}, \tag{12}$$

where $\triangledown v_{s,i}(\mathbf{s}^{(k)})$ denotes the conjugate derivative of $v_{s,i}(\mathbf{s}^{(k)})$. Due to limited space, we omit the detailed results of this calculation for $\hat{v}_{s,i}(\mathbf{s}^{(k)}, \mathbf{s})$. Note that $\hat{v}_{s,i}(\mathbf{s}^{(k)}, \mathbf{s})$ is an affine function of $\mathbf{s}$. By introducing the following variables:

$$\begin{aligned}\mathbf{x}^{(a,b)}_{s,i,i} = \Big[&\mathbf{w}^H_{s,a,i}\text{diag}\{\mathbf{H}^{(a,b)}_{i,i}\mathbf{f}_{1,b,i}\}\mathbf{d}_i, \ldots,\\ &\mathbf{w}^H_{s,a,i}\text{diag}\{\mathbf{H}^{(a,b)}_{i,i}\mathbf{f}_{s-1,b,i}\}\mathbf{d}_i,\\ &\mathbf{w}^H_{s,a,i}\text{diag}\{\mathbf{H}^{(a,b)}_{i,i}\mathbf{f}_{s+1,b,i}\}\mathbf{d}_i, \ldots,\\ &\mathbf{w}^H_{s,a,i}\text{diag}\{\mathbf{H}^{(a,b)}_{i,i}\mathbf{f}_{M,b,i}\}\mathbf{d}_i\Big]^T,\end{aligned} \tag{13}$$

$$\begin{aligned}\mathbf{y}^{(a,b)}_{s,i,j} = \Big[&\mathbf{w}^H_{s,a,i}\text{diag}\{\mathbf{H}^{(a,b)}_{i,j}\mathbf{f}_{1,b,j}\}\mathbf{d}_i, \ldots,\\ &\mathbf{w}^H_{s,a,i}\text{diag}\{\mathbf{H}^{(a,b)}_{i,j}\mathbf{f}_{M,b,j}\}\mathbf{d}_i\Big]^T,\end{aligned} \tag{14}$$

$$\begin{aligned}\mathbf{z}_{s,i} = [&\mathbf{y}^{(2,1)T}_{s,i,1}, \ldots, \mathbf{y}^{(2,1)T}_{s,i,i-1}, \mathbf{y}^{(2,1)T}_{s,i,i+1}, \ldots,\\ &\mathbf{y}^{(2,1)T}_{s,i,K}, \mathbf{y}^{(2,2)T}_{s,i,1}, \ldots, \mathbf{y}^{(2,2)T}_{s,i,i-1}, \mathbf{y}^{(2,2)T}_{s,i,i+1}, \ldots, \mathbf{y}^{(2,2)T}_{s,i,K}]^T,\end{aligned} \tag{15}$$

the first set of the constraints in (10) can be reformulated as

$$\begin{aligned}\Bigg\|\Bigg[&\mathbf{x}^{(2,1)T}_{s,i,i}, \mathbf{y}^{(2,2)T}_{s,i,i}, \mathbf{z}^T_{s,i}, \sigma_{2,i}(\text{diag}\{\mathbf{w}_{s,2,i}\}^H\mathbf{d}_i)^T,\\ &\omega_i\mathbf{w}^T_{s,2,i}, \frac{\hat{v}_{s,i}(\mathbf{s}^{(k)},\mathbf{s})-1}{2}\Bigg]\Bigg\| \leq \frac{\hat{v}_{s,i}(\mathbf{s}^{(k)},\mathbf{s})+1}{2}.\end{aligned} \tag{16}$$

Similarly, with the following variables:

$$\begin{aligned}\widetilde{\mathbf{x}}^{(a,b)}_{i,j} = \Big[&(\text{diag}\{\mathbf{H}^{(a,b)}_{i,j}\bar{\mathbf{f}}_{1,b,j}\}\mathbf{d}_i)^T, \ldots,\\ &(\text{diag}\{\mathbf{H}^{(a,b)}_{i,j}\bar{\mathbf{f}}_{M,b,j}\}\mathbf{d}_i)^T\Big]^T,\end{aligned} \tag{17}$$

$$\begin{aligned}\widetilde{\mathbf{z}}_i = \Big[&\widetilde{\mathbf{x}}^{(2,1)T}_{i,1}, \ldots, \widetilde{\mathbf{x}}^{(2,1)T}_{i,i-1}, \widetilde{\mathbf{x}}^{(2,1)T}_{i,i+1}, \ldots,\\ &\widetilde{\mathbf{x}}^{(2,1)T}_{i,K}, \widetilde{\mathbf{x}}^{(2,2)T}_{i,1}, \ldots, \widetilde{\mathbf{x}}^{(2,2)T}_{i,i-1}, \mathbf{x}^{(2,2)T}_{i,i+1}, \ldots, \widetilde{\mathbf{x}}^{(2,2)T}_{i,K}\Big]^T,\end{aligned} \tag{18}$$

the second set of constraints in (10) can be formulated as

$$\begin{aligned}\Bigg\|\Bigg[&\widetilde{\mathbf{x}}^{(2,1)T}_{i,i}, \widetilde{\mathbf{x}}^{(2,2)T}_{i,i}, \mathbf{z}^T_i,\\ &\sigma_{2,i}\mathbf{d}^T_i, \frac{q_i - \frac{t\psi_i}{\xi_i} - 1}{2}\Bigg]\Bigg\| \leq \frac{q_i - \frac{t\psi_i}{\xi_i} + 1}{2},\end{aligned} \tag{19}$$

where $q_i = \sum_{s'=1}^{M} \|\mathbf{H}^{(2,1)}_{i,i}\mathbf{f}_{s',1,i}\|^2 + \sum_{s'=1}^{M} \|\mathbf{H}^{(2,2)}_{i,i}\mathbf{f}_{s',2,i}\|^2 + \sum_{j \neq i}^{K}\sum_{c=1}^{2}\sum_{s'=1}^{M} \|\mathbf{H}^{(2,c)}_{i,j}\mathbf{f}_{s',c,j}\|^2 + \sigma^2_{2,i}N_i$. Thus, in the kth iteration of the proposed CCCP based algorithm, we formulate the

$$
\begin{aligned}
&\min_{\{\mathbf{F}_{s,a,i}\}} \sum_{i=1}^{K}\sum_{a=1}^{2}\sum_{s=1}^{M} \mathrm{Tr}\{\mathbf{F}_{s,a,i}\} \\
&\text{s.t. } \frac{1}{\gamma_{s,b,i}}\mathbf{w}_{s,b,i}^H \bar{\mathbf{H}}_{i,i}^{(b,a)}\mathbf{F}_{s,a,i}\bar{\mathbf{H}}_{i,i}^{H(b,a)}\mathbf{w}_{s,b,i} - \sum_{s'\neq s}^{M}\mathbf{w}_{s,b,i}^H \bar{\mathbf{H}}_{i,i}^{(b,a)}\mathbf{F}_{s',a,i}\bar{\mathbf{H}}_{i,i}^{H(b,a)}\mathbf{w}_{s,b,i} \\
&- \sum_{s'=1}^{M}\mathbf{w}_{s,b,i}^H \bar{\mathbf{H}}_{i,i}^{(b,b)}\mathbf{F}_{s',b,i}\bar{\mathbf{H}}_{i,i}^{H(b,b)}\mathbf{w}_{s,b,i} - \sum_{j\neq i}^{K}\sum_{c=1}^{2}\sum_{s'=1}^{M}\mathbf{w}_{s,b,i}^H \bar{\mathbf{H}}_{i,j}^{(b,c)}\mathbf{F}_{s',c,j}\bar{\mathbf{H}}_{i,j}^{H(b,c)}\mathbf{w}_{s,b,i} \geq \theta_{b,i}, \\
&\sum_{s'=1}^{M}\mathrm{Tr}\{\boldsymbol{\Phi}_i\mathbf{H}_{i,i}^{(2,1)}\mathbf{F}_{s',1,i}\mathbf{H}_{i,i}^{H(2,1)}\boldsymbol{\Phi}_i\} + \sum_{s'=1}^{M}\mathrm{Tr}\{\boldsymbol{\Phi}_i\mathbf{H}_{i,i}^{(2,2)}\mathbf{F}_{s',2,i}\mathbf{H}_{i,i}^{H(2,2)}\boldsymbol{\Phi}_i\} \\
&+ \sum_{j\neq i}^{K}\sum_{c=1}^{2}\sum_{s'=1}^{M}\mathrm{Tr}\{\boldsymbol{\Phi}_i\mathbf{H}_{i,j}^{(2,c)}\mathbf{F}_{s',c,j}\mathbf{H}_{i,j}^{H(2,c)}\boldsymbol{\Phi}_i\} \geq \frac{\psi_i}{\xi_i} - \sigma_{2,i}^2\|\mathrm{vec}\{\boldsymbol{\Phi}_i\}\|^2, \\
&\mathbf{F}_{s,a,i} \succeq \mathbf{0},\ i\in\mathcal{K}, s\in\mathcal{M}, a,b\in\{1,2\}, a\neq b,
\end{aligned} \tag{8}
$$

$$
\begin{aligned}
&\max_{\mathbf{s}}\ f(\mathbf{s}) \\
&\text{s.t. } u_{s,i}(\mathbf{s}) - v_{s,i}(\mathbf{s}) \leq 0 \\
&\sum_{s'=1}^{M}\|\mathrm{diag}\{\mathbf{H}_{i,i}^{(2,1)}\mathbf{f}_{s',1,i}\}\mathbf{d}_i\|^2 + \sum_{s'=1}^{M}\|\mathrm{diag}\{\mathbf{H}_{i,i}^{(2,2)}\mathbf{f}_{s',2,i}\}\mathbf{d}_i\|^2 + \sum_{j\neq i}^{K}\sum_{c=1}^{2}\sum_{s'=1}^{M}\|\mathrm{diag}\{\mathbf{H}_{i,j}^{(2,c)}\mathbf{f}_{s',c,j}\}\mathbf{d}_i\|^2 + \sigma_{2,i}^2\|\mathbf{d}_i\|^2 \\
&\leq \sum_{s'=1}^{M}\|\mathbf{H}_{i,i}^{(2,1)}\mathbf{f}_{s',1,i}\|^2 + \sum_{s'=1}^{M}\|\mathbf{H}_{i,i}^{(2,2)}\mathbf{f}_{s',2,i}\|^2 + \sum_{j\neq i}^{K}\sum_{c=1}^{2}\sum_{s'=1}^{M}\|\mathbf{H}_{i,j}^{(2,c)}\mathbf{f}_{s',c,j}\|^2 + \sigma_{2,i}^2 N_i - \frac{t\psi_i}{\xi_i}, \\
&0\leq\rho_{n,i}\leq 1,\ n\in\mathcal{N}_i, i\in\mathcal{K}, s\in\mathcal{M}.
\end{aligned} \tag{10}
$$

TABLE II
ALTERNATING OPTIMIZATION DESIGN ALGORITHM

1. Initialize $\{\mathbf{w}_{s,a,i}\}$ and $\{\mathbf{f}_{s,a,i}\}$, define the tolerance of accuracy δ_2 and the maximum number of iteration N_{max}^2.
2. **Repeat**
   - 2.1 Solve an approximation of problem (10) based on Table I with fixed $\{\mathbf{w}_{s,a,i}\}$ and $\{\mathbf{f}_{s,a,i}\}$ to obtain the updated $\{\mathbf{d}_i\}$.
   - 2.2 Compute (7) with fixed $\{\mathbf{f}_{s,a,i}\}$ and $\{\mathbf{d}_i\}$ to obtain the updated $\{\mathbf{w}_{s,a,i}\}$.
   - 2.3 Solve problem (8) with fixed $\{\mathbf{w}_{s,a,i}\}$ and $\{\mathbf{d}_i\}$ to obtain the updated $\{\mathbf{f}_{s,a,i}\}$.
3. **Until** the total power consumption between two adjacent iterations is less than δ_2 or the maximum number of iterations is reached.

following SOCP problem

$$
\begin{aligned}
&\max_{\mathbf{s}}\ f(\mathbf{s}) \\
&\text{s.t. } (16),\ (19), \\
&0\leq\rho_{n,i}\leq 1,\ n\in\mathcal{N}_i, i\in\mathcal{K}, s\in\mathcal{M}.
\end{aligned} \tag{20}
$$

The CCCP based iterative algorithm to solve problem (10) is summarized in Table I, while the proposed alternating optimization algorithm is summarized in Table II.

IV. Analysis of the Proposed Algorithm

1) Convergence analysis: The proposed alternating optimization design algorithm iterates over steps 2.1-2.3. We note that in step 2.1 and 2.2, the feasible region of $\{\mathbf{f}_{s,a,i}\}$ is enlarged, and consequently the total transmission power is decreased in step 2.3. Thus, the monotonic convergence of the algorithm is ensured.

2) Complexity analysis: As we can see, the complexity of the alternating optimization design algorithm is dominated by solving problem (8) N_{max}^2 times and solving problem (10) $N_{max}^1 N_{max}^2$ times. Similar to the analysis in [16], the complexity of solving (8) can be expressed as $C_1 = \sqrt{2KM(N+1)+K}\cdot n_1\cdot[2KM+K+2KMN^3+n_1(2KM+K+2KMN^2)+n_1^2]$, where $n_1=\mathcal{O}(2KMN^2)$, and the complexity of solving problem (10) can be expressed as $C_2 = \sqrt{2(M+N)K+2K}\cdot n_2\cdot[2NK+2NKn_2+MK(2MK+N+1)^2+K(2NMK+N+2)^2+n_2^2]$, where $n_2 = O(NK+1)$. Thus, the overall complexity can be expressed as $N_{max}^2 C_1 + N_{max}^1 N_{max}^2 C_2$.

V. Simulations

In this section, we compare the proposed FD joint transceiver design algorithm with its HD counterpart[4] in terms of the transmitted power consumption. The nominal system configuration is defined by the following choice of parameters: $T_i = N_i = 4$, $K=3$, $M=2$, $\xi_i=1$, $\sigma_{a,i}^2=\sigma^2=-30$dBm, and $\omega_i^2=\omega^2=-20$dBm. In addition, we assume equal transmission rate and EH targets at the destination receivers, i.e., $\varphi_{s,a,i}=\varphi$, $\psi_i=\psi$, $\forall i\in\mathcal{K}$, $\forall s\in\mathcal{M}$, $\forall a\in\{1,2\}$, for simplicity. In the implementations of the various algorithms, the tolerance parameters are chosen as $\delta_1 = 1\times10^{-4}$, $\delta_2 = 1\times10^{-3}$, and the maximum iteration numbers are chosen as $N_{max}^1=20$, $N_{max}^2=30$. Furthermore, we assume that the interference channel gain from the nodes in the jth pair to the nodes in the ith pair is given by -10dB, $i\neq j$, and the residual self-interference channel gain is denoted as -20dB. All convex problems are solved by CVX [19] on a desktop Intel (i3-2100) CPU running at 3.1GHz with 4GB RAM.

Fig. 2 (a) shows the average power consumption versus node 2 EH target ψ for the FD and HD joint transceiver design algorithms, where the transmission rate is given by $\varphi = 20/6$ bps/Hz. From the results, we can see that the proposed FD joint transceiver design algorithm outperforms its HD counterpart. In particular, the proposed FD transceiver design algorithm can save 5dB in transmitted power for $\psi=-15$dBm, compared to the HD case. The performance of the FD and HD schemes becomes closer when increasing the EH requirement. This can be intuitively explained by noting that in order to support large

[4]The HD joint transceiver design can be obtained straightforwardly based on the proposed algorithm for the FD case.

harvested energy, the transmission power of node 1 in a given pair must be much larger than that of its corresponding node 2, and therefore the advantage of the FD scheme would vanish in this case. Fig. 2 (b) show the average power consumption versus transmission rate for the analyzed algorithms, where we fix $\psi = 0$dBm. We can see that the performance of the proposed FD transceiver design algorithm is also better than that of its HD counterpart. The gain becomes larger for higher rate.

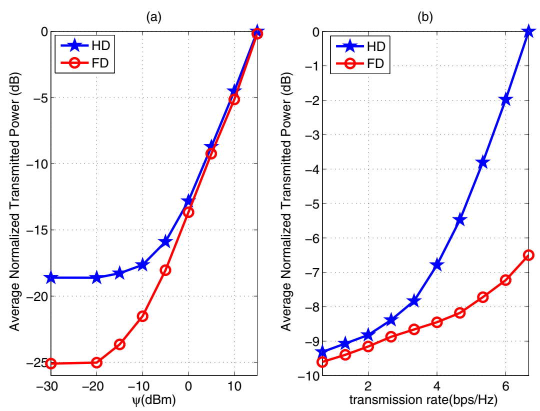

Fig. 2. The average normalized transmission power versus: (a) harvested power; (b) transmission rate φ.

VI. Conclusion

We proposed a joint transceiver design algorithm in a FD K-pair MIMO interference channel with SWIPT. An alternating optimization based iterative algorithm was proposed to successively optimize the transceiver coefficients in order to minimize the total transmission power under both transmission rate and EH constraints. Simulation results were presented to verify that the proposed FD joint transceiver design algorithm outperforms its HD counterpart.

Appendix A
The Proof of Lemma 1

Suppose that $\{\mathbf{F}_{s,a,i}^*\}$ are the optimal solutions to (8) and $\text{Rank}(\mathbf{F}_{s,a,i}^*) \geq 1$, then according to [20], we have the following inequality about the rank property of (8):

$$2MK \leq \sum_{i=1}^{K}\sum_{a=1}^{2}\sum_{s=1}^{M}(\text{Rank}(\mathbf{F}_{s,a,i}^*))^2 \leq 2MK + K, \quad (21)$$

When $K = 2$, inequality (21) becomes

$$4M \leq \sum_{i=1}^{2}\sum_{a=1}^{2}\sum_{s=1}^{M}(\text{Rank}(\mathbf{F}_{s,a,i}^*))^2 \leq 4M + 2, \quad (22)$$

from which we can infer that $\text{Rank}(\mathbf{F}_{s,a,i}) = 1, \forall s, a, i$. Since if there exists one set of indexes $\{\tilde{s}, \tilde{a}, \tilde{i}\}$ such hat $\text{Rank}(\mathbf{F}_{\tilde{s},\tilde{a},\tilde{i}}) = 2$, then inequality (21) would become

$$4M \leq 4M - 1 + 4 \leq 4M + 2, \quad (23)$$

which is impossible.

When $K = 3$, inequality (21) becomes

$$6M \leq \sum_{i=1}^{3}\sum_{a=1}^{2}\sum_{s=1}^{M}(\text{Rank}(\mathbf{F}_{s,a,i}^*))^2 \leq 6M + 3, \quad (24)$$

from which we can see that there is at most one $\mathbf{F}_{s,a,i}$ that is rank-2 and the others are rank-one. Thus, the optimal solution of problem (8) is not always rank-one when $K = 3$ and this completes the proof.

References

[1] 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.

[2] Q. Shi, W. Xu, L. Liu and R. Zhang, "Joint transmit beamforming and receive power splitting for MISO SWIPT systems," *IEEE Trans. Wireless Commun.*, vol. 13, no. 6, pp. 3269–3280, Jun. 2014.

[3] S. Timotheou, I. Krikidis, G. Zheng and B. Ottersten, "Beamforming for MISO interference channels with QoS and RF energy transfer," *IEEE Trans. Wireless Commun.*, vol. 13, no. 5, pp. 2646–2658, May 2014.

[4] Q. Shi, W. Xu, T.-H. Chang, Y. Wang, and E. Song, "Joint beamforming and power splitting for MISO interference channel with SWIPT: An SOCP relaxation and decentralized algorithm," *IEEE Trans. Signal Process.*, vol. 62, no. 23, pp. 6194–6208, Dec. 2014.

[5] Z. Zong, H. Feng, F. R. Yu, N. Zhao, T. Yang, and B. Hu, "Optimal transceiver design for SWIPT in K-user MIMO interference channels," to appear in *IEEE Trans. Wireless Commun.*.

[6] Z. Ding, C. Zhong, D. W. K. Ng, M. Peng, H. A. Suraweera, R. Schober, and H. V. Poor, "Application of smart antenna technologies in simultaneous wireless information and power transfer," *IEEE Commun. Mag.*, pp. 86–93, Apr. 2015.

[7] H. Ju, E. Oh, and D. Hong, "Improving efficiency of resource usage in two-hop full duplex relay systems based on resource sharing and interference cancellation," *IEEE Trans. Wireless Commun.*, vol. 8, no. 8, pp. 3933C3938, Aug. 2009.

[8] D. Nguyen, L. Tran, P. Pirinen, and M. Latva-aho, "On the spectral efficiency of full-duplex small cell wireless systems," *IEEE Trans. Wireless Commun.*, vol. 13, no. 9, pp. 4896-4910, Sep. 2014.

[9] M. Duarte, C. Dick, and A. Sabharwal, "Experiment-driven characterization of full-duplex wireless systems," *IEEE Trans. Wireless Commun.*, vol. 11, no. 12, pp. 4296C4307, Dec. 2012.

[10] W. Li, J. Lilleberg, and K. Rikkinen, "On rate region analysis of half- and full-duplex OFDM communication links," *IEEE J. Sel. Areas Commun.*, vol. 32, no. 9, pp. 1688C1698, Sep. 2014.

[11] G. Zheng, I. Krikidis, J. Li, A. P. Petropulu, and B. Ottersten, "Improving physical layer secrecy using full-duplex jamming receivers," *IEEE Trans. Signal Process.,* vol. 61, no. 20, pp. 4962-4974, Oct. 2013.

[12] G. Zheng, "Joint beamforming optimization and power control for full-duplex MIMO two-way relay channel," *IEEE Trans. Signal Process.,* vol. 63, no. 3, pp. 555-566, Feb. 2015.

[13] A. C. Cirik, R. Wang, Y. Rong, and Y. Hua, "MSE-based transceiver designs for full-duplex MIMO cognitive radios," *IEEE Trans. Commun.,* vol. 63, no. 6, pp. 2056-2070, Jun. 2015.

[14] A. C. Cirik, R. Wang, Y. Rong, and Y. Hua, "Weighted sum-rate maximization for full-duplex MIMO interference channels," *IEEE Trans. Commun.,* vol. 63, no. 3, pp. 801-815, Mar. 2015.

[15] R. H. Tütüncü, K. C. Toh and M. J. Todd, "Solving semidefinite-quadratic-linear programs using SDPT3," *Math. Program., Ser. B*, vol. 95, no. 2, pp. 189–217, 2003.

[16] M. M. Zhao, Y. Cai, Q. Shi, B. Champagne and M. Zhao, "Robust transceiver design for MISO interference channel with energy harvesting," available on-line at arXiv: 1501.07658.

[17] D. H. Brandwood, "A complex gradient operator and its application in adaptive array theory," in *Proc. Inst. Elect. Eng.*, vol. 130, no. 1, pp. 11–16, 1983.

[18] Y. Cheng and M. Pesavento, "Joint optimization of source power allocation and distributed relay beamforming in multiuser peer-to-peer relay networks," *IEEE Trans. Signal Process.*, vol. 60, no. 6, pp. 2962–2973, Jun. 2012.

[19] C. R. Inc., "Cvx: Matlab software for disciplined convex programming," available: http://cvxr.com/cvx, Sept. 2012.

[20] Y. Huang and D. P. Palomar, "Rank-constrained separable semidefinite programming with applications to optimal beamforming," *IEEE Trans. Signal Process.*, vol. 58, no. 2, pp. 664–678, Feb. 2010.