Robust Energy Harvesting FD Transmission: Interference Suppression Versus Exploitation

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***Abstract*—We explore robust designs to jointly minimize the total uplink and downlink transmit power and maximize the total harvested energy in a full duplex system with imperfect channel state information. We first formulate an optimization, where multiuser interference (MUI) is suppressed. We then propose an optimization, where the MUI is rather exploited, both as useful energy and information power, for guaranteeing quality of service and energy harvesting constraints. To tackle the non-convexity of the formulations, we employ convex relaxations. Simulation results show the effectiveness of interference exploitation compared with interference suppression in terms of both power consumption and energy transfer.**

***Index Terms*—Full duplex (FD), interference exploitation, robust design, multi-objective optimization.**

I. Introduction

FULL DUPLEX (FD) systems, have recently been brought at the forefront of 5G technologies, while major breakthroughs have been made with respect SI cancellation [1], [2]. On the other hand, simultaneous wireless information and power transfer (SWIPT) is also being considered for 5G for prolonging the lifetime of communication networks. Towards this direction research efforts have involved employing energy and information receivers (EIR) [3] as well as SWIPT relays [4]. The integration of FD with SWIPT is promising since the EIR can be simultaneously served thereby improving the spectrum and energy efficiency of the system [5]. Most relevant to the focus of this letter, in [6], the authors proposed a multi-objective optimization problem (MOOP) via the weighted Tchebycheff method to investigate the resource allocation for FD-SWIPT systems with separated EIR. Their MOOP jointly minimizes the uplink and downlink transmit power and maximizes the total energy harvested.

Accordingly, in this work, we aim to investigate precoding solutions for FD-SWIPT. Inspired by [6], here we first derive a channel state information (CSI)-robust MOOP based on suppressing interference. We then go one step further to reformulate the optimization such that the multi-user interference is exploited as a useful resource both for energy and information power. While the concept of interference exploitation has been studied thoroughly for half-duplex (HD) in [7]–[9], providing significant downlink power gains, the FD setup investigated here provides the opportunity to extend these gains to the uplink power budget.

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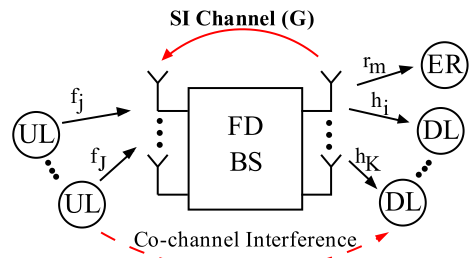


Fig. 1. A multi-user FD SWIPT system.

II. System Model

We consider a multiuser communication system defined in [6] and shown in Fig. 1. A FD base station (BS) with N transmit and N receive antennas simultaneously serves K single-antenna downlink users, J uplink users and M energy receivers (ERs). The transmitted signal by the FD BS is expressed as $\mathbf{t} = \sum_{i=1}^{K} \mathbf{w}_i d_i + \mathbf{q}$, where, $\mathbf{w}_i \in \mathbb{C}^{N\times 1}$ and d_i denote the beamforming vector and the unit data symbol for the *i-th* downlink user, respectively. The vector $\mathbf{q} \in \mathbb{C}^{N\times 1}$ is the energy signal sent by the FD BS to facilitate energy transfer [6]. Let $\mathbf{h}_i \in \mathbb{C}^{N\times 1}$, $\mathbf{f}_j \in \mathbb{C}^{N\times 1}$ and $\mathbf{r}_m \in \mathbb{C}^{N\times 1}$ be the channels between the FD BS and the *i-th* downlink user, the *j-th* uplink user, the *m-th* ER, respectively. Therefore, the received signals at the *i-th* downlink user, the FD BS and the *m-th* ER are respectively given by

$$y_i^{\mathrm{DL}} = \mathbf{h}_i^H \sum_{k=1}^{K} \mathbf{w}_k d_k + \mathbf{h}_i^H \mathbf{q} + \sum_{j=1}^{J} \sqrt{p_j}\ell_{j,i} x_j + n_i, \quad (1)$$

$$\mathbf{y}^{\mathrm{BS}} = \sum_{j=1}^{J} \sqrt{p_j}\mathbf{f}_j x_j + \mathbf{G}\mathbf{t} + \mathbf{n}_j, \quad (2)$$

$$y_m^{\mathrm{ER}\,1} = \mathbf{r}_m^H \mathbf{t} + n_m, \quad (3)$$

where, p_j and x_j denote the uplink transmit power and the data symbol from the *j-th* uplink user, respectively. $\ell_{j,i}$ is the channel between the *j-th* uplink user and the *i-th* downlink user. We denote $n_i \sim \mathcal{CN}\left(0, \sigma_i^2\right)$, $\mathbf{n}_j \sim \mathcal{CN}(0, \sigma_j^2)$ and $n_m \sim \mathcal{CN}(0, \sigma_m^2)$ as the additive white Gaussian noise at the *i-th* user, the FD BS and the *m-th* ER, respectively. The matrix $\mathbf{G} \in \mathbb{C}^{N\times N}$ denotes the SI channel at the FD BS. In order to isolate our proposed scheme from the specific implementation of any passive or active SI mitigation techniques, we consider the deterministic model to represent the residual-SI channel after cancellation, that is known imperfectly at the BS. Accordingly, the SI channel, which typically follows Rician distribution [6], is expressed as $\mathbf{G} = \check{\mathbf{G}} + \mathbf{E}_G$, where $\check{\mathbf{G}}$, denotes the SI channel estimate known to the FD BS which can be cancelled, and $\mathbf{E}_G$ represents the SI channel uncertainties, for which $\|\mathbf{E}_G\|_F^2 \leq \epsilon_G^2$, for some $\epsilon_G \geq 0$. We denote $\|\cdot\|_F$ as the Frobenius norm.

[1]In the adopted system model, the ERs only receive energy from the FD BS, while we ignore the potential energy received by the uplink users for simplicity.

We define the signal-to-interference plus noise ratio (SINR) at the *i-th* downlink user and at the FD radio BS respectively as

$$\Gamma_i^{\mathrm{DL}} = \frac{|\mathbf{h}_i^H \mathbf{w}_i|^2}{\sum_{k\neq i}^{K} |\mathbf{h}_i^H \mathbf{w}_k|^2 + |\mathbf{h}_i^H \mathbf{q}|^2 + \sum_{j=1}^{J} p_j |\ell_{j,i}|^2 + \sigma_i^2}, \quad (4)$$

$$\Gamma_j^{\mathrm{UL}} = \frac{p_j |\mathbf{f}_j^H \mathbf{u}_j|^2}{\sum_{n\neq j}^{J} p_n |\mathbf{f}_n^H \mathbf{u}_j|^2 + |\mathbf{u}_j \mathbf{E}_G \mathbf{t}|^2 + \sigma_j^2 \|\mathbf{u}_j\|^2}, \quad (5)$$

where, $\mathbf{u}_j \in^{N\times 1}$ is the receive beamforming vector for detecting the received symbol from the *j-th* uplink user. Following [6], we adopt zero-forcing (ZF) beamforming at the FD BS for the detection of uplink signals.

The total harvested energy at the *m-th* ER is modelled as [3] $E_m^{\mathrm{ER}} = \zeta_m \|\mathbf{r}_m^H \mathbf{t}\|^2$, where, $0 \leq \zeta_m \leq 1$ represents the energy conversion efficiency and we assume the noise power is negligibly small compared to the power of the received signal [6].

In contrast to [6], in this letter, we focus on the case where imperfect CSI for the uplink, downlink, CCI and SI channels are available at the FD BS. We model these additive errors as norm-bounded, in the form $\mathbf{h}_i = \check{\mathbf{h}}_i + \mathbf{e}_{h,i}, \|\mathbf{e}_{h,i}\|^2 \leq \epsilon_{h,i}^2, \forall i$, $\mathbf{f}_j = \check{\mathbf{f}}_j + \mathbf{e}_{f,j}, \|\mathbf{e}_{f,j}\|^2 \leq \epsilon_{f,j}^2, \forall j$ and $\ell_{j,i} = \check{\ell}_{j,i} + e_{j,i}, |e_{j,i}|^2 \leq \epsilon_{j,i}^2, \forall j, i$, where $\check{\mathbf{h}}_i, \check{\mathbf{f}}_j$ and $\check{\ell}_{j,i}$ denote the downlink, uplink and CCI CSI estimates known to the FD BS, respectively, and $\mathbf{e}_{h,i}, \mathbf{e}_{f,j}$ and $e_{j,i}$ represent the downlink, uplink and CCI CSI uncertainties, respectively. On the other hand, the FD BS need only to know the channel gain r_m of the ERs' channel to achieve a specified energy harvested target.

III. Robust Design With Interference Suppression

The system design objective is to jointly minimize the total downlink and uplink transmit power while maximizing the total harvested energy subject to QoS constraints (4) and (5), where multi-user interference is treated as harmful signal. This can be mathematically formulated as

$$\begin{aligned}
\mathcal{P}1: \min_{\mathbf{w}_i,\mathbf{q},p_j} \; & c_1 \cdot \left(\sum_{k=1}^{K} \|\mathbf{w}_k\|^2 + \|\mathbf{q}\|^2 \right) + c_2 \cdot \sum_{j=1}^{J} p_j - c_3 \cdot \sum_{m=1}^{M} E_m^{\mathrm{ER}} \\
\text{s.t. } & \mathrm{A1}: \Gamma_i^{\mathrm{DL}} \geq \Gamma_i, \forall \|\mathbf{e}_{h,i}\|^2 \leq \epsilon_{h,i}^2, \forall |e_{j,i}|^2 \leq \epsilon_{j,i}^2, \; \forall i, \\
& \mathrm{A2}: \Gamma_j^{\mathrm{UL}} \geq \Gamma_j, \forall \|\mathbf{E}_G\|_F^2 \leq \epsilon_G^2, \forall \|\mathbf{e}_{f,j}\|^2 \leq \epsilon_{f,j}^2, \forall j, \\
& \mathrm{A3}: \zeta_m r_m \left(\sum_{k=1}^{K} \|\mathbf{w}_k\|^2 + \|\mathbf{q}\|^2 \right) \geq P_m^{\min}, \forall m, \\
& \mathrm{A4}: \sum_{k=1}^{K} \|\mathbf{w}_k\|^2 + \|\mathbf{q}\|^2 \leq \mathrm{P}_{\max}^{\mathrm{DL}}, \; \mathrm{A5}: p_j \leq \mathrm{P}_{\max}^{\mathrm{UL}}, \forall j,
\end{aligned} \quad (6)$$

where $c_1 + c_2 + c_3 = 1$ are the weights given to each of the system's design objectives, respectively. Constraints A1 and A2 ensure that the minimum SINR, Γ_i and Γ_j, is achieved for the *i-th* downlink user and *j-th* uplink user, respectively. Constraint A3 ensures that the minimum harvested energy, P_m^{min}, for the *m-th* ER is achieved while A4 and A5 denote the maximum downlink and uplink transmit power constraints, respectively. The evidently non-convex problem (6) can be solved by formulating it as a semi-definite program (SDP) which can be transformed into linear matrix inequalities (LMI) by using the S-procedure. Accordingly, by defining $\mathbf{W}_i = \mathbf{w}_i \mathbf{w}_i^H, \mathbf{Q} = \mathbf{q}\mathbf{q}^H$ and $\mathbf{U}_j = \mathbf{u}_j \mathbf{u}_j^H$. Constraint A1 can be expressed as the following two constraints

$$(\check{\mathbf{h}}_i + \mathbf{e}_{h,i})^H \mathbf{Y}_i (\check{\mathbf{h}}_i + \mathbf{e}_{h,i}) - \Gamma_i(\sigma_i^2 + L_i) \geq 0, \quad \forall i, \quad (7)$$

$$\sum_{j=1}^{J} p_j (\check{\ell}_{j,i} + e_{j,i})^H (\check{\ell}_{j,i} + e_{j,i}) \leq L_i, \quad \forall i, \quad (8)$$

where we introduce auxiliary variable $L_i \geq 0$ and $\mathbf{Y}_i \triangleq \mathbf{W}_i - \Gamma_i \left(\sum_{k\neq i}^{K} \mathbf{W}_k + \mathbf{Q} \right)$. For constraint A2, we define two vectors $\widetilde{\mathbf{f}} = [\check{\mathbf{f}}_j^H, \ldots, \check{\mathbf{f}}_J^H]^H \in \mathbb{C}^{NJ\times 1}$ and $\widetilde{\mathbf{e}}_f = [\mathbf{e}_{f,j}^H, \ldots, \mathbf{e}_{f,J}^H]^H \in \mathbb{C}^{NJ\times 1}$. Hence, we can define any $\check{\mathbf{f}}_j = \mathbf{B}_j \widetilde{\mathbf{f}}$ and $\mathbf{e}_{f,j} = \mathbf{B}_j \widetilde{\mathbf{e}}_f$, for $j = 1, \ldots, J$, with $\mathbf{B}_j \in \mathbb{R}^{N\times NJ}$ defined as $\mathbf{B}_j = [\mathbf{B}_{j,1}, \ldots, \mathbf{B}_{j,J}]$, where $\mathbf{B}_{j,j} = \mathbf{I}_N$ and $\mathbf{B}_{j,n} = \mathbf{0}_N$, for $n = 1, \ldots, J, n \neq j$. We have $\mathbf{I}_N$ and $\mathbf{0}_N$ to be an $N \times N$ identity matrix and zero matrix, respectively. Hence, A2 can be rewritten as

$$\frac{p_j \left((\mathbf{B}_j \widetilde{\mathbf{f}} + \mathbf{B}_j \widetilde{\mathbf{e}}_f)^H \mathbf{U}_j (\mathbf{B}_j \widetilde{\mathbf{f}} + \mathbf{B}_j \widetilde{\mathbf{e}}_f) \right)}{\sum_{n\neq j}^{J} p_n \left((\mathbf{B}_n \widetilde{\mathbf{f}} + \mathbf{B}_n \widetilde{\mathbf{e}}_f)^H \mathbf{U}_j (\mathbf{B}_n \widetilde{\mathbf{f}} + \mathbf{B}_n \widetilde{\mathbf{e}}_f) \right) + S_j} \geq \Gamma_j, \quad (9)$$

where $S_j = \mathrm{Tr}\left\{ \mathbf{E}_G \left(\sum_{k=1}^{K} \mathbf{W}_k + \mathbf{Q} \right) \mathbf{E}_G^H \mathbf{U}_j \right\} + \sigma_N^2 \mathrm{Tr}\{\mathbf{U}_j\}$. Furthermore, we introduce $\mathbf{Z}_j \triangleq P_j \mathbf{B}_j^T \mathbf{U}_j \mathbf{B}_j - \Gamma_j \sum_{n\neq j}^{J} P_n \mathbf{B}_n^T \mathbf{U}_j \mathbf{B}_n$ and auxiliary variable S_j^{SI}, such that (9) can be written as the following two constraints

$$\left(\widetilde{\mathbf{f}} + \widetilde{\mathbf{e}}_f \right)^H \mathbf{Z}_j \left(\widetilde{\mathbf{f}} + \widetilde{\mathbf{e}}_f \right) \geq S_j^{\mathrm{SI}} \Gamma_j, \quad \forall j, \quad (10)$$

$$\mathrm{Tr}\left\{ \mathbf{E}_G \left(\sum_{k=1}^{K} \mathbf{W}_k + \mathbf{Q} \right) \mathbf{E}_G^H \mathbf{U}_j \right\} + \sigma_N^2 \mathrm{Tr}\{\mathbf{U}_j\} \leq S_j^{\mathrm{SI}}, \quad \forall j. \quad (11)$$

Thus, using $\mathrm{Tr}\{\mathbf{ABCD}\} = \mathrm{vec}\left(\mathbf{A}^H\right)^H \left(\mathbf{D}^T \otimes \mathbf{B}\right) \mathrm{vec}(\mathbf{C})$, and defining $\mathbf{P} = \mathrm{diag}(p_1, \ldots, p_J), \check{\ell}_i = \left[\check{\ell}_{1,i}, \ldots, \check{\ell}_{J,i}\right], \mathbf{e}_{\ell,i} = [e_{1,i}, \ldots, e_{J,i}]$ and $\mathbf{e}_g = \mathrm{vec}(\mathbf{E}_G{}^H)$, where $\mathrm{vec}(\cdot)$ stacks the columns of a matrix into a vector and $\otimes$ stands for Kronecker product, constraints (7),(8), (10) and (11) can be expanded and transformed to LMIs using S-procedure as shown in (12) and (13), as shown at the top of the next page, respectively. Thus, (6) can be re-expressed as

$$\begin{aligned}
\mathcal{P}2: \min_{\substack{\mathbf{W}_i,\mathbf{Q},p_j,\\ \delta_i,\mu_j,\rho,S_j^{\mathrm{SI}},}} \; & \mathrm{Tr}\left\{ \sum_{k=1}^{K} \mathbf{W}_k + \mathbf{Q} \right\} \left(c_1 - c_3 \sum_{m=1}^{M} \zeta_m r_m \right) + c_2 \cdot \sum_{j=1}^{J} p_j \\
\text{s.t. } & \widetilde{\mathrm{A1a}}, \widetilde{\mathrm{A1b}}, \widetilde{\mathrm{A2a}}, \widetilde{\mathrm{A2b}}, \mathrm{A4}, \mathrm{A5}, \\
& \widetilde{\mathrm{A3}}: \zeta_m r_m \mathrm{Tr}\left\{ \sum_{k=1}^{K} \mathbf{W}_k + \mathbf{Q} \right\} \geq P_m^{min}, \quad \forall m, \\
& \mathbf{W}_i \succeq 0, \forall i, \mathbf{Q} \succeq 0, \delta_i \geq 0, \\
& \forall i, \mu_j \geq 0, \; \forall j, \rho \geq 0,
\end{aligned} \quad (14)$$

$$\widetilde{\text{A1a}} \Rightarrow \begin{bmatrix} \delta_i \mathbf{I} + \mathbf{Y}_i & \mathbf{Y}_i \check{\mathbf{h}}_i \\ \check{\mathbf{h}}_i^H \mathbf{Y}_i & \check{\mathbf{h}}_i^H \mathbf{Y}_i \check{\mathbf{h}}_i - \Gamma_i \left(\sigma_i^2 + L_i\right) - \delta_i \epsilon_{h,i}^2 \end{bmatrix} \succeq 0, \quad \widetilde{\text{A1b}} \Rightarrow \begin{bmatrix} \lambda_i \mathbf{I} - \mathbf{P} & -\mathbf{P}\check{\ell}_i \\ -\check{\ell}_i^H \mathbf{P} & -\check{\ell}_i^H \mathbf{P} \check{\ell} - \lambda_i \epsilon_{\ell,i}^2 - L_i \end{bmatrix} \succeq 0, \tag{12}$$

$$\widetilde{\text{A2a}} \Rightarrow \begin{bmatrix} \mu_j \mathbf{I} + \mathbf{Z}_j & \mathbf{Z}_j \widetilde{\mathbf{f}} \\ \widetilde{\mathbf{f}}^H \mathbf{Z}_j & \widetilde{\mathbf{f}}^H \mathbf{Z}_j \widetilde{\mathbf{f}} - S_j^{\text{SI}} \Gamma_j - \mu_j \epsilon_f^2 \end{bmatrix} \succeq 0, \; \widetilde{\text{A2b}} \Rightarrow \begin{bmatrix} \rho \mathbf{I} - \left(\mathbf{U}_j^T \otimes \left(\sum_{k=1}^K \mathbf{W}_k + \mathbf{Q}\right)\right) & 0 \\ 0 & S_j^{\text{SI}} - \sigma_N^2 \text{Tr}\left\{\mathbf{U}_j\right\} - \rho \epsilon_G^2 \end{bmatrix} \succeq 0. \tag{13}$$

where we have dropped the rank constraints on $\mathbf{W}_i, \forall i$. Note that the problem (14) is a relaxed form of (6). While it is difficult to prove analytically, our simulations have shown that problem (14) always returns rank-one solutions. Still, in the unlikely case of a non rank-one solution, valid solutions can always be obtained by randomization.

IV. Robust Design With Interference Exploitation

We design our system to exploit interference rather than suppressing it as in Section III. Constructive interference (CI) is the interference that pushes the received signal away from the detection thresholds [7]. The concept of CI has been thoroughly studied in the literature for both PSK and QAM modulation in [7] and references therein, where analytical criteria are also derived. For notational convenience, we focus on PSK here. To reformulate (6) for interference exploitation, we first write the received signal at the *i-th* downlink user as

$$\begin{aligned} \widetilde{y}_i &= \left(\check{\mathbf{h}}_i + \mathbf{e}_{h,i}\right)^H \left(\sum_{k=1}^K \mathbf{w}_k e^{j(\phi_k - \phi_i)} + \mathbf{q} e^{-j\phi_i}\right) \\ &= \left(\check{\mathbf{h}}_i + \mathbf{e}_{h,i}\right)^H \mathbf{a}, \end{aligned} \tag{15}$$

where we have omitted the noise term, $\mathbf{a} = \sum_{k=1}^K \mathbf{w}_k e^{j(\phi_k - \phi_i)} + \mathbf{q} e^{-j\phi_i}$ and the unit-energy PSK symbol for the *i-th* downlink user is represented as $d_i = de^{\phi_i}$.

As detailed in [7], for any given PSK constellation point, to guarantee CI, $\widetilde{y}_i$ must fall within the CI region of the constellation. The size of the region is determined by $\theta = \pm\frac{\pi}{B}$, which is the maximum angle shift within the CI region for a modulation order B. Accordingly, the downlink SINR constraint that guarantees CI at the *i-th* downlink user [7] is

$$|\Im\left(\widetilde{y}_i\right)| \leq \left(\Re(\widetilde{y}_i) - \sqrt{\Gamma_i \sum_{j=1}^J p_j |\check{\ell}_{j,i} + e_{j,i}|^2 + \Gamma_i \sigma_i^2}\right) \tan\theta, \tag{16}$$

where $\Re$ and $\Im$ are the real and imaginary parts, respectively. In a similar fashion to Section III, the robust system design for CI can be formulated as

$$\begin{aligned} \mathcal{P}3: \; & \min_{\mathbf{a},\{p_j\}} \; c_1 \cdot \|\mathbf{a}\|^2 + c_2 \cdot \sum_{j=1}^J p_j - c_3 \cdot \sum_{m=1}^M \zeta_m r_m \|\mathbf{a}\|^2 \\ & \text{s.t. B1}: (16), \; \forall \|\mathbf{e}_{h,i}\|^2 \leq \epsilon_{h,i}^2, \; \forall |e_{j,i}|^2 \leq \epsilon_{j,i}^2, \; \forall i, \\ & \quad \text{B2}: \Gamma_j^{\text{UL}} \geq \Gamma_j, \forall \|\mathbf{E}_G\|_F^2 \leq \epsilon_G^2, \forall \|\mathbf{e}_{f,j}\|^2 \leq \epsilon_{f,j}^2, \; \forall j, \\ & \quad \text{B3}: \zeta_m r_m \|\mathbf{a}\|^2 \geq P_m^{\min}, \; \forall m, \\ & \quad \text{B4}: \|\mathbf{a}\|^2 \leq \text{P}_{\max}^{\text{DL}}, \, \text{B5}: p_j \leq \text{P}_{\max}^{\text{UL}}, \forall j. \end{aligned} \tag{17}$$

Problem (17) is a non-convex problem. To solve (17), we transform each constraint to a convex form separately in the following. Let's consider the downlink SINR constraint B1, which can be rewritten as the following two constraints

$$\left|(\underline{\check{\mathbf{h}}}_i + \underline{\mathbf{e}}_{h,i})^H \underline{\mathbf{a}}\right| - ((\underline{\check{\mathbf{h}}}_i + \underline{\mathbf{e}}_{h,i})^H \mathbf{\Pi} \underline{\mathbf{a}} - \sqrt{\Gamma_i} L_i^{\text{CI}}) \tan\theta \leq 0, \quad \forall i, \tag{18}$$

$$\sqrt{\sum_{j=1}^J p_j |\check{\ell}_{j,i} + e_{j,i}|^2 + \sigma_i^2} \leq L_i^{\text{CI}}, \quad \forall i. \tag{19}$$

Accordingly, (18) can be relaxed to the following two robust formulations

$$\begin{aligned} & \underline{\check{\mathbf{h}}}_i^H (\underline{\mathbf{a}} - \mathbf{\Pi}\underline{\mathbf{a}} \tan\theta) + \epsilon_{h,i} \|\underline{\mathbf{a}} - \mathbf{\Pi}\underline{\mathbf{a}} \tan\theta\| \\ & \quad + \sqrt{\Gamma_i} L_i^{\text{CI}} \tan\theta \leq 0, \quad \forall i, \end{aligned} \tag{20}$$

$$\begin{aligned} & \underline{\check{\mathbf{h}}}_i^H (-\underline{\mathbf{a}} - \mathbf{\Pi}\underline{\mathbf{a}} \tan\theta) + \epsilon_{h,i} \|-\underline{\mathbf{a}} - \mathbf{\Pi}\underline{\mathbf{a}} \tan\theta\| \\ & \quad + \sqrt{\Gamma_i} L_i^{\text{CI}} \tan\theta \leq 0, \quad \forall i, \end{aligned} \tag{21}$$

where $\underline{\mathbf{a}} = \left[\Re(\mathbf{a})^H \; \Im(\mathbf{a}^H)\right]^H$, $\mathbf{\Pi} = \begin{bmatrix} \mathbf{0}_N & -\mathbf{I}_N \\ \mathbf{I}_N & \mathbf{0}_N \end{bmatrix}$, $\underline{\check{\mathbf{h}}}_i = \left[\Im(\check{\mathbf{h}}_i)^H \; \Re(\check{\mathbf{h}}_i)^H\right]^H$, $\underline{\mathbf{e}}_{h,i} = \left[\Im(\mathbf{e}_{h,i})^H \; \Re(\mathbf{e}_{h,i})^H\right]^H$. Furthermore, by using the inequality $\sqrt{x^2 + y^2} \leq |x| + |y|$, (19) can be relaxed to the following robust formulation

$$\left|\sum_{j=1}^J \sqrt{p_j} \left(|\check{\ell}_{j,i}| + \epsilon_{j,i}\right)\right| + |\sigma_i| \leq L_i^{\text{CI}}, \forall i. \tag{22}$$

Next, we consider the uplink SINR constraint B2, which can be written as

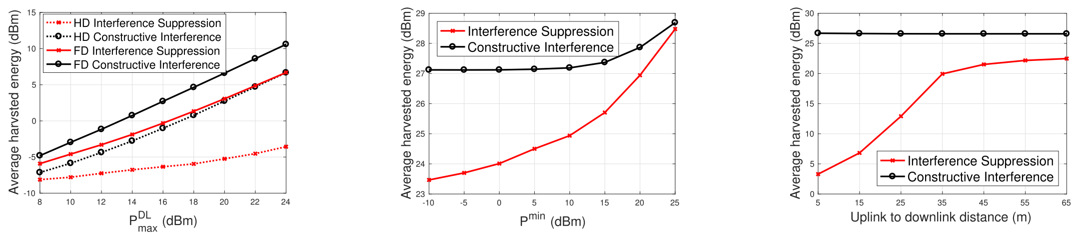
$$\begin{aligned} & p_j \left|\left(\check{\mathbf{f}}_j + \mathbf{e}_{f,j}\right)^H \mathbf{u}_j\right|^2 \\ & \quad \geq \Gamma_j \left[\sum_{n \neq j}^J p_n \left|\left(\check{\mathbf{f}}_n + \mathbf{e}_{f,n}\right)^H \mathbf{u}_j\right|^2 \right. \\ & \qquad \left. + |\mathbf{u}_j \mathbf{E}_G \mathbf{a}|^2 + \sigma_j^2 \|\mathbf{u}_j\|^2 \right], \end{aligned} \tag{23}$$

which can be relaxed using the inequality $\|\mathbf{x} + \mathbf{y}\|^2 \leq (\|\mathbf{x}\| + \|\mathbf{y}\|)^2$ to give the following robust formulation

$$\begin{aligned} & p_j \left(|\check{\mathbf{f}}_j^H \mathbf{u}_j| + \epsilon_{f,j} \|\mathbf{u}_j\|\right)^2 \\ & \quad \geq \Gamma_j \left[\sum_{n \neq j}^J p_n \left(|\check{\mathbf{f}}_n^H \mathbf{u}_j| + \epsilon_{f,n} \|\mathbf{u}_j\|\right)^2 \right. \\ & \qquad \left. + (\epsilon_G \|\mathbf{u}_j\| \|\mathbf{a}\|)^2 + \sigma_j^2 \|\mathbf{u}_j\|^2 \right] \end{aligned} \tag{24}$$

Accordingly, from (20) we have

$$-\frac{\underline{\check{\mathbf{h}}}_i^H \left(\mathbf{I} - \mathbf{\Pi} \tan\theta\right) \underline{\mathbf{a}} + \sqrt{\Gamma_i} L_i^{\text{CI}} \tan\theta}{\epsilon_{h,i} \|\mathbf{I} - \mathbf{\Pi} \tan\theta\|} \leq \|\underline{\mathbf{a}}\|. \tag{25}$$



(a) $P^{min} = -10dBm$, (b) $\mathrm{P}^{\mathrm{DL}}_{\max} = 40$dBm, (c) $P^{min} = -10dBm, \mathrm{P}^{\mathrm{DL}}_{\max} = 40$dBm

Fig. 2. Average harvested energy vs a) P^{DL}_{max}, b)P^{min}, and c) Uplink to Downlink distance

Hence, an upper bound for the ER constraint in (17) is

$$-\frac{\check{\mathbf{h}}_i^H\left(\mathbf{I}-\mathbf{\Pi}\tan\theta\right)\underline{\mathbf{a}}+\sqrt{\Gamma_i}L_i^{\mathrm{CI}}\tan\theta}{\epsilon_{h,i}\left\|\mathbf{I}-\mathbf{\Pi}\tan\theta\right\|}\geq\sqrt{\frac{P_m^{min}}{\zeta_m r_m}},\quad\forall i,\forall m. \tag{26}$$

Finally, the transformed problem (17) can be expressed as

$$\begin{aligned}\mathcal{P}4:\min_{\substack{\mathbf{a},\underline{\mathbf{a}},p_j,\beta_m,\\ L_i^{\mathrm{CI}},S_j^{\mathrm{SI\text{-}CI}}}}\ & c_1\cdot\left\|\underline{\mathbf{a}}\right\|^2+c_2\cdot\sum_{j=1}^{J}p_j-c_3\cdot\sum_{m=1}^{M}\zeta_m\beta_m\\ \text{s.t.}\ & (20),\ (21),\ (24),\ (26),\ \left\|\mathbf{a}\right\|^2\leq\mathrm{P}^{\mathrm{DL}}_{\max},\ p_j\leq\mathrm{P}^{\mathrm{UL}}_{\max},\forall j\\ & -\frac{\check{\mathbf{h}}_i^H\left(\mathbf{I}-\mathbf{\Pi}\tan\theta\right)\underline{\mathbf{a}}+\sqrt{\Gamma_i}L_i^{\mathrm{CI}}\tan\theta}{\epsilon_{h,i}\left\|\mathbf{I}-\mathbf{\Pi}\tan\theta\right\|}\geq\frac{\beta_m}{\sqrt{r_m}},\\ & \forall i,\quad\forall m.\end{aligned} \tag{27}$$

$\mathcal{P}4$ is jointly convex with respect to the optimization variables, thus can be optimally solved using standard convex solvers.

At this point, we emphasize the flexibility provided by the MOOP $\mathcal{P}2$ and $\mathcal{P}4$ with respect to optimization variables. There is a strong interdependency between the optimization variables, in that, increasing the downlink transmit power to satisfy the SINR constraints increases the SI power, which hinders the reception of uplink signals. At the same time, if the uplink transmit power is increased in order to satisfy the SINR constraints, co-channel interference (CCI) is increased at the downlink users. Similarly, minimizing the downlink transmit power reduces the amount of energy transferred to ERs.

V. Simulation Results

We consider the system with the FD BS at the center of a cell with $N = 6$. We assume $K = J = 3$ downlink and uplink users, are randomly and uniformly distributed between the distance of 10m and 50m and $M = 2$ ERs are randomly and uniformly distributed between the distance of 2m and 10m. We model the channels to the uplink and downlink users as Rayleigh fading. By assuming the same parameters as in [6], $G_t = 10$dBi$, G_r = 0$dBi$, freq = 915$MHz$, d = 5$, and using Friis equation we have an estimate channel gain $r_m = 0.00027$. Furthermore, we consider $\epsilon_h = \epsilon_f = \epsilon_G = \epsilon_\ell = 0.001, \Gamma^{\mathrm{DL}} = 8dB, \Gamma^{\mathrm{UL}} = 2dB, \zeta = 0.4, \sigma_i = -60dBm, \sigma_j = -70$dBm and QPSK modulation in all cases.

In Fig. 2, we investigate the performance of our proposed schemes with $c_1 = 0.1, c_2 = 0.1$ and $c_3 = 0.8$. In Fig. 2a, we show the average harvested energy for varying $\mathrm{P}^{\mathrm{DL}}_{\max}$. First, it can be seen that for the same overall data rate requirement the FD systems outperform the corresponding HD transmission. More importantly, it can be seen that with the proposed CI scheme more energy is harvested as $\mathrm{P}^{\mathrm{DL}}_{\max}$ increases. This occurs because less power is required to satisfy the downlink and uplink QoS constraints for the CI scheme compared to the interference suppression (IS) scheme, hence, more power is available to be harvested by the ERs. Furthermore, Fig. 2b shows the average harvested energy for different minimum harvested energy thresholds. Clearly, the CI scheme is less sensitive to the P^{min} threshold values since more transmit power is being saved from exploiting interference, while for the IS scheme less energy can be harvested. In Fig. 2c, we show the average harvested energy with respect to the distance between uplink and downlink users, that determines the CCI. The CI scheme is less sensitive to CCI compared to the IS schemes, which further highlights the effectiveness of the interference exploitation approach.

VI. Conclusion

In this letter, we studied the CSI-robust transmit power and harvested energy optimization problem in a multiuser FD SWIPT system. The proposed CI scheme shows a significant performance improvement over the conventional interference cancellation-based scheme.

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